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European Market Observatory for Fisheries and Aquaculture Products

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LIST OF ACRONYMS

AAC	Aquaculture Advisory Council
ACAC	Association of Commercial Aquaponics companies
AMPS	Alliance for Meat, Poultry & Seafood
APIVA	*AquaPonie, Innovation Végétale, Aquaculture*
ARPA-E	Advanced Research Projects Agency – Energy (US)
ASC	Aquaculture Stewardship Council
AUD	Australian Dollars
AZA	Allocated Zones for Aquaculture
BAP	Best Aquaculture Practice
BAU	Business as Usual
CAD	Canadian Dollars
CAGR	Compound Annual Growth Rate
Cefas	Centre for Environment, Fisheries and Aquaculture Science (UK)
CF	Conversion Factor
CIMTAN	Canadian IMTA Network
CN	Combined Nomenclature
COST	European Cooperation on Science and Technology
CPB	Cartagena Protocol on Biosafety
CRISPR	Clustered Regularly Interspaced Short Palindromic Repeats
CRSP	Collaborative Research Support Program
CTC	Carbon Trading Credit
DFO	Department of Fisheries and Oceans (Canada)
DG	Directorate-General (EU Commission)
DM	Dry Matter
DW	Dry Weight
EIA	Environmental Impact Assessment
EIS	Environmental Impact Survey
EC	European Commission
ECACC	European Collection of Authenticated Cell Cultures
EFSA	European Food Safety Authority
ESG	Environmental, Social and Governance (standards)
EU	European Union
EUMOFA	European Market Observatory for Fisheries and Aquaculture
FAO	Food and Agriculture Organization (UN)
FAP	Fishery and Aquaculture Products
FDA	Food and Drug Administration (US)
FIC	Food Information to Consumers
GAA	Global Aquaculture Alliance
GFCM	General Fisheries Commission for the Mediterranean
GHG	GreenHouse Gas
GIS	Geographic Information System
GM	Genetically Modified
GMO	Genetically Modified Organism
GSI	Global Salmon Initiative
GSSI	Global Sustainable Seafood Initiative

GWh	GigaWatt Hours
HORECA	Hotel, Restaurants and Cafés
HTL	Hydrothermal Liquefaction
ICAM	Integrated Coastal Area Management
ICZM	Integrated Coastal Zone Management
IDH	Sustainable Trade Initiative
IMTA	Integrated Multi-Trophic Aquaculture
IRC	International Research Consortium (EU)
ITAVI	Institut Technique de l'Aviculture
KIC	Knowledge and Innovation Community
KNR	Kilogram Nitrogen Removed
LCA	Life-Cycle Assessment
LMO	Living Modified Organism
MAP	Measuring and Accelerating Performance (of global seafood supply)
MASP	Multi-Annual Strategic Plans for Aquaculture
MCS	Main Commercial Species
MEP	Member of the European Parliament
MSFD	Marine Strategy Framework Directive
MUP	Multi-use Platform
MPP	Multi-Purpose Platform
MS	Member State
mt	million tonnes
mtpa	million tonnes per annum
MUSES	Multi-Use in European Seas
MW	MegaWatt
NAQUA	National Aquaculture Group (Saudi Arabia)
NBT	New plant Breeding Techniques
ND	No Data
NERS	Nutrient Eutrophication Reduction Services
NGO	Non-Governmental Organisation
NOAA	National Oceanic and Atmospheric Administration (US)
NOK	Norwegian Krone
NTC	Nitrogen Trading Credit
NTNU	Norwegian University of Science and Technology
OWF	Offshore Wind Farm
PAH	Polycyclic Aromatic Hydrocarbons
PAM	Partnership Assurance Model
PCA	Plant Cell Atlas
PCB	Polychlorinated Biphenyl
PCC	Plant Cell Culture
PTC	Phosphorus Trading Credit
PUFA	PolyUnsaturated Fatty Acid
R&D	Research and Development
RAS	Recycling Aquaculture Systems
RRM	Rest Raw Material
SARF	Scottish Aquaculture Research Forum
SEPA	Scottish Environment Protection Agency
SINTEF	Norwegian Institute of Technology

SLO	Social License to Operate
SME	Small and Medium-size Enterprises
SOFIA	State of World Fisheries and Aquaculture report
TL	Trophic Level
TPA	Tonnes Per Annum
USAID	United States Agency for International Development
USD	United States Dollar
WFD	Water Framework Directive
WFE	Whole Fish Equivalent
WTG	Wind Turbine Generator
WW	Wet weight

GLOSSARY

Aquaponics. A combination of aquaculture and hydroponic growing systems in which the outflows of nutrients and wastes from fish culture are used as inflows for crop culture, typically horticulture, with appropriate treatments such as sedimentation, nutrient correction, filtration *en route*. These are usually land-based recirculating aquaculture systems (RASs) but may in some countries involve a combination of engineered systems and ponds or tanks.

Benthic. Related to the sea floor, in this case the footprint under fish cages or nets.

Carrageenans. a family of linear sulfated polysaccharides that are extracted from red edible seaweeds. They are widely used in the food industry, for their gelling, thickening, and stabilizing properties. Their main application is in dairy and meat products, due to their strong binding to food proteins

CRISPR. Clustered Regularly Interspaced Short Palindromic Repeats are segments of DNA containing short repetitions of base sequences, involved in the defence mechanisms of prokaryotic organisms to viruses. In this report, the acronym is mostly used to describe a gene-editing technique, in which CRISPR and the RNA segments and enzymes it produces are used to identify and modify specific DNA sequences in the genome of other organisms

Detritivores and grazers. Usually, benthic organisms such as sea urchins or sea cucumbers that have diets of particulate matter on the sea floor. Can also be organisms such as abalone or starfish, that actively erode seaweeds and organisms such as sponges and corals. Some fish are grazers and detritivores, including carp and grey mullet.

Extractors. Organisms that absorb nutrients, such as seaweeds, or filter out particulate materials such as bivalves.

Hydrocolloids. Hydrocolloids are gums that are added to foodstuffs in order to control their functional properties, such as thickening or gelling.

Integrated multi-trophic aquaculture (IMTA). The practice which combines, in the appropriate proportions, the cultivation of fed aquaculture species (e.g. finfish/shrimp) with organic extractive aquaculture species (e.g. shellfish/herbivorous fish) and inorganic extractive aquaculture species (e.g. seaweed) to create balanced systems for environmental sustainability (biomitigation), economic stability (product diversification and risk reduction) and social acceptability (better management practices)[1].

Integrated aquaculture. Aquaculture system(s) sharing resources, water, feeds, management, etc., with other activities, mainly including agricultural, agro-industrial and infrastructural (wastewaters, power stations activities.

Microbiome. The collective microbial population living in or on objects, aquatic plants and animals, and circulating in the water. Periphyton is the microbiome on plant material that in land-based freshwater IMTA.

Peptides. Chemical agents belonging to the protein family. A peptide is composed of a mixture of several amino acids. Because of the near-infinite number of structure combinations of the constituent amino acids, peptides are widely used in medicine and industry for everything from anti-aging creams to sweetening coffee.

Recirculating aquaculture systems (RASs). These necessitate treatment of outflow water so it can be used as input water. The treatments can be physical and chemical, including sedimentation,

[1] The FAO: http://www.fao.org/faoterm/services/entryDetails.html?entryId=41410&lang=en&language=en&isWidget=true

ozonification, pH correction and filtration, or they can be biological, using molluscs, seaweeds, plants, settlement ponds, microbiome; or a combination for depuration.

Seston. All floating particles in water, whether organic, such as faeces, waste food, seaweed fragments or plankton, or inorganic, such as stirred-up sediment or sand – they include both particulate wastes from aquaculture and natural-occurring material.

FOREWORD

In 2018, EUMOFA released a groundbreaking "Blue bioeconomy: situation report and perspectives" report that provided a comprehensive overview of the blue bioeconomy sector in the European Union. By definition, "blue bioeconomy" incorporates any economic activity associated with the use of renewable aquatic biological resources to make products. Examples of these wide-ranging products include novel foods and food additives, animal feeds, nutraceuticals, pharmaceuticals, cosmetics, materials (e.g. clothes and construction materials) and energy. Businesses that grow the raw materials for these products, or that extract, refine, process and transform the biological compounds, as well as those developing the required technologies and equipment all participate in the blue bioeconomy.

The report was meant to be a one-of-kind publication for EUMOFA, which traditionally deals with typical aquaculture and fisheries, where the fish or shellfish are caught or produced for human consumption. Of course, these typical entities are still blue bioeconomy, but "traditional" ones, whereas the report focused on cutting-edge applications of aquatic biomass.

EUMOFA's foray into new territory was quite well received by the sector, when the report was presented at the kick-off event of the Blue Bioeconomy Forum in December 2018. In the wake of this success, it was decided to make the Blue Bioeconomy Report a regular publication, to be released every other year.

Building on the findings of the first report, EUMOFA hosted a stakeholder workshop that took place at the European Maritime Day in Lisbon in May 2019. An open consultation ensued, with the aim of letting stakeholders have their say on what topics the next edition, this one, would have to cover. Three topics unequivocally emerged as the most requested:

1. Integrated Multi-Trophic Aquaculture (IMTA)
2. Innovative uses for fish rest raw material (RRM)
3. Cell-plant technology and cellular mariculture

Thus, this edition of the Blue Bioeconomy Report is structured in three sections: the first overviews the past, present and future of IMTA, the second is a case study on the use of fish rest raw materials in Demark, and the third reports on the emerging technology of cellular mariculture.

Integrated Multi-Trophic Aquaculture

IMTA can be defined as the practice which combines, in the appropriate proportions, the cultivation of fed aquaculture species (e.g. finfish, shrimp) with organic extractive aquaculture species (e.g. shellfish, herbivorous fish) and inorganic extractive aquaculture species (e.g. seaweed) to create balanced systems for environmental sustainability (biomitigation), economic stability (product diversification and risk reduction) and social acceptability (better management practices)[2]. Its basic mission goals call for: i) environmental remediation of wastes from finfish farming, and ii) prospects of additional income from the added biomass of the other components.

IMTA has progressed from the land-based co-culture of fish and rice, shown in clay models of rice fields and aquatic life dating back 2 000 years to the late Han period[3], to holistic aquaculture introduced in the 1970s, to the concepts of today. References to the use of different trophic levels in aquaculture or polyculture for remediation of nutrient overloads or additional productivity date from the early

[2] http://www.fao.org/faoterm/services/entryDetails.html?entryId=41410&lang=en&language=en&isWidget=true

[3] Halwart M & Gupta MV (eds.) (2004) *Culture of fish in rice fields* FAO and The WorldFish Center http://www.fao.org/3/a-a0823e.pdf

1970s, and IMTA was in essence a reality in Sanggou Bay and elsewhere in China in the 1980s[4]. The actual phrase "integrated multi-trophic aquaculture" was introduced in 2004 by Thierry Chopin and Shawn Robinson, Canadian IMTA champions.

The report takes a good look at the state of play of IMTA in the EU and worldwide, with an analysis of its potential and of its challenges. IMTA has obtained encouraging but not commercial-scale results in most of its work to date, and has shown promising environmental and economic benefits. But difficulties remain in encouraging established mainstream producers, such as salmon farms and off-shore wind farms, to integrate the types of IMTA offered. Thus, it would seem that a new direction needs to be taken – away from the classic model of finfish cage at top, bivalve lines or cages round-about or below, and seaweed on the sea bottom. The evidence for this model is excellent in research scale and *in silico* modelling but dubious or at least inconsistent and not robust enough in real life for industry to invest and undertake the additional operational complexities that would be needed.

Moving forward in Europe, the European Parliament report of 2018[5] has proven to be a key starting point for policy changes and actions that can aid aquaculture innovations, including IMTA. It specifically calls for pilot projects on IMTA, agreeing with the Food from the Oceans scientific report that the only way to obtain significantly more food and biomass from the ocean in a short period of time is to harvest organisms at the bottom of the food chain, such as macroalgae and bivalve molluscs[6]. Even though the conditions are not yet fully in place in Europe for the wide-scale adoption of IMTA, commercial and consumer interests are both growing in light of an economic and environment case for adoption of IMTA, as well as clear policy drivers for its future development[7].

Case study: fish rest raw materials in Denmark

The case study on the use of fish rest raw materials in Demark follows a recommendation from the Roadmap for the blue bioeconomy published in December 2019, which called for options to "increase the valorisation of rest raw material from fisheries and other aquatic biomass"[8]. Rest raw material (RRM), a literal translation of the Norwegian term "restråstoff", comprises all the potentially useful material that is removed in order to prepare biomass for food use. Traditional processing of finfish, such as Atlantic cod, produces only the fillets for human consumption. In the past, everything else (the RRM) was either used for animal feed or simply wasted. Increasingly, efforts are being made to utilise RRM, extracting as much value as possible by processing it for human consumption[9].

Denmark is a big seafood nation in the EU in terms of fishery, aquaculture, fish meal/oil production, and trade. Based on the methodology for this report, the total available volume of RRM in Denmark in 2019 was between 530 000 and 540 000 tonnes. This included between 167 000 and 175 000 tonnes of RRM from the food and aquaculture for human consumption supply chain, and the 8 500 tonnes of RRM Danish fishers assumedly discarded at sea – discards that had potential for entering the economy if brought ashore. Plus, aquaculture production provided almost 18 000 tonnes of by-products (fish

[4] Fang J, Zhang J *et al*. (2016) Integrated Multi-Trophic Aquaculture (IMTA) in Sanggou Bay, China *Aquacult Environ Interact* 8: 201-205 doi: 10.3354/aei 00179

[5] Towards a sustainable and competitive European aquaculture sector P8_TA(2018)0248 European Parliament resolution of 12 June 2018 https://www.europarl.europa.eu/doceo/document/TA-8-2018-0248_EN.pdf

[6] High-Level Group of Scientific Advisors *Food from the Oceans* Scientific Opinion No. 3/2017 doi: 10.2777/66235

[7] *Beyond Fish Monoculture. Developing Integrated Multi-Trophic aquaculture in Europe* Final report of IDREEM project ETA-Florence Renewable Energies 2016 http://www.idreem.eu/cms/wp-content/uploads/2016/10/IDREEM_FINALREPORT_PRINT_710_web_2.pdf

[8] Blue Bioeconomy Forum – Roadmap for the Blue Bioeconomy, European Commission, December 2019. Available online at: https://op.europa.eu/en/publication-detail/-/publication/7e963ebb-46fc-11ea-b81b-01aa75ed71a1/language-en/format-PDF/source-115609569

[9] Ibid.

manure and self-dead fish) which were utilised in the Danish biogas plants, and Denmark had a net import of 345 000 tonnes of other marine by-products.

The case study found that RRM is mainly used for fishmeal and fish oil, animal feed, biogas and indirect human consumption, the latter use achieving the highest prices when utilised for food additives or supplements, such as the oil in Omega-3 capsules.

Cellular mariculture and cell-based seafood

The emerging technology of cellular mariculture, defined as the production of marine products from cell cultures rather than from whole plants or animals, is attracting growing interest due to its potential to address public health, environmental and animal welfare challenges. For seafood from fish cell and tissue-cultures, it represents an emerging approach to address similar challenges with industrial aquaculture and marine capture systems.

Plant cell culture systems represent a potential renewable source of valuable compounds, flavours, fragrances, and colorants which cannot be produced by microbial cells or chemical synthesis. The principal advantage of this technology is that it may provide a continuous, reliable source of plant pharmaceuticals and could be used for the large-scale culture of plant cells from which these metabolites can be extracted.

Cell-based seafood, in contrast with animal-based seafood, can combine developments in biomedical engineering and modern aquaculture techniques. Biomedical engineering developments, such as the closed system bioreactor production of animal cells, create a basis for the large-scale production of marine animal cells. Aquaculture techniques such as genetic modification and closed system aquaculture have achieved significant gains in production that can pave the way for innovations in cell-based seafood production.

The EUMOFA team acknowledges with grateful thanks the input, feedback and expertise provided by the wide range of representatives from the bioeconomy sector who kindly cooperated in the compilation of this study. A special mention goes to Meredith Lloyd-Evans, who authored the first section of the report, and to Pierre and Nicolas Erwes, who authored the third section.

1 INTEGRATED MULTI-TROPHIC AQUACULTURE

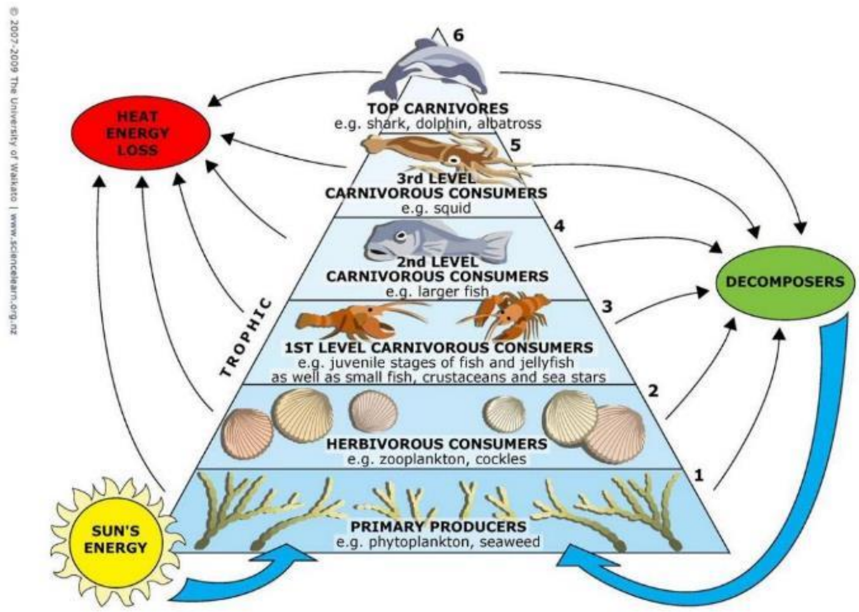
*Chapter authored by Meredith Lloyd-Evans

1.1 History and development of IMTA

> *Integrated multi-trophic aquaculture (IMTA) is "the farming, in proximity, of aquaculture species from different trophic levels, and with complementary ecosystem functions, in a way that allows one species' uneaten feed and wastes, nutrients, and by-products to be recaptured and converted into fertilizer, feed and energy for the other crops, and to take advantage of synergistic interactions between species."*
>
> Thierry Chopin, IMTA researcher, Canada (*pers. comm.* 2020)

Essentially, integrated multi-trophic aquaculture (IMTA) calls for bringing representatives of several trophic (food-chain) levels into the same production system. As shown in Figure 1.1[1], IMTA has four levels of carnivorous consumers, one of grazers and filter-feeders (herbivores) and one of absorbers ("primary producers"). Trophic level 1 (TL1) organisms include plants, microalgae, phytoplankton and macroalgae, essentially absorbers of light, nutrients and carbon; TL2 includes grazers, detritivores, and filter-feeders such as bivalves, gastropods such as abalone or whelk, and sea cucumbers and grazing fish such as carp; and TL3 includes carnivores or piscivores such as crustacea, squid and the top carnivores, such as shark, dolphin, and tuna.

Figure 1.1: Aquatic trophic levels from top carnivores to absorption organisms



Source: New Zealand Science Learning Hub; www.sciencelearn.org.nz

1.1.1 History of IMTA

IMTA has progressed from land-based co-culture of fish and rice, shown in clay models of rice fields and aquatic life dating back 2 000 years to the late Han period[2], to holistic aquaculture introduced in the 1970s, to the concepts of today. The actual phrase "integrated multi-trophic aquaculture" was introduced in 2004 by Thierry Chopin and Shawn Robinson, Canadian IMTA champions. However, references to the use of different trophic levels in aquaculture or polyculture for remediation of nutrient overloads or additional productivity date from the early 1970s, and IMTA was, in essence, a reality in Sanggou Bay and elsewhere in China in the 1980s[3].

In the 1980s, Atlantic Silver, a local producer, asked the Canadian Department of Fisheries and Oceans (DFO) for assistance in establishing mussels as a coexistent component of salmon farming, and work was initiated in the Bay of Fundy, on Canada's east coast. The scientific literature of the day reported that salmon converted only about 30% of their feed on a dry weight (DW) basis, which led to a discussion on how to access the other 70%. Recovering these lost nutrients became a driver for IMTA in general[4]. Chopin and colleagues initiated a "beyond monoculture"[5] discussion, as a result of a series of DFO-supported projects, starting in the Bay of Fundy in 2001 and in British Columbia on the west coast. In 2003, the European Aquaculture Society's "Beyond Monoculture" conference theme increased interest in the concept.

It is important to note that Canada's DFO was one of the earliest supporters of research into and development of IMTA[6]. Activities in the Atlantic coast Bay of Fundy have provided one of the most studied model systems for finfish-orientated IMTA since 2001 and, combined with sites on its Pacific coast, it has generated much of the initial positive data for benthic IMTA, finfish-mussels and seaweed IMTA. These study sites, followed for >5 years, demonstrated that on a small scale, mussels performed appropriately as particulate extractors, kelp and other seaweeds acted as dissolved nutrient extractors for salmon cages, and the sea cucumber (*Parastichopus californicus*) successfully browsed uneaten food and faeces from sable-fish farming on the west coast[7]. The green sea urchin (*Strongylocentrotus droebachiensis*) was also used as a grazer in benthic IMTA to reduce the impact of salmon farming, with some commercial interest from Cooke Aquaculture, a major multinational[8]. DFO supported the Canadian IMTA Network (CIMTAN) 2010–2017, which received more than CAD 19 million in direct and in-kind funding from DFO, the Natural Sciences and Engineering Research Council, and partners Cooke Aquaculture Inc., Kyuquot SEAfoods Ltd. and Marine Harvest Canada Ltd, plus eight universities, six federal DFO laboratories and one provincial laboratory.

The *Canadian Aquaculture R&D Review*, accessible on-line and published every two years, provides a panorama of pre-commercial work undertaken in classic IMTA (fish, mussels, seaweeds), seaweed-focused IMTA, benthic work using detritivores and grazers, plus the interactions between IMTA and microbiomes[9] which is a newer focus for investigation. Few if any projects seem to have resulted in long-term industrial use. Although the Canadian Government established two major funding programmes in 2018 – the Atlantic Fisheries Fund with CAD 400 million over 7 years[10], and the more market-orientated Canadian Fish and Seafood Opportunities Fund, with CAD 43 million[11] – at this point, there is no major programme on IMTA in Canada[12].

Outside Canada, a rough timeline of IMTA development dates from the 1980s.

- 1980s–2010. The Bellona Foundation, a Norwegian NGO, noted in 2013 that studies from the 1980s onwards had found that mussels grew faster or larger, or contained more omega-3 fatty acids and nutrient values, when grown adjacent to fish cages or in the water column 200 metres below. Kelp was able to remove 30–100% of fish-produced nitrogen and grew better in IMTA conditions rather than monocultures[13]. Given the scale of salmonid production in Norway in 2009, just over 1 mt of fish, the output of 42 750 tonnes of inorganic and bound nitrogen might have produced 1.9 mt wet weight (WW) seaweed and 64 000 tonnes of blue mussels. Mussels alone would have had a market value of NOK 3.2 bn.
- 2004–2016. Projects on IMTA began in Norway in 2004 through direct funding or as part of EU-funded projects with Norwegian partners, notably POLYCULT 2004–2006, INTEGRATE 2006–2011, MACROBIOMASS 2010–2012 and MAXIMTA, EXPLOIT and IDREEM, all 2012–2016[14].
- 2010. The first US-based workshop on IMTA was held in Port Angeles, Washington State[15]. Thierry Chopin noted that of the 96 salmon or cod mariculture sites in the Bay of Fundy area,

8 were operating IMTA with mussels and kelp, and 8 others were in the process of establishing it.

- 2010. Chopin put IMTA within the broader framework of Integrated Coastal Zone Management (ICZM), and explained that ecosystem services provided by IMTA provided justifications for investment in implementation, and establishment of nutrient and carbon trading credits[16].

In 2009, Barrington *et al.*[17] saw the necessary considerations for establishing and expanding IMTA as:

- establishing the economic and environmental value of IMTA systems and their co-products;
- selecting the right species and available technologies appropriate to the habitat and environmental and oceanographic conditions;
- ensuring species are complementary in their ecosystem function;
- matching growth rates and achievable biomass to needs for biomitigation;
- promoting effective government legislation/regulations and incentives to facilitate the development of IMTA practices and the commercialisation of products of IMTA;
- recognising the benefits of IMTA and educating stakeholders about this practice;
- establishing the research and development (R&D) and commercial continuum for IMTA.

Table 1.1shows the strengths, weaknesses, opportunities and threats (SWOT) responses of the 2010 Port Angeles Workshop, focusing on those where ≥50% (≥20/40) respondents were in agreement (numbers shown in red).

Table 1.1: Port Angeles Workshop: Perceived SWOT of IMTA

SWOT	Ecological Impacts	Economic Impacts	Social Impacts
Top Strengths	Nutrient recycling (**32**) Reduced demand for feed from pelagic fish and land crops (**23**) Increased farm production (**20**)	A new image of differentiated coastal aquaculture (**28**) Operational efficiencies with labour, operational rates, leasing (**23**) Marketing advantages (**21**)	None ≥20
Top Weaknesses	Lack of thorough understanding of environmental impacts (**32**) Currently emphasises only high value products and thus less likely to contribute to world food needs (except seaweeds) (**31**) Converts more resilient food webs to more vulnerable food chains (**21**)	Complexity: marketing, operations, juveniles, business planning (**30**) Regulatory complexity (**26**) Site-specific criteria (due to multiple species): salinity, current, temperature (**20**) Greater capital start-up costs (**20**)	Complexity (**26**)
Top Opportunities	Remediation of anthropogenic eutrophication (**21**)	"Sustainable" image (**31**) Market: pricing, high value products, packaging, niche opportunities (**21**) Use IMTA as launching platform for national aquaculture vision (**20**)	None ≥20
Top Threats	Potentially lower profitability in the short term compared with existing aquaculture systems (**31**) Not enough public funding (i.e. political will) for developing a network of demonstration and research sites to examine feasibility of IMTA (**31**) Larger scale applications may have greater environmental impact and thus less social licence (**28**)	Social acceptance, public perception (**25**) Natural threats of disease, parasites, storms (**25**) Greater regulatory requirements (**25**)	Misinformation (**30**)

Source: Bellona Report 2013 Traditional and Integrated Aquaculture

These responses show that there were more negatives than positives, with commercial, economic, regulatory and social-acceptance concerns of cost and complexity that would need to be overcome for the positives to be achieved. These and the points made by Barrington *et al*. (2009)[18] remain valid today.

1.1.2 China

No discussion on IMTA would be complete without considering China and its activities. China is the world's largest producer and consumer of fish, shellfish and seaweeds. Asia, including China, India, Viet Nam, Thailand and Indonesia, has by far the largest workforce involved directly in aquaculture. Of the 20.5 million employed globally in aquaculture in 2018, 19.6 million were in Asia and accounted for 34.5% of the total 59.5 million employed in fisheries and aquaculture[19]. China is often denoted as a model for the application of principles of IMTA. Sanggou Bay (detailed below) has been the most important example of IMTA since the 1990s[20], but China has over 50 major bay systems, many >400 km^2 in area, and with 1.3 million inshore hectares suitable for mariculture of the total 10 million hectares of coastal waters $\leq$10 m in depth.

Three types of IMTA exist in China: incidental, transitional and engineered.

- *Incidental (extensive).* The most common and almost accidental IMTA, it occurs when extractive species and fed species are farmed in the same semi-enclosed bays, leading to natural waste assimilation.
- *Transitional systems.* Intentionally optimized, these systems result when IMTA species from multiple trophic levels are selected specifically to supplement overall farm production.
- *Engineered systems.* These intensive systems remain mainly experimental in China[21], though there is an intensive programme of marine ranching involving establishment of artificial reefs[22].

The Scottish Aquaculture Research Forum (SARF) Report of 2015[23] noted that, though different species are farmed in close proximity in China, with seaweed and bivalves grown together on shared structures, the appearance of IMTA is really a coincidence of aquaculture expansion. Pollution from aquaculture and from terrestrial activities including urban, industrial and agricultural runoff and sewage is a serious problem. It has led to microalgal blooms and, starting in the late 2000s, caused seaweed blooms up to 40 000 km^2 in area due to *Porphyra*, *Ulva* and *Enteromorpha*[24]. Without the remediating effect of extractive species, fish and shellfish aquaculture would not be possible.

Sanggou Bay. Sanggou Bay's area is 163 km^2, with an average depth of 7–10 metres that increases to 20 metres at its mouth. There are shrimp farms along the inner coast, finfish farmed in the inner bay, scallops and oysters in the mid-bay, and bivalves farmed in combination with macroalgae in the outer-mid-bay. Sugar kelp seaweeds (*Saccharina japonica)* together with abalone predominate at the mouth of the bay, covering >100 km^2 and providing both a food source and waste reduction, with abalone feeding on kelp, and the kelp taking up nutrients released from the abalone. In addition, seaweeds with different growing seasons – kelp and *Gracilaria lemaneiformis* – are combined so nutrients are absorbed by the algae throughout the year, and multiple species of molluscs, other marine invertebrates and fish are farmed or harvested.

Management practices involve many small servicing and harvesting boats so that seaweed, other species and finfish can be sited very close together. The dominant system in China's coastal bays – suspended mariculture – began with seaweed in the 1950s, added scallops in the 1960s, and expanded to large-scale suspended fish cage culture in the 1980s[25]. However, Sanggou Bay supports long-lines, cages, bottom-sowing of seaweed, farming in pools in the intertidal zone and tidal flat culture[26]. The Bay's aquaculture output amounts to 120 000 tonnes of oysters in-shell, 84 500 tonnes DW of *Laminaria japonica*, 10 000 tonnes of scallop in-shell, 2 000 tonnes of abalone in-shell, 100 tonnes of finfish and 100 tonnes of sea cucumbers WW[27].

The markets for seaweeds in China have adjusted from commodity alginates, as high as 80%–90% of biomass in the early 1990s to around 60% in the mid-2000s. Since 2005, the importance of animal feed, human food and abalone farming has increased, leading to 60%–70% usage of total farmed seaweed output for food and feed, and 30%–40% for abalone and sea cucumbers, by 2018[28].

Why does IMTA work in China and not in Europe?

In China, the need for production efficiency to bolster food security and meet consumer demand is a very strong driver. In Europe, the big issue is how to find and make the markets for the additional products from IMTA[29]. The Chinese experience does not provide a suitable model for aquaculture focused on marine finfish elsewhere, except in three respects: the use of local species with high commercial value[30], the large-area approach and the application of benthic IMTA[31].

- Pollution from agricultural and human activities on land has driven China's IMTA to harness natural overgrowths of seaweed in response to eutrophicating run-offs. The degree of pollution to be remediated in Europe and the Americas hardly matches the levels in Asia, so IMTA has a proportionally much smaller impact.
- All produce from an integrated area such as Sanggou Bay finds a ready market, from seaweeds, sea cucumbers and abalone to carp, catfish and tilapia. The focus of established aquaculture in Europe and the Americas tends to be monocultures of salmonids, sea bream and sea bass, perhaps tuna or halibut, mussels and oysters.
- The price differential between high-value finfish and other harvests is much wider in Europe and the Americas than in Asia.
- Labour is still cheap in China. This makes it easier to integrate the different harvesting cycles and equipment needed for IMTA in, for example, Sanggou Bay, than on a large Norwegian fish farm or off-shore wind farm. The management and harvesting of the kelp-oyster-abalone-finfish long-lines and cages is labour intensive. For kelp in China, many small wooden boats are fitted out to allow moving in confined spaces. They can harvest 8–10 tonnes per boat at a time. Larger boats are used only to tow multiple small boats back to reception piers, where the kelp is extracted by tractor and transported to sun-drying spaces or platforms, or to pre-treatment workshops by the piers or up to 5–8 km away[32].
- Chinese markets are not squeamish about edible food for humans being fed on excreta and other wastes, while consumer opinion and legislation in other parts of the world may find this idea unacceptable.

Intent on greatly expanding its aquaculture output, China has already established more than 200 marine ranches[33,34], first in northern China and more recently, in southern, more tropical China near Hainan Island. There are special policies to support development in southern China, as part of the outward-looking reforms to increase the economy linked with establishing a Free Trade Zone[35]. A National Key Laboratory for Marine Ranching has been established at Hainan University. Along the north-south extent of the coasts, the planned state investment for growth in marine ranching by 2025 exceeds €2.35 bn, comprising 178 pilot projects with 50 million m^3 of artificial reefs in an area of 2 700 km^2. The ranch sites involve establishment or re-establishment of biodiversity and seaweeds using artificial reefs and production of economically important species such as sea cucumbers, abalone and scallops (Dalian and Hebei in the north and mid-east), fish species (in Jiangsu and Shandong in the mid-east), and fish, cephalopods and crustacea (Zhejiang in the south-east).

Guangdong in the south will capitalise on marine conservation and tourism, and Shanghai will focus on river-mouth restoration. Shandong province, home to Sanggou Bay, will have five types of marine ranches – artificial reefs, bottom-seeding, pastoral restoration in wetlands and shallow coastal waters, large offshore net cages using heavy equipment, and angling. The minimum area envisaged for full-stage marine ranches is 10 000 ha, as ranches smaller than this offer little environmental or economic benefit. The average cost for a full-scale ranch is estimated at around €700 million, but the Chinese state plan envisages income of almost six times this in annual revenue from leisure fishing, tourism and edible produce. The issues with marine ranches – including reliance on a single economic species, ignoring or destroying local ecodiversity such as mangrove forests and existing wild seaweed and bivalve beds, and building too close to the shore – will require management and best practice.

1.1.3 The market context for IMTA

FAO data shows global aquaculture output in 2018 reached 1 134.5 mt worth US$2 64 bn to the producers[36]. Overall, inland production of food fish remained predominant, accounting for 62.5% of the 82 mt of aquatic animals (virtually all fish and shellfish). There were also almost 32.5 mt of farmed aquatic algae (mainly seaweeds).

Table 1.2: EU trade in fish and shellfish 2018 – the top 5 source countries

Trade	EU-28	China	USA	Japan	Norway	Thailand
Total	€32.3 bn	€30.9 bn	€22.4 bn	€15.1 bn	€11 bn	€15.1 bn
Total Imports	€26.5 bn	€12.5 bn	€17.5 bn	€13.1 bn	€1.1 bn	€3.4 bn
Total Exports	€5.8 bn	€18.5 bn	€4.9 bn	€2.0 bn	€9.9 bn	€5.0 bn

Source: The EU Fish Market 2019 Edition EUMOFA; data rounded to 1 decimal place

Market forecasts suggest that the total seafood and aquaculture market will rise in value from €155 bn (US$180 bn) to €193 bn (US$224 bn) in the period 2018–2022[37], and will reach US$209 bn by 2025[38], with aquaculture overtaking marine fisheries. The market will remain dominated by China, which accounts for 75% of volume and value, is established in freshwater fish, seaweed and molluscs, and has a projected annual growth rate of around 4% to 2022. Of the other top nine producers, Norway and the UK are European; India, Indonesia, Japan and South Korea are in Asia; and Chile and USA are in the Americas. Indonesia and South Korea are expected to have annual growth rates of 15%–17% to 2025, while the rest are projected at 4%–9%.

Table 1.3: EU imports of fish and seafood

Country	Share of imports
Norway	26%
China	7%
Ecuador	5%
Morocco	5%
Iceland	5%
Viet Nam	4%
USA	4%
India	3%
Russian Federation	3%
Argentina	2%

Source: The EU Fish Market 2019 Edition EUMOFA

The main species imported into the EU are salmon, warmwater shrimps, other shrimps, Alaskan pollock, cod and other groundfish, tuna and swordfish. EU consumption of fish and seafood was 12.45 mt in 2017.[39] Its combination of import, export and internal sales, €32.28 bn in 2018, made the EU the world's largest single bloc market. The split between wild-caught and farmed fish and other seafood is 74%:26%, and there is around a 43% self-sufficiency. Also in 2017, within-EU production of farmed fish and shellfish reached 1.37 mt, worth around €5.1 bn.

Table 1.4 shows the main produce by volume and value. The value and volume differentials between species accounts for a large part of the reluctance of fish farming in Europe to take on IMTA involving shellfish such as mussels, and even more the integration of seaweed production.

Table 1.4: Main species of fish and other seafood produced in the EU by volume and value 2017

Species	EU output by volume	EU output by value
Mussels	35%	9%
Salmon	15%	26%
Trout	14%	14%
Oysters	7%	10%
Gilthead seabream	7%	9%
Seabass	6%	10%
Carp	6%	4%
Clams	3%	6%
Bluefin tuna	1%	5%
Total	1.37 million tonnes	€5.06 bn

Source: The EU Fish Market 2019 Edition, EUMOFA

Freshwater production accounts for about 25% of EU aquaculture output. The most important species – trout and carp – represent 93% of the freshwater production volume and 86% of the value.

Global algae production, the vast majority of which is farmed seaweed, accounts for about 28% of all aquaculture, dominated by China for microalgae, and China, Indonesia and other Asian countries for seaweeds – see Table 1.5. In 2018, aquaculture output reached 114.5 mt, worth US$263.6 bn at farmgate, with aquatic algae accounting for 28% of mass (32.5 mt) and 5% of value[40]. This differential between mass and value definitely contributes to the poor industrial uptake of IMTA involving seaweeds, except in China and other countries where seaweeds are valued as food irrespective of price. From 2000 to 2018, farmed seaweed production rose from 10.6 mt to 32.4 mt. The top five producers – China, Indonesia, South and North Korea and the Philippines – accounted for 97.5% of production, with China alone contributing 57%. The established markets for marine hydrocolloids continue to affect growth in farmed seaweed production. For example, from 2010 to 2018, Indonesia's output of farmed *Kappaphycus alvarezii* and *Eucheuma* spp. increased from <4 mt per annum (mtpa) to >11 mtpa, driven by the increase in demand for carrageenans.

Table 1.5: Seaweed production by country 2014 and 2018

Country	Output by year (000s tonnes WW)	
	2014	2018
China	13 572	18 506
Indonesia	10 148	9 320
The Philippines	1 550	1 478
RoK	1 097	1 711
Japan	455	390
KDPR	444	553
Chile	430	21
Malaysia	245	174
Norway	154	nd
Tanzania	133	103
EU	93	nd
Of which		
FR	59	
IE	30	
ES	2.2	
IT	1.2	

Source: Species Analyses 2014–2018 Edition EUMOFA[41] and *FAO SOFIA Report 2020; nd = no data; WW = wet weight*

The main species grown are Japanese kelp, *Eucheuma* and *Kappaphycus* (for carrageenans), *Gracilaria* (red algae), *Porphyra* and *Undinaria* (edible nori, laver and wakame), together amounting to over 30 mt WW (see Table 1.6).

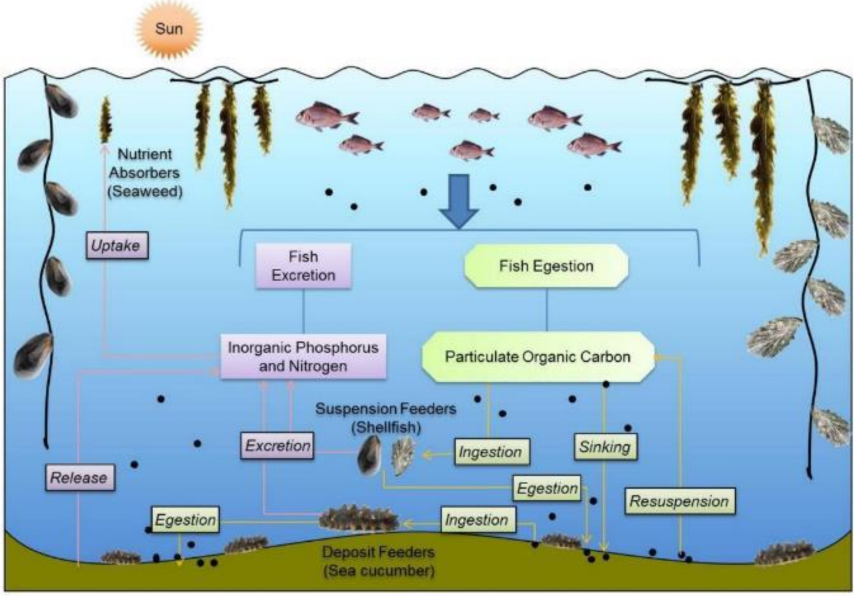
Table 1.6: Global seaweed production by species 2018

Species	Output 2018 (000s tonnes WW)
Saccharina japonica (sugar kelp)	11 448
Eucheuma spp inc *E denticulatum*	9 411
Gracilaria spp	3 455
Porphyra spp (nori) inc *P tenera* (laver)	2 873
Undinaria (wakame)	2 320
Kappaphycus alvarezii (Elkhorn sea moss)	1 597
Brown seaweeds	892
Sargassum fusiforme	269
Spirulina microalgae	70
Unspecified seaweeds and other algae	51

Source: FAO SOFIA Report 2020

Growth of benthic IMTA is favoured due to the high value of detritus feeders, such as sea cucumbers and sea urchins, especially in Asia. They can cope with particles of different sizes including finfish and shellfish faeces, mussel pseudofaeces and food debris. They can easily be introduced to finfish and seaweed farming, given appropriate containment. Figure 1.2 illustrates the typical Chinese concept for benthic IMTA.

Figure 1.2: Model format of benthic IMTA, China



Source: Zhang and Zhang et al 2019

Most of Europe's exports come from Spain, and European species, such as *Holothuria arguinensis,* can be sold for >€250/kg DW[42]. About 10 000 tonnes of dried sea cucumbers (or about 200 million individuals) are traded annually, but the majority of natural habitats have been overfished, with considerable poaching or illegal harvesting in the rest of Europe. To overcome this, Spain and Portugal have made farming sea cucumbers the focus of development projects and commercial activities.

1.1.4 EU support for IMTA and aquaculture

Since the 1980s, there has been widespread support of IMTA and integration of aquaculture with other activities such as horticulture or off-shore wind-power, from national R&D and EU funding sources.

Although it is difficult to pinpoint specific industrial uptake, commercial-scale outcomes appear to have been achieved by very few of the projects supported, though there are promising results. The following section is not intended to be exhaustive, but it highlights notable programmes and projects that provide a good resource for understanding the targets, progress and effects of IMTA. That said, a directory of aquaculture and IMTA projects would be useful, but would be a separate exercise.

Under Horizon 2020, the EU's Framework R&D and Research & Innovation Programmes, and Interreg, its interregional policy support programme, the EU has funded many projects on different aspects of IMTA. These include seaweed cultivation and valorisation, and integration of aquaculture with other marine activities such as windfarms. The Projects Annex summarises EU-funded IMTA and aquaculture projects.

The following highlights five EU-funded projects that have been, or are likely to be, important in terms of enhancing the credentials of IMTA and exploring its practical challenges.

ASTRAL[43] (2020–2024). Astral aims at Atlantic markets, with 15 partners from Norway, Spain, France, Ireland, UK, Portugal, South Africa, Nigeria, Argentina and Brazil. It focuses on: i) creating new sustainable value chains for IMTA outputs of fish, mollusc, echinoderm, crustacea and algae production, with revenue diversification, target profit increases of 30% and target circularity increases of 50% to 60% compared with monocultures; and ii) creating engineering and IT systems to support these objectives. There are several industrial partners, including Viking Aquaculture, which is involved in mariculture in South Africa, Bioceanor, which provides real-time water monitoring and the French cluster Pôle Mer Bretagne Atlantique.

AquaVitae[44](2019–2023). With 70 scientists from 16 countries on 4 continents, AquaVitae's overall objective is to increase sustainable aquaculture production in and around the Atlantic Ocean by growing new and emerging low trophic species and improving the productivity of existing aquaculture, including macroalgae production and IMTA, and production of new echinoderm species as well as of existing shellfish and finfish species[45]. Because many of the species have been studied but have not advanced to their commercial potential, AquaVitae aims to: i) create active networks of Atlantic region researchers, industry and other aquaculture stakeholders; and ii) expand the possibilities for viable farming of low-trophic species, on the grounds that they have virtually no input requirements during growth and can provide significant environmental and economic benefits while also increasing resilience and adaptive capacity, biodiversity and robustness in the European and Atlantic aquaculture industries.

IMPAQT[46] (2018–2021). IMPAQT is looking to develop, test, validate and establish practical monitoring, decision-making and actuating systems for IMTA management – inland, coastal and off-shore. Essentially, this will mean creating a multi-purpose, multi-sensing and multi-functional management platform for sustainable IMTA production[47]. Even in countries where IMTA is already practiced (mainly in Asia), management of large-scale IMTA areas remains difficult, because there is limited knowledge of how the separate components in the IMTA ecosystem interact and function as a whole, as well as what the impact is on the environment and the broader community in regions that practice it[48]. So IMPAQT focuses on understanding the interactions with the environment on the scale of an ecosystem – in a way that can be used for planning decisions by both farmers and regulators, as well as producing an integrated management system and operating at the scale of an IMTA farm. There are six test sites validating the new systems:

- seaweed and mussels on the same long-lines (UK);
- seaweed, floating solar panels, shellfish cultivation and shellfish-bank restoration, with passive fishery such as lobster cages (NL);
- lobsters in stacked plastic trays, fish (currently *Salmo salar*) in 20-metre diameter circular plastic pens, and seaweed across the pens and on long-lines, with potential to change seaweed spp from *Ulva* and add lumpfish and wrasse cultivation (IE);

- commercial land-based RAS with perch (*Perca fluviatilis), Artemia* feed production on-site and duckweed (*Lemna)* bioremediation (IE);
- commercial sea bass in cages with mussels and later *Ulva* and *Gracilaria* on long-lines (TR);
- commercial IMTA site in Sanggou Bay with multiple aquaculture industries, 0.5–2.0 km off-shore, using seaweed and shellfish on long-lines, benthic culture of sea cucumber, sea urchin, finfish, abalone, clam and sea snails, an artificial reef and seagrass beds (CN).

IDREEM[49] (2012–2016). The IRC-IMTA IDREEM included the North-West Europe and Mediterranean seaweeds, finfish, mussels, oysters, scallops and detritivores in its remit. Most of its results were neutral, mildly positive or disappointingly negative, some because of difficulties of managing biology (e.g. the variable growth of seaweed from season to season), some because lines were 150 to 300 metres from the finfish and thus too far to show successful nutrient remediation, others because the generally poor nutrient availability in the Mediterranean limited the growth of the IMTA species. IDREEM concluded that: i) instituting larger scale uptake of IMTA in Europe required standards for IMTA and certification systems to secure market benefits; ii) a water-body approach to IMTA might be more effective than a site-by-site approach; iii) a better, more coherent, more favourable regulatory framework was essential, within a clear policy; iv), a focus on benthic IMTA is attractive for site-by-site IMTA as it enables sea-bed nutrients to be used and the immediate environment remediated; and v) development of sustainable markets for aquaculture seaweed biomass in Europe is needed[50].

Individual countries in Europe support aquaculture and have supported IMTA strongly, including Portugal, Norway, Scotland, Spain and Germany. In Germany, for example, projects initiated by the Alfred Wegener Institute for Polar and Marine Research since 2000 have largely focused on open-water multi-use/multi-purpose platforms and on IMTA. Much work has been done under the aegis of the SUBMARINER Network and the EU-funded projects in which it has been a partner, such as the Multi-Use in European Seas (MUSES)[51] project.

1.2 IMTA today

1.2.1 Species for IMTA

In 2009, Barrington *et al.*[52] identified species with high potential for IMTA systems in marine temperate waters to be grown with primary finfish*.* The species included:

- seaweeds – *Laminaria, Saccharina, Sacchoriza, Undaria, Alaria, Ecklonia, Lessonia, Durvillaea, Macrocystis, Gigartina, Sarcothalia, Chondracanthus, Callophyllis, Gracilaria, Gracilariopsis, Porphyra, Chondrus, Palmaria, Asparagopsis* and *Ulva*;
- molluscs – *Haliotis, Crassostrea, Pecten, Argopecten, Placopecten, Mytilus, Choromytilus* and *Tapes*;
- sea cucumbers and sea urchins – *Strongylocentrotus, Paracentrotus, Psammechinus, Loxechinus, Cucumaria, Holothuria, Stichopus, Parastichopus, Apostichopus* and *Athyonidium*;
- polychaete marine worms – *Nereis, Arenicola, Glycera* and *Sabella*;
- crustaceans – *Penaeus* and *Homarus*;
- finfish – *Mugil*, grey mullet.

Kleitou *et al.*[53] surveyed producers involved in aquaculture and IMTA and found that, as of 2018, there had been little progress in Europe. Only *Alaria*, sugar kelp (*Saccharina)*, mussels and scallops were being used as extractive or filtration species in commercial aquaculture and only 6 of the 12 European countries involved were in their survey (DK, IE, NO, PT, ES, UK). The tables in Annex II summarise Kleitou *et al.*'s findings.

The primary finfish that are the focus of aquaculture and IMTA in Europe are just a few of the potential species Barrington *et al.* (2009) identified. These include Atlantic salmon (*Salmo*)*,* Pacific salmon

(*Oncorhynchus*), turbot (*Scophthalmus*), seabass (*Dicentrarchus*), Atlantic cod (*Gadus*), sablefish (*Anoplopoma*), halibut (*Hippoglossus*), haddock (*Melanogrammus*), and flounders (*Paralichthys* and *Pseudopleuronectes*). In Europe, predominantly Atlantic salmon, seabass and sea bream have been taken up in IMTA, with grey mullet as browsers. The list is similarly short in freshwater IMTA, with carp species, *Tilapia* and, in Eastern Europe, sturgeon.

Mussel, oyster and scallop farming are well-established in Europe, and the potential for co-culture with seaweed is high. As is pointed out elsewhere in this chapter, certainly mussels and seaweeds will co-exist on the same longlines. In IMTA, interest is extending to invertebrates besides molluscs and crustacea, including cephalopods, sea urchins and sea cucumbers.

> *"Much work has been done on farming of those cephalopods [that have been considered for IMTA with finfish]. However, success in commercial implementation has been hampered by the need for expensive live food. In the UK, common octopus* (*Octopus vulgaris*) *disappeared around 1962–63 because of cold winters and is now just making the first steps back. However, there are still not enough juveniles in UK waters for them to be collected for growing in cages in the Channel, as was done in the past, so it is not possible to see what might be commercially viable."*[54]
>
> Vladimir Laptikhovsky, Cefas (*pers. comm.* 2020)

The potential of cephalopods is an interesting topic. Of their total body weight, 80–85% is edible, 75–85% of their dry weight is protein, their live weight gain can be 10% or more daily with feed conversion ratios of 2:1 or 3:1, and rather than the 3 years required for salmon, a crop can be ready in 4–18 months depending on species[55]. There are buoyant cephalopod markets in Europe and Asia, especially Spain, Italy and Japan, but hatching and breeding in quantity has not been solved. Wild-catching of juveniles and fattening them to harvest are the norm for octopus, sepia and other cephalopods. Small-scale and artisanal farming are used for the European cuttlefish (*Sepia officinalis*), the bigfin reef squid (*Sepioteuthis lessoniana*) and the Mexican four-eyed octopus (*Octopus maya*), which all produce relatively large and mature benthic-type hatchlings with good survivability. *Octopus vulgaris* is widely captured wild as semi-adult and finished in cages, e.g. in the Canary Islands. IMTA has been considered for cuttlefish or octopus with finfish. Cephalopod excreta is a mix of particulate faeces and ammonia, so there may also be a role for IMTA using bivalves, seaweeds and detritivores. Seaweeds would also provide substrates for egg masses. IMTA involving these would need to take account of the culture conditions that trigger the maturation from hatchlings to market-weight adults, as well as the specific behaviours of different species. Currently, in cultivation, larval crustacea, crabs or shrimps form the main part of feed for growing cephalopods. The skeleton shrimps (*Caprella equilibra* and *Caprella scaura*), which can be grown in IMTA, are potentially a feed source for a variety of higher trophic species including finfish and cephalopods, due to their high content of polyunsaturated fatty acid (PUFA), polar lipids and protein[56].

> *"It is possible to envisage where seaweeds might be grown to provide remediation by mapping run-off. Sometimes this might amount to IMTA, but actually the seaweed itself is enough to provide the desired ecosystem service. A problem with IMTA using seaweed is the value differential between the seaweed and finfish, and the increased need for investments. However, the positive impact of seaweeds means that this aspect can continue even if fish farming moves off-shore to deeper water. The end effect, if there happen to be shellfish or finfish farms nearby, might be equivalent to IMTA – they would not be co-located as long as appropriate nutrients are available for encouragement of seaweed growth."*[57]
>
> Pi Nyvall Collén, Scientific Director, Olmix Group (*pers. comm.* 2020)

Seaweeds are regarded as the IMTA species *par excellence*, capable of absorbing dissolved nutrients and growing faster in season than land crops. In Europe, the classic IMTA assemblage of salmon, mussels and macroalgae was first studied for its ability to capture waste nutrients from fish farming in Norway[58]. Norway has an explicit strategy for a Norwegian bio-economy based on cultivated seaweeds, building on its experimental cultivation of kelps in 2005 and its first commercial permits for seaweed farms issued in 2014. The Norwegian Institute of Technology (SINTEF), the Norwegian University of Science and Technology (NTNU) and The Research Council of Norway have been strong players in this, and *The Research Council of Norway* is currently funding projects on the remediation and diversity potential of seaweeds as low-trophic marine crops[59]. There have been many positive results from seaweed either in IMTA or monoculture in the broader water areas near fish farms, with glimmerings of commercial viability, and these are shown in the Project Annex I.

Commentators can see pros and cons of seaweed IMTA and tend to view spatial IMTA as more promising than co-located site-specific IMTA. The challenges come from practicalities of culture and harvesting, especially in close proximity to fish farms, preservation and transport, and the need to establish and maintain economic processes, viable new end-products and profitable value chains.

The following identifies some activities that are or will become commercially-successful.

- *Seaweed Energy Solutions*[60], established in 2009 in Frøya, Norway, operates one of the largest seaweed farms in Europe. It develops cultivation technology including its Seaweed Carrier, to make in-sea farming easier, and has been or is a partner in several EU-funded projects using this for economic large-scale production, such as GENIALG. *Lerøy Seafood Group, EWOS, Bellona* and others are establishing the best production technology for winter production of *Alaria esculenta*, *Laminaria digitata*, *Porphyra* and *Saccharina latissima*, looking at biogas, fertiliser, restaurant food and fish feeds as end-products.
- *Lerøy Ocean Harvest*, a joint venture between Lerøy Seafood Group and the NGO, Bellona Foundation[61], provides a positive case study for successful integration of seaweeds into a commercial salmon farming operation[62]. The collaborative work began using very traditional IMTA with sugar kelp (*Saccharina latissima*) on lines next to the fish cages. The idea was to capture N, P and C, sell the seaweed, and thus establish a new aquaculture species for Europe. To get a direct benefit, Lerøy found that the seaweed should be no more than 100 metres, but ideally 50 metres from the cages. The main issue was with the boats servicing the fish for feeding, grading, sea-lice treatments, vet care and harvesting – this led to too much complexity, with 10^3s metres of long-line when seaweed was growing out. Space for operations was ultimately the deciding factor against co-location. In discussion with Bellona, it was agreed that there was no need to capture the N, P, C from the fish themselves, as long as the biomass could be shown to capture it from the local environment using accepted measurement methods. This has allowed Lerøy Ocean Harvest to separate the fish farms and the seaweed, and choose sites with optimum growing conditions for each species instead of a compromise, in what can be called "decoupled mass balance IMTA". The company is also growing blue mussels but again on separate sites. It has found that separate sites are definitely needed to harvest the different biomasses properly.
- There have been few problems with fouling, even when growing seaweeds alongside the cages, as seaweed is harvested before sexual maturity. It has been working hard on industrialisation of the process, and improved harvest from 4 tonnes per day to 4 to 5 tonnes per hour. Separate sites also allow proper conservation of seaweeds. So, it has been able to reduce the cost considerably. Scaling-up will present some challenges, e.g. whether to set up near the coast or further out, with the weather and wave problems of open-sea farming. However, fish farmers should be able to build on their knowledge of operating in the oceans to grow seaweed, and new tools will make the biology as efficient as possible.
- *Tassal*, an Australian company, has been investigating kelp IMTA as a nitrogen-bioremediation system for Atlantic salmon farming[63,64]. Earlier research showed that nitrogen from fish pens is quickly dispersed in the water column from 100 metres down-current, so Tassal is looking at nitrogen balance across larger sea areas, such as the D'Entrecasteaux Channel where the Tasmanian Government has imposed a nitrogen cap that restricts aquaculture growth. Of the >1 000 native seaweeds, three have the most potential for long-line cultivation – giant kelp (*Macrocystis pyrifera*), golden kelp (*Ecklonia radiata*) and Tasmanian kombu (*Lessonia corrugata*) – and all have existing markets. Tassal is studying these at all its fish farm sites, with a view to harvesting for human consumption and alginates. *Giant kelp* can also be used for aquaculture feeds and extraction for bioactive fucoidans. A seaweed nursery has been

established and surplus seedlings of giant kelp are being used to re-forest areas where they had been abundant but disappeared in recent times.

IMTA may have merit when it is used for self-sufficiency or for decentralised food production for smaller community farms where seaweed and bivalves can be grown on the same lines[65].

Another potential component of IMTA, the microbiome, has only recently come under investigation. The list below identifies some of the interesting results associated with microbial manipulation.

- *Intensive production of sturgeon (Acipenser*) – the use of earth ponds with common carp (*Cyprinus carpio*), silver carp (*Hypophthalmichthys molitrix*) and common nase (*Chondrostoma nasus)* as detritivores and plant grazers, with plastic substrates for periphyton, the aquatic attached microbiome, and methanol added as a fertiliser, led to improved water quality, higher total fish production and greater individual weights of lower-trophic fish[66].
- *Increased lengths and weights of tilapia seen* at harvest, in experiments using bundles of sugarcane bagasse as substrates for periphyton microbes, which the tilapia then graze on[67].
- *Improved productivity of polyculture systems* involving carp with Nile tilapia (*Oreochromis niloticus*) and sahar (*Tor putitora*) without increasing inputs. This resulted from enhanced periphyton growth in aquaculture ponds, which removed excess nutrients, decreased negative environmental effects and increased the weight-gains of periphyton feeders such as rohu, catla, and common carp, in a project supported by the AquaFish Innovation Lab of Oregon State University, USA[68].
- *Use of metagenomics in aquaponics* to investigate the microbes responsible for the plant growth-promoting effects and antifungal activity of aquaculture effluents against the plant fungal pathogens *Pythium ultimum* and *Fusarium oxysporum.* Investigations were supported by the Canadian DFO[69].

With increasing use of metagenomics and the continued expansion of effective prebiotics and probiotics to replace antibiotics, manipulation of microbiome is likely to become more important in aquaculture itself, and could provide an opportunity for IMTA.

1.2.2 IMTA systems

Pellegrom *et al*. (2018)[70] provide a useful summary of different aquaculture systems, including IMTA, RAS and aquaponics (see Table 1.7).

These systems all build on the two traditions – marine finfish monoculture of Europe and the Americas, and coastal polyculture of Asia. Benthic IMTA focuses on mitigating impacts of monoculture on the water column and seabed directly below, or making use of the different layers of marine habitat in an area. Multi-use or multi-purpose platforms (MUPs or MPPs) initially explore the potential for integration of monoculture (salmon, seaweed, possibly bivalves) into oil, gas, wind or wave energy installations, then secondarily offer opportunities for IMTA.

There is a move towards concepts of "ecological engineering", spatial IMTA and other terms that suggest that the different trophic levels are not tightly co-located but are separated in a way that recognises prevalent hydrological characteristics such as current flow, tidal and wave dynamics and water-column mixing. In 2014–2015, the KOMBI project in Denmark established a full-scale IMTA farm using this concept, where mussels on nets were trialled for bioremediation several miles away from rainbow trout[71]. Lerøy Ocean Harvest's commercial success, as mentioned earlier, depends on acceptance of spatial IMTA.

Table 1.7: Pros and Cons of different aquaculture systems

System	Positive outcomes	Negative aspects
IMTA	Sustainable use of nutrients Mitigation of environmental impacts	Potential for increase in disease spread due to close proximity of spp. Not so suitable for large-scale farms No consensus on feasibility and economic outputs of upscaling
Open-cage	Low investment costs	Risk of eutrophication Escapees due to damaged cages Cross-breeding with native fish through spawning
Multi-use	Lower investment in infrastructure Combined maintenance Efficient use of space	Clashes of interest between aquaculture and the other industries involved Lack of incentives for windfarm industry to cooperate Integration of management difficult Knowledge gaps Highly site-specific
RAS	Sustainable use of nutrients Mitigation of environmental impacts Potentially interesting in combination with renewable energy sources	High energy consumption Expensive systems, large investments
Aquaponics	Sustainable source of nutrients for agriculture Suitable for small-scale farming Potential for urban food supply	Little stimulus to apply due to perception that incentives are low and risks are high Use of chemicals in agriculture may be a hazard for aquaculture
Automation and digital technology	Useful for regions with high labour costs Better resource efficiency Better management of environmental impacts Better monitoring of condition, disease, performance Make aquaculture in less-accessible places feasible, such as Multi-Use, Wind Farms, Ocean ranching Potentially better integration with infrastructure and logistics of other industries	Technology gaps Expensive to develop and install Potential economic gains do not yet justify uptake Labour costs in many aquaculture regions are low, reducing applicability and/or attractiveness

Source: adapted from Pellegrom et al. (2016)

Benthic IMTA. By contrast to spatial IMTA, the essential aspect of benthic IMTA is to confine the remediation effect and additional species to the footprint of the primary production. This becomes more manageable than area IMTA or larger-scale seaweed cultivation, though the challenges of harvesting and clashes with infrastructure and operational management need to be overcome. Benthic culture also fits the diversification driver for IMTA.

Benthic IMTA seems to have reasonable prospects, though in 2017, Seas At Risk noted that there was still a need for research in the EU into the technical and biological constraints[72]. Sea cucumbers, the favoured component of benthic IMTA concepts, perform well in association with seaweeds such as *Ulva lactuca,* molluscs such as Pacific oysters[73] and finfish such as sea bream (*Sparus aurata*)[74]. Maintaining them efficiently in benthic IMTA requires commercial farming, and there are very few successful large-scale holothurian hatcheries, mainly in China, Madagascar and Australia. Saudi Arabia's National Aquaculture Group (NAQUA) grows sea cucumber (*Holothuria scabra*) in the Red Sea[75], and the conservation group Blue Ventures[76] has been working with local communities in Madagascar and Tanzania to encourage sea cucumber farming for over 10 years. In Tanzania, co-culture of sea cucumber and red seaweed (*Eucheuma denticulatum*) (a carrageenan producer) successfully increased the rate of seaweed growth and reduced the organic matter content of sediments[77]. At the moment, there is no fully commercial sea cucumber producer in Europe. Marine Resources Management (MaReSMa)[78], based near Faro, Portugal, has worked with sea cucumbers since 2012, identifying the local species *Holothuria arguinensis* and *H. polii* as the best culture candidates for the Mediterranean region, and investigating how to farm them in benthic IMTA[79]. A MaReSMa researcher has set up the university spin-out Guatizamar[80] in Spain, which received a hatchery licence in 2019. The hatchery will use *Holothuria arguinensis* so that habitats can be replenished, benthic IMTA can be promoted, harvesting and export can be managed sustainably, illegal fishing can be reduced and spawn can be provided to other companies for farming.

Good results on growth and waste nutrient recycling have been reported from more complex benthic IMTA, including combinations of the northern sea cucumber (*Cucumaria frondosa*), the green sea urchin (*Strongylocentrotus droebachiensis*) and the sea scallop (*Placopecten magellanicus*) in Canada between 2014 and 2016[81], the purple sea urchin (*Paracentrotus lividus*) with *Ulva lactuca* in effluents from gilthead bream aquaculture in Israel[82], and polychaetes (marine worms high in oils and protein and usable in fish feeds) in cultivation trays under salmon cages, in The Research Council of Norway's Havbruk 2019 low-trophic organisms programme[83]. The skeleton shrimps (*Caprella equilibra* and *Caprella scaura*) may also be suitable as detritivores and components of benthic IMTA, and have a high content of PUFA, polar lipids and protein[84].

It is also possible to combine herbivorous fish and detritivores with primary finfish, a good example being flathead grey mullet (*Mugil cephalus*), a Mediterranean and warmwater fish, grown in Israel with gilthead seabream as part of the IDREEM project, with promising positive impacts on fish growth, waste nutrient recycling and ecoremediation[85]. The nutrients from the seabream also stimulated a 10-fold increase in the growth and yield of *Ulva lactuca* seaweed seeded under the seabream cages.

Multi-use and multi-purpose platforms. This concept deliberately combines aquaculture with off-shore energy generation or oil or gas extraction. IMTA may develop from this, by establishing more than one farmed species or because biodiversity is stimulated around an off-shore multi-use or multi-purpose platform (MUP, MPP) or wind-pylon, and the yield of saleable species may be enough to justify deliberate harvesting.

> *"The potential around the UK coast is huge for wind-farms but the timescales for permits, building and planning are too long for IMTA. New designs of wind-farm machines and lay-outs may incorporate IMTA, for example as in the Netherlands and Belgium, where new wind-farm licences are favourably-viewed if aquaculture or IMTA is included."*
>
> Andy Wilkinson, COO of seaweed-extraction company, Oceanium (*pers. comm.* 2020)

This approach is at a much earlier stage of investigation than RAS, mariculture or benthic systems. Indeed, even integration of fish, shellfish or seaweed monoculture with off-shore structures is contentious, partly because licences for off-shore wind farms (OWFs) do not normally allow other activities in the permit area, and the interests of OWF operators rather than aquaculture operations are paramount.

Schulz-Zehden *et al*. (2018)[86] see mussels and seaweeds as the most promising species for MUPs/MPPs, because these extractive species are relatively low maintenance and require less hands-on management than primary finfish in cages. There have been encouraging results with these on OWFs in Wales[87], the German North Sea[88], and the EDULIS project[89] in Belgium where the pilot wind farms are 27 km and 46 km from the coast. The insurance company Lloyds Register, via its Foundation, is looking at the risks for food safety and quality, employee health and environmental pollution of seaweed aquaculture-OWF Multi-Use, to develop better assessment of insurance risk, in the SOMOS project[90], which has itself led to five further EU-funded projects.

Managed "natural" IMTA. Natural IMTA includes artificial reefs and marine ranching. It can be possible in European waters. Obsolete oil rigs have great potential as artificial reefs, supporting fish larval production and marine biodiversity. The Rigs-to-Reefs organisation estimates the cost of a single rig-to-reef conversion is >5 times cheaper than dismantling and removing a rig entirely (Schulz-Zehden *et* *al*. 2018). Oil company AGIP's Paguro platform sank in the northern Adriatic Sea in 1965 and became heavily colonised down to 15 metres by mussels and from 15–25 metres by oysters, provided habitats for invertebrates such as sea urchins and polychaetes, and gave some optimism for ecological services, if not potential harvesting[91]. Repurposing of oil and gas structures would also enable fish farming to move further offshore. Reefs can be built from waste materials such as oyster shells. In a study of these in China's Shandong peninsula, they attracted a wide range of biodiversity and harvestable species, including sea cucumbers, bivalves and detritivores, and the finfish that fed on them[92].

Marine ranching. This is aimed at deeper water mariculture and encourages species to establish themselves, to be followed by the harvest. It may involve establishing artificial reefs or seaweed forests to provide catchment. The SUBMARINER programme set up a natural IMTA project in which plastic nets were installed in the Rødsand 2 OWF in the North Sea in order to harvest the biofouling organisms, in collaboration with the E.ON energy company[93]. E.ON's boat allowed installation but was too big for sampling and harvesting trips, so the project team recruited local fishermen's boats. During the project, the nets were colonised by mussels and the seaweeds *Ceramium* sp, *Polysiphonia* sp, *Pilayella littoralis* and E*ctocarpus siliculosus*. It was possible to harvest 15 kg mussels/m^2 of nets, with the projected total biomass equivalent to 2.6 tonnes of sequestered N/ha. If this harvest could be maintained over a larger area, only 25% of the Rødsand 2 field would be needed to satisfy 13% of Denmark's 2021 commitment to N reduction. Although this project was regarded more as an exploration of MUPs than of marine ranching, it may help develop a blueprint for European marine ranching on the lines of those in China[94], as mentioned in Section 2.2.

Recirculating aquaculture systems. RASs require creation of a closed or virtually-closed system by taking outflows from the main crop tanks or ponds, passing them through a range of physical and biological treatments to remove wastes, particles and pollutants, and then returning the improved water into the system.

> *Land-based recirculating aquaculture systems (RAS) could reduce potential impacts on the marine environment and the nutrient rich effluent can be further used in the food production system … However, economic analysis currently indicates this technology is uncompetitive and liable to fail commercially unless the product is a high value and/or niche species … such systems also require high capital costs and energy requirements [but] may offer more potential opportunity with any future technological advancements in energy production.* (Roberts, Newton *et al*. 2015)[95]

RASs are now widely used for on-land production of marine fish, freshwater fish and freshwater stages of marine fish, such as salmon fry and fingerlings. Establishment of RASs has been driven by the need to conserve water, the possibility of recovering nutrients from waste feed and excreta, and the chance to avoid diseases that could emerge within extensive mariculture or earth pond freshwater production. On the engineering side, denitrification reactors, sludge thickening technologies (to >15% DM) and the use of ozone have been highly effective. On the biological side, IMTA and aquaponics are both seen as opportunities to make use of nitrogen, phosphorus and carbon in water outflows. In RASs, the CO_2 levels increase by at least three orders of magnitude, and seaweeds as part of RAS IMTA could therefore act as a carbon-capture corrective[96].

The Recirculating Farms Coalition[97] promotes RAS as a more efficient and environmentally friendly form of aquaculture that can be instituted for local sustainable food production in coastal, rural and urban settings. Integration between fish production and capture of waste nutrients via plant and crop production is seen as an integral part of this.

Land-based salmon farms, most focused on Atlantic salmon, are increasing in number throughout the world. If all projects succeed, the planned output is 1.7 million tonnes by 2030 (E Junge Hess, Senior Analyst, Kontali 2020). Atlantic Sapphire, with 3 000 tpa planned in Denmark, is adding a RAS farm in Florida capable of satisfying 50% of the US's projected demand by 2030, investing US$350 million to produce 220 000 tpa. Nordic Aquafarms is aiming to increase its output from 1 500 tpa at its Frederikstad Seafoods RAS farm in Norway by building in Maine and California, planning to produce 25 000 tpa at each site[98]. Salmon RAS is also established in the United Arab Emirates. In addition to other projects from Scandinavian producers, salmon RAS farms are in progress in Poland, Russia, Iceland and Switzerland, in a First Nation land in British Columbia, Canada (Kuterra), and in Chile, Japan, China and South Africa.

Fish other than salmon can be combined with seaweeds or halophyte plants in RASs. ALGAplus, Portugal, has made progress in this, with its early work showing that the local seaweed (*Gracilaria vermiculophylla)* removed nitrogen from the effluent of a land-based turbot and sole RAS, suggesting a requirement for a 0.36 ha seaweed farm for 100% removal (Abreu *et al*. 2011)[99]. Food halophytes such as sea aster (*Tripolium pannonicum*), buck's-horn plantain (*Plantago coronopus*) and the glasswort or samphire (*Salicornia dolichostachya)* have been grown in the water treatment system of an RAS for European sea bass (*Dicentrarchus labrax)*, with positive impact on growth of fish and plants, plus retention of 9% of the phosphorus and 10% of the nitrogen produced by the fish[100].

Irish company Keywater Ltd, based on work in the IMPAQT EU project[101], produces trout and perch (*Perca fluviatilis*) for sale[102] on a land-based windfarm site that also has on-site *Artemia* production and a duckweed pond for bioremediation.

RASs involving abalone (*Haliotis midae)* and seaweeds, originally *Ecklonia maxima* and later *Ulva* and *Gracilaria*, have had to be instituted in South Africa to keep the markets satisfied for the abalone, as it has become impossible to sustain wild harvesting of the seaweed. By the early-to-mid 2000s, 13 farms were producing >850 tonnes of abalone a year, requiring > 6 000 tonnes a year of kelp[103]. RASs here have proved successful, with seaweed as feed for abalone and removing ammonia from the outflow, enabling partial water recirculation, saving up to 40% of water pumping costs and greatly reducing the ecological footprint of the operation[104].

Shrimp in coastal ponds are no better than salmon at making use of their feed: up to 40% is lost due to their nibbling behaviour, and they fail to absorb an estimated $\leq$77% of the nitrogen and $\leq$89% of the phosphorus in feed pellets, leading to eutrophication, algal blooms, light reduction in ponds, bacterial overgrowth and hypoxia[105]. A 2007 estimate that 43 billion tonnes of wastewater from shrimp farming are released into Chinese coastal waters every year shows the scale of potential pollution. This level of environmental challenge from feed and faecal nutrients will respond positively to IMTA, with bivalves and seaweed proposed as feasible, using water capture from pond outflows, aeration systems, and recycling via mussels, oysters and seaweed in tanks.

EUMOFA has just produced a specific report on RASs, and the reader is directed to that for more detail – *Recirculating Aquaculture Systems*[106] (ISBN 978-92-76-25202-3 doi: 10.2771/66025).

Aquaponics. This takes RASs one stage further, bringing fish production and horticulture crop production into a recirculating system, either integrated in one activity or as connected parallel production sites.

> *Using an aeroponic array as a water filter to maintain a good, clean and highly oxygenated water environment for invertebrates and fish is a good idea as long as the horticulture crop, although usually very good quality produce, is considered as secondary and fish health is prioritised.*
>
> Jason Hawkins-Row, CEO of vertical crop company, Aponic Ltd

The horticultural side is intended to benefit from the nutrients in the fish effluents and can be either tank based or vertical. The European Parliament Research Services 2018–2019 named aquaponics one of the "ten technologies which could change our lives." It was also named an enabling technology in the Climate-KIC 2019 competition on Urban Food from Residual Heat and the 2018 Reinventing Cities competition[107].

There are commercial land-based RAS salmon farms that use aquaponics to recapture waste nutrients, especially phosphorus, examples being a hatchery operated by Cooke Aquaculture in Canada[108], and Superior Fresh, located in Hixton, Wisconsin, USA, and stated to be the world's largest aquaponics site[109]. This produced 72 tonnes of salmon in 2018 and is planning expansion of its crops, spinach, rocket, leaf greens and plants capable of being packed as mixed leaves. A useful resource is provided by websites that show sites of aquaponics activities. APIVA's, in France, identifies 16 established commercial operations, 22 businesses trialling aquaponic production and 5 development and research organisations[110]. EU-wide intelligence including sites of commercial operations is provided by the EU Aquaponics Hub[111]. Examples of initiatives in aquaponics are given in the Projects Annex.

1.3 The challenges for IMTA

> *"The fundamental question is "what is IMTA for?" If it is for environmental mitigation, is the carbon-capture or nitrogen+nutrient capture aspect more important? Societal pressure and subsidies may promote use of IMTA, but this still leaves the question of whether IMTA as envisaged actually is a "more sustainable way" of doing aquaculture."*
>
> Dr Steven Prescott, Aquaculture Consultant, AquaBio Tech Group, Malta (*pers. comm.* 2020)
>
> *"There are problems of focus for IMTA. If the target is nutrient recycling, then the extractive species does not definitely need to share the same water, but we need to demonstrate that whatever uptake of nutrients may occur at distance allows the nutrient availability from the primary species to be balanced. If the reason for using IMTA is the environmental potential, the viability is still unproven at the commercial stage. The data and numbers produced so far don't indicate enough impact on the environment, since the biomass of the polluting element is much higher than the biomass of the remediation element. Reducing the environmental load from salmon by 80% would need 80 to 100 ha of kelp or 10-20 hectares of bivalves in the same water space. This is especially because salmon in cages increase cubically but seaweeds increase on a square area basis as they need access to light."*
>
> Professor Alejandro Buschmann Universidad de Los Lagos Chile (*pers. comm.* 2020)
>
> *"The practical establishment of IMTA in the aquaculture industry is still in its infancy. There is a lack of understanding of the biology, no models for commerce to take up, no extrapolations to scale and conflicts over space use between users."*
>
> Dr Mike Allen, Dr Sophie Parsons, aquatic sustainability researchers, UK (*pers. comm.* 2020)

The concept of IMTA has received considerable academic attention during the last two decades, but it has not yet become a commercial reality in European mariculture. The quotes above offer some reasons. Kleitou *et al.* (2018) interviewed 34 aquaculture farmers and scientists with IMTA experience from 12 European countries (DK, NO, NL, UK, IE, GR, IT, CY, IL, FR, PT, ES)[112]. They found disincentives included the lack of direct financial benefits for the farmer and the need for more efficient integrated farming systems to reduce complexity and allow processing of all crops, as well as inadequate support from policy and regulatory bodies to enable and incentivise the adoption of IMTA. As summarised in Table 1.8 to Table 1.10, most had attempted or used IMTA in order to achieve environmental benefits, explore sustainable farming or increased production, while a minority (1–3) had aimed for diversification or PR purposes, or they were taking advantage of local food production policies.

Table 1.8: Motivations for using IMTA

Reason	% of respondents
Mitigation & nitrogen removal	56%
Researching species suitability	50%
Enhanced production	47%
General R&D of sustainable mariculture	24%
Examination of IMTA suitability	18%

Source: adapted from Kleitou et al. 2018

Table 1.9: Existing bottlenecks or challenges for IMTA

Type	Number of respondents		Total %
	Marine	Land-based	
Markets uncertain, unprofitable or undeveloped	10	4	41%
Legislation	9	1	29%
Systems (harvesting and processing) and expertise inadequate	6	1	21%
Multi-operations generate too much complexity or constraints	4	1	15%
Seed unavailability	3	2	15%

Source: Kleitou et al. 2018; Note: only those identified by at least 10% of respondents are included

Understandably, the existing bottlenecks or challenges were reflected by the future challenges identified by respondents (Table 1.11). Notwithstanding, 26/34 respondents believed in a high potential for IMTA in Europe.

Table 1.10: Challenges to overcome for IMTA

Type	Number of respondents
Lack of funding or promotion by government and industry	12
Licensing and regulatory systems too complex or time-consuming	11
Undeveloped and unprofitable markets and inadequate value-adding activities	10
Insufficient operational feasibility of technology, knowledge and cross-industry collaboration	10
General lack of scientific and economic knowledge in R&D	6
Social acceptance of aquaculture and IMTA	5

Source: Kleitou et al. 2018; Note: only those identified by at least 10% of respondents are included

1.3.1 IMTA in general

The Scottish Aquaculture Research Forum (SARF) Report of 2015[113] offered some clues as to why there is doubt about IMTA's capacity to solve aquaculture's problems. It reviewed published life cycle analyses (LCAs) to provide a commentary on the potential of increasing mariculture to reduce the global footprint of food production by 2050 – in terms of greenhouse gas (GHG) emissions, and land and water use. Five theoretical future food production scenarios were analysed: Scenario 1, business as usual (BAU), with projections based on current meat and fish production; Scenarios 2 and 3, in which a proportion of meat output was replaced by fish; and "visionary scenarios", 4, in which 50% of the projected protein demand in 2050 would be provided by oysters and mussels, and 5, in which global per capita fish supply would be increased to 70 kg/person for a population of 9 billion people, which would require 630 million tonnes (mt) of mariculture products.

The analysis of these scenarios suggested that increasing the proportion of food production from mariculture would indeed contribute to an overall reduction in GHG emissions, and land and water use, but freshwater aquaculture would also need expanding, as would sectors such as renewable energy and feed sustainability where seaweed has a role. Crude estimates of the increases in sea area required for the projected levels of mariculture production in 2050 ranged from 171% in BAU to 5 855% in Scenario 5. Yet achieving even the BAU figure can be questioned, in the absence of integrated coastal and marine zonal management. The SARF report also acknowledged the contribution that IMTA might make to food biomass and ecosystem services, especially to bioremediation, with a focus on lower trophic species. However, the scale of IMTA required in the context of projected demands for aquaculture production seems problematic without considerable policy and financial promotion.

A viable current view of IMTA prospects was expressed succinctly by Hughes and Black, 2016[114]:

- increasing productivity is of no interest to a monoculture farmer who is already highly productive, since to offset salmon impacts by seaweed would require a 1 000% increase in biomass (WW relative to the fish production) for only a 166% increase in protein production;

- output per hectare is 1 125–1 750 tonnes for fish, but only 76 tonnes for mussels and 1 tonne for seaweed, making it unrealistic to use available space for the production of anything other than the primary fin-fish product;
- the value of bivalves is 30%–50% that of salmon, and seaweed is no more than 10%, while the effort to obtain licences, through uncoordinated licensing points, is the same for each species, thus it makes far more sense to focus efforts and investment on fish;
- the need for space around fish cages for the well boats (75 metres long) means mussels or seaweed need to be in areas beyond any proven direct and consistent impact on salmon feed and waste pollution;
- the production of alternative proteins and oils in the EU from seaweeds or mussels is theoretically attractive, but legal and economic constraints make this unfeasible in the foreseeable future;
- spatial IMTA has potential in the short term by taking over licensed but defunct sites and using seaweed or bivalves for mass-balance remediation or biosecurity buffers.

Commentary from those involved in aquaculture and IMTA supports this overall view. For example, Longline Environment, a consultancy and project company, is currently modelling biological effects in chains and networks involving multiple species in the environment. According to company CEO, Rui Gomes Ferreira (*pers. comm.* 2020), even if IMTA seems to work *in silico* and in small-scale research, effects are not detectable in practice, and there are too many problems, such as insufficient information, data gaps and a lack of thinking about governance and supply chain.

The following identifies IMTA's major issues for 2020 and beyond.

- *Reality of benefits.* Not measurable in real life, except perhaps for PR purposes, which are not sufficient to overcome economic concerns.
- *Operational challenges.* Question of how to synchronise the harvesting of the different crops and manage the infrastructures needed to deal with them[115], such as boat manoeuvrability[116].
- *Biological challenges.* In practice, there is a lack of control over interactions between the multiple trophic levels[117].
- *Policy and regulation.* Tools that support and streamline processes and drive the application of IMTA are absent. At the moment, farms are licenced using defined biomass criteria, which militates against larger scale thinking[118].
- *Spatial IMTA management.* In Europe and the Americas, environment-scale remediation versus specific farm remediation may be more appropriate, depending on the scale of investment and management systems needed. Over a broader area, ecological management could use IMTA, taking into account, e.g. water quality, currents and topography, and adopting a holistic adaptive management approach in which IMTA is more akin to carbon offset, i.e. not co-located but "elsewhere"[119].
- *Differential market values of outputs.* Existing produce, e.g. finfish, has high value compared with the low value density of the additions, e.g. bivalves and seaweeds. However, in China, where molluscs and seaweed are much closer in market value to finfish[120], there is a strong incentive.
- *Investment and scale.* Investment is clearly a barrier. If an aquaculture company had £10 million to invest, would it put it into more salmon where corporate value is €3–4/kg or mussels where it is <€1/kg?[121]

- *Consumer acceptance.* The acceptability of human food produced by feeding excreta[122] – the concept looks beneficial, but problems arise from food safety, market and industry acceptability. In Europe, the prime point is whether there is consumer demand to pull the products of IMTA through to the market.
- *Societal acceptance.* IMTA could be aided by the social licence to operate (SLO), which is being increasingly recognised. But there is probably not enough information and data, which suggests a project is needed. Most salmon companies would have a direct interest in increasing the SLO[123].

The following sections explore these issues in more detail, providing links to important related articles as well as personal communications received from senior aquaculture and environmental specialists in relevant research institutions, industry and organisations who were canvassed for their thoughts on IMTA's challenges and opportunities.

1.3.2 Seaweed IMTA

For seaweed specifically, the Norway-based environmental NGO Bellona Foundation says it has no doubt that IMTA represents the future of aquaculture, and seaweed biomass is important for bioenergy production via bioethanol or biogas, as well as acting as a carbon sink[124]. However, hurdles are still seen.

- Message. "*IMTA needs to find the starting message – for seaweed IMTA, mitigating the carbon footprint of fish farming is the main starting point. Lines need to be 300–1 000 metres from the cages because, if they are too close, there is obstruction of maintenance vessels. From a broader life cycle/value-chain perspective, regardless of the carbon source, there will be many opportunities for the carbon within seaweed to enter the atmosphere once harvested. Plus, the economic activity required to farm, harvest and process/utilise seaweed may actually release more CO_2 equivalents than seaweed can sequester. The evidence for direct transfer is poor and most of the case rests on modelling*" (*pers. comm.* 2020: Dr Steven Prescott, AquaBio Tech Group, Malta).
- Ecological impacts. There may be unforeseen ecological impacts of seaweed, such as genetic interactions between cultivated and wild crops. Stévant *et al.* (2017), writing for *Aquaculture International*[125] about future perspectives for seaweed aquaculture in Norway, proposed addressing ecological impacts by sourcing local species, ensuring that impacts of seaweed cultivation on surrounding ecosystems are minimal, dealing with unwanted epiphytes and diseases, and coping with threats from climate change.
- Investments. "*In the case of ocean energy and integration with seaweeds, the scale of seaweed area needed is much larger than the R&D so far. Investment would be needed, which is a very big risk for industry, especially as the costs of large-scale production and use of seaweed are still largely unknown. A positive note is the willingness of public organisations to provide funding for development of seaweed energy initiatives*" (*pers. comm.* 2020: Ian Ashton, researcher, University of Exeter, UK). On the topic of investments, Stévant *et al*. (2017) determined that working out best area utilisation would still be a challenge, which would be answered by ensuring that seaweed aquaculture and IMTA were automatically included in marine and coastal zonal plans.
- Repeat harvests. "*Repeat harvesting of seaweed when used in IMTA is not reliable. The experience in practice has been that the first harvest is okay, but after that, it decreases. Reported results need careful examination for internal inconsistencies – e.g. the logic gap between promotion of seaweeds for eco-remediation and then selling the produce or using it. The development of legislation in UK and Europe calling for 10% of all plastics to be of biological origin may be a driver for seaweed production but, thus far, there has been no full*

life cycle assessment (LCA) of seaweed culture" (*pers. comm.* 2020: Dr Mike Allen and Dr Sophie Parsons, aquatic sustainability researchers, UK).

- Biorefinery volume. "*The seaweed biorefinery concept does not always fit with seaweed in IMTA, because the volumes needed for high-value components are small. Bioplastics might fit, as they demand high volumes of seaweed production. Climate change mitigation could also be a justifying concept, especially if one could develop a way of sinking seaweed to the bottom and keeping it there. Seaweed can also be seen as a nursery for biodiversity*" (*pers. comm.* 2020: Professor Alejandro Buschmann, Universidad de Los Lagos, Chile).
- Incremental development pathway. "*The overall development level is closer to the problems for wave power than for wind power, but the development pathway can be incremental. The scale needed will have to reflect the scale potentially required to be competitive in the plastics and energy markets*" (*pers. comm.* 2020: Ian Ashton University of Exeter UK).
- New technology needs. "*In practice, each piece of the chain needs analysing to identify challenges and address what new technologies are needed. This includes seeding the lines, harvesting, getting to and moving from dockside. A method for mass-handling seaweeds is also needed because, to be economic, processing must handle at least 5 000 tonnes WW at a time*" (*pers. comm.* 2020: Andy Wilkinson, Oceanium, UK). This also includes drying of algae, which the IDREEM project identified as one of the main bottlenecks in algae culturing[126].
- Demand. "*Western Europe does not have same amount of space as China for traditional seaweed production, and the demand for high-value food outputs is not as high. Current seaweed economics don't add up. However, current costs are reasonable compared with how marine wind power began, which is now of course economical. With minimal support to encourage maturing of markets by identifying viable products, while simultaneously supporting producers that reduce production costs for seaweed aquaculture, the current surge in interest for seaweed aquaculture has the potential to follow marine wind energy and develop a new industrial sector for the UK and Europe*" (*pers. comm.* 2020: Ian Ashton University of Exeter UK).

1.3.3 Invertebrate and seaweed-mussels IMTA canvassing

For seaweed-mussels IMTA, concerns and challenges include the following.

- *Biofouling.* Biofouling of nets and cages can lead to cage breakups. Putting mussel farms even half a mile from salmon nets and cages produces biofouling that is known to cause sinking and collapse (*pers. comm.* 2020: Rui Gomes Ferriera, CEO Longline, UK)[127].
- *Biomass supply.* Ensuring a reliable supply of biomass as feedstock for next stages introduces high commercial risks (*pers. comm.* 2020: Ian Ashton, University of Exeter, UK)[128].
- *Harvest schedule and infrastructure.* Even if seaweed and bivalves can be grown on the same lines, there will be problems with when and how to harvest. Current harvesters are designed to strip mussels off the header rope, not seaweed. The boats sent to do this can manage the 8-tonne lift needed for a mussel rope, but it is not clear whether this would do for seaweed. Currently, three people are needed for mussel stripping, meaning there are implications for personnel numbers and economic efficiency, especially in unfavourable weather or water conditions (*pers. comm.* 2020: Adam Hughes, SAMS, Scotland)[129].

There are also concerns and challenges for successful IMTA use of sea cucumbers, starting with the need to establish hatcheries in Europe. But there are issues with the sea cucumbers themselves:

- their feeding and growth cease when water temperatures fall too low – e.g. <19°C for *H. arguinensis* – which underlines the need to use local species;
- they may lose weight, as they digest their intestines during low-nutrient periods;

- they may become overloading with nutrients if fish density is too high[130];
- they may cause short-term benthic fouling due to their own faeces[131].

1.3.4 Aquaponics and RASs

A significant challenge with aquaponics is that at commercial scale, according to Jason Hawkins-Row of Aponic Ltd (*pers. comm.* 2020), there are "*variables that are not easily mitigated and usually demand conditions that compromise the health and well-being of either the plants or the fish*[132]. Surveys in France and the EU of people actively involved in aquaponics, or intending to be, found that many had experience of or training at academic or practical level in aquaculture, but none had horticulture experience. So it is not surprising that balancing the needs of both components can be difficult[133]. However, it is essential. A study in Canada found that the horticulture element of aquaponics can account for as much as 70% of the profitability of a successful operation[134].

The main challenges are:

- budgeting the cost of complex physical and biological technologies needed in high-performance RASs;
- managing the dynamics of nutrient rebalancing for fish-crop interactions;
- ensuring that any disease risks from either partition do not spill over into the other or into the environment or the human food outputs;
- ensuring the right mix of expertise and knowledge to manage all aspects of the set-ups.

Anglesey Sea Bass, formerly owned by Selonda UK, is a case study of the pitfalls of a RAS enterprise[135]. Initiated in Wales as the Penmon Fish Farm in 2003 – with £12 million establishment costs covered by grants of >£5 million in Welsh and European funding – Selonda UK intended to produce sea bass in RAS. The farm was not completed until 2009 because of problems with the RAS technology and meeting environmental regulations. Selonda had already been fined for discharging pollution from the RAS and the monitoring of the support grants was criticised by the Welsh Audit Office[136]. By 2012, Selonda UK was bankrupt and the aquaculture division of Linnaeus Capital partners, Tethys Ocean, bought the assets for £1.2m[137]. Anglesey Sea Bass, under its new owners, reared sea bass from fry for the UK supermarket Waitrose and its captive consumers, who could pay a premium. By 2015, cheap sea bass arrived from Turkey and Greece and the company closed, in spite of hoping to replace sea bass by higher-value salmon, turbot or sole[138]. Marine Harvest (now Mowi) bought the farm in 2017 to establish a wrasse production site starting January 2018, to provide fish for biological control of sea lice at its salmon farms[139]. It produced the first batch in 2020 and is expected to produce between 800 000 and 1 million fish per year[140]. In another UK instance, a group of Yorkshire pig farmers established a tilapia group, The Fish Company, in 2010, with four farms in Yorkshire and Lincolnshire[141], selling via UK supermarket Tesco and the local Gurkha garrison, aiming to produce between 400 and 700 tpa using RAS, but they couldn't maintain water quality, the pig-farm effluents tainted the fish, and the Gurkha garrison was closed so there were no local consumers.

1.3.5 Multi-use/Multi-purpose platforms

Specific technical and practical challenges to establishing a viable operation with MUPs and MPPs (with or without IMTA) emerged with the MUSES project[142] on aquaculture, and at Denmark's Rødsand 2, in an OWF project that was part of the SUBMARINER[143] project on natural IMTA.

- *Technology.* Necessary technology readiness levels have not been reliably reached, especially with regards to harsh environmental conditions in offshore areas. There are incompatibilities between the technologies used for different types of aquaculture (e.g. cage vs line) and OWF (e.g. floating vs jacket vs monopile).

- *Financial incentives.* There are no planning and financial incentives targeting aquaculture+open-ocean installations.
- *Permit processes.* The permit processes for combined activities are unclear. Project finance and maritime permits and licences given for specific technical proposals are acquired at a certain estimated risk level and cannot be amended past the project planning stage. Plus, co-localisation or combinations of uses have not been considered in the process of licensing offshore wind parks and different agencies are involved – energy, fisheries and environment.
- *Risk assessment.* There are unassessable risks, leading to very complicated insurance implications.
- *Equipment and infrastructure.* Local operation and maintenance equipment and routines in OWFs are not tailored to match the needs of operating mariculture systems and sampling/harvest. There are usually no suitable *in situ* boats for harvesting and OWF maintenance vessels are unsuitable for aquaculture maintenance and harvesting. Mariculture installations cannot possibly be attached to turbine foundations due to interference with the anticorrosive equipment, cables and scour protection.
- *OWF vs aquaculture.* The power imbalance between the two sectors does not favour aquaculture. Operators of the already licensed or operational OWFs have priority over other maritime users, including aquaculture and fisheries.
- *Investment needs.* Investment demands are very high and beyond the capacity of most aquaculture operations, and there is insufficient proof-of-concept to engage large investors. Investment capacity for seaweed is even lower, and markets for high-value products remain insufficiently developed.
- *Water conditions.* There is often a mismatch between optimal current, salinity and other water conditions for windfarms and mariculture. In addition, there are unknown risks of aquaculture biofouling offshore installations.
- *Weather conditions*. Weather conditions can make inspection, sampling and harvesting difficult or impossible, and the distance to shore adversely impacts the 2-day freshness window for molluscs.
- *Tenure.* Tenure security is related to the requirement to remove installations completely at the end of the licence period.

The EU-funded MERMAID project specifically focused on determining the legal, policy, social, environmental, technical and economic issues that stood in the way of successful implementation of aquaculture-MPP initiatives[144]. Among the issues it identified:

- complicated bureaucracy with poor dialogue between public institutions;
- difficulties identifying responsibilities for permits;
- lack of codes and standards;
- conflict with other near-shore and offshore users including fisheries, tourism and shipping;
- social unacceptability of changes;
- insurance costs and complexities;
- the financial feasibility of combining activities.

MERMAID also identified three major risks related to implementation of conventional large fish cages within OWFs:

- most fish cages and their mooring systems have been designed for operation at inshore protected sites;

- placing fish cages with their mooring systems within the wind farm might increase collision risks with the operation, service and large maintenance vessels;
- conflicts can emerge between the offshore wind and aquaculture farms during the installation and operation phases[145].

Efforts can be made to overcome some of these constraints. MERMAID developed a special installation vehicle and proposed that floating wind turbine generators (WTGs) – which typically have more space between them due to the need for mooring lines and anchors – might leave more space for aquaculture.

1.3.6 The realities of experience versus research

> *"The scale of research that is possible in fish farms has also militated against take-up of ideas, and there is widespread expressed need in research for large-scale units where the issues of logistics, management and economics can be properly tackled. It has been impossible in the experimental systems studied to date to demonstrate an improved environment for fish. Studies so far are seen as too small-scale and experimental to justify industry adopting IMTA, and a commercial-scale experimental farm is needed."*[146]
>
> *Professor Alejandro Buschmann, Universidad de Los Lagos, Chile* (*pers. comm.* 2020)
>
> *"Currently it is only China with large commercial success stories in IMTA, although other countries are testing pilot-scale operations. Even though the world salmon industry does occasionally get affected by oversupply, the industry is still so profitable that it does not need to adopt IMTA practices at this time. Off-shore there is lower environmental benthic organic loading from waste feed and excreta due to the larger dispersion area, so IMTA is not seen as being needed or practical. We should perhaps see IMTA as part of the ecological engineering tools available for deploying Fish Aggregating Devices, like artificial reefs or the attraction of many different species to mussel rafts and fish cages."*[147]
>
> *Shawn Robinson, Fisheries and Oceans, Canada* (*pers. comm.* 2020)

Significant work and advocacy are continuing at research and academic levels, in spite of low industrial interest. The failure to translate research results into commercial reality in Saudi Arabia has proven to be a typical case of the mismatch between research and industry. Work was carried out in a government station, but there was no clear commercial end-point and no allowances made for the logistics of working in 10–12 metre depths. There was no long-term plan and, without proof of commercial viability under local conditions and given the difficulties in receiving permits and licenses, results were never carried forward into industrially relevant use[148].

Seaweed can absorb excess dissolved nutrients from fish farm cages, but doing so requires macro-algae farms to be located near the salmon farms. The effects cannot be differentiated from environmental nutrients beyond 300–500 metres, where the additional load is relatively low. This is the case in most waters around Europe and the Americas which are tidal and oceanic rather than the sheltered bays found in China, where excess nutrients from aquaculture and coastal run-off clearly produce eutrophication.

In reviewing 10 years of IMTA research in Norway, from the project POLYCULT 2004–2006 to IDREEM 2012–2016, Jansen *et al.* 2015[149] noted that, after early enthusiasm, limitations and restrictions were realised as time went on. Although seaweed productivity was 150–300% higher when co-located with salmon farms, this effect was seen only within 100–200 metres of the cages, because of quick dilution of nutrients from the salmon, as shown by experience at a Marine Harvest (now Mowi) salmon farm[150]. The seasonality, the large areas needed for bioremediation and the growth increase were not commercially relevant. A 220-ha seaweed establishment would be needed close to a salmon farm to remove 100% of the dissolved ammonia in the growth period. 100% removal of the nitrogen output of Norway's salmon farms, estimated at 40 km^2 in 2010, would require up to 247 km^2 of seaweed with a potential biomass of around 1.4 mt WW.

The question of distances between fish cages and extractive species is neatly answered by a study of bivalves, seaweed and fish, where bivalves next to or 1–60 metres from fish cages showed significantly higher biomass production relative to controls grown at >60 metres separation. But for better seaweed growth, there had to be no separation at all[151]. The efficiency of bivalves such as mussels as extractors is highly impacted by the time available to intercept waste feed particles and excreta, current speed, tidal movements, and availability of natural suspended nutrients (seston). This means their use in open water systems on lines or nets adjacent to fish cages is likely to remove far less nitrogen and carbon in reality than is theoretically estimated or modelled[152].

A 2020 review of mariculture and ecosystem services concluded that though harvesting of molluscs and seaweeds can remove large amounts of carbon from the environment (e.g. in China an estimated 1.2 billion tonnes a year), whether this carbon is actually sequestered or released back into the environment depends on the fate of the harvested product[153]. Of the 56 studies identified, 44 focused on the role of seaweeds and the remainder on oysters, other bivalves and detritivores, demonstrating removal of nutrients from fish aquaculture. Many were in IMTA. But few studies looked at real-life in-sea data. Of those that did, one showed that mussels farmed in a Danish fjord were a sink of nitrogen for their first year, but after that, they became a net source of nitrogen due to their nutrient excretion and contribution to sediments. Other work on Sweden's west coast found optimal growth for blue mussels (*Mytilus edulis*) in sheltered inner water areas but best growth for sugar kelp (*Saccharina latissima*) in outer water facing open ocean, and co-cultivation gave no benefit of additional growth for either species[154].

1.3.7 The policy environment

> *Much aquaculture regulation was established more than 20 years ago, in the framework of finfish monoculture and this legacy now results in regulatory and economic hurdles which need removing if IMTA is to be implemented as part of Integrated Coastal or Marine Zone Management.*[155]
>
> Thierry Chopin, aquaculture champion, International Aquafeed interview (2020)

IMTA does have a foundation of policy support in Europe.

The European Parliament report of 2018 found that "*the sustainable growth of aquaculture needs to be based on business investment predictability and legal certainty, which requires, notably: simplification and acceleration of administrative procedures – less red tape – at EU, national and regional level…; improved transparency and proper planning; … fast, clear and transparent licensing procedures accompanied by limited timelines for agreement, so as not to discourage investors; … adequate public financial support at EU and national level for sustainable and responsible aquaculture production, innovation and development; better incorporation of the aquaculture and fisheries perspective in the Union's trade agreements …*"

In addition:

- IMTA is eligible for support from the European Maritime and Fisheries Fund as part of sustainable production, and because it might meet the concerns of other users of coastal or sea space (EC communication COM/2012/494)[156].
- IMTA has been included in a strategy for sustainable aquaculture in Europe by EC communication COM/2013/229[157], which additionally recommended simplification of regulations and administrative procedures, such as Norway's introduction of a single contact point, introduction of coordinated spatial planning, financial support for business development and coordinated RDI funding for sustainable aquaculture.

The EU Aquaculture Advisory Council[158] and Multi-Annual Strategic Plans for Aquaculture (MASPs)[159] are also seen as important in achieving sustainability in aquaculture. MASPs are produced by each EU Member State (MS) and can be regarded as having policy commitment. Though the MASP summary does not specifically mention IMTA, it recognises market deficiencies and identifies challenges that could favour or be assisted by uptake of IMTA.

- Marine finfish
    - Insufficient available space in inshore sheltered areas forces development of offshore aquaculture (UK) or optimisation of productivity on existing sites (GR, IT, IE, ES), to improve production efficiency and product costs (CY, FR, GR, IE, IT, ES).
    - All MSs intended to simplify administrative procedures for national and regional environmental laws impacting marine inshore areas.
- Shellfish
    - Insufficient available space in inshore sheltered areas but there are opportunities for rope-based offshore aquaculture (ES, FR, IT) and optimisation of production on existing sites, which could favour IMTA.
    - Techniques to extend shelf-life will encourage market growth.
    - R&D is aimed at operational efficiency, and resilience to environmental hazards.
- Bluefin tuna
    - Aquaculture requires capture of juveniles for on-growing, but is limited by lack of understanding of the breeding cycle of tuna.
    - Producing juveniles in aquaculture systems will eliminate the reliance on fisheries to provide the input for fattening. However, this could be done using RASs with IMTA.
- Seaweed farming
    - This sector is poised for growth with high-value applications in food, feed and cosmetics, plus its potential for producing biofuel may also support further development in Europe.
- Freshwater aquaculture
    - Most production originates from small-scale farmers with limited access to credit and low capacity to invest.
    - Relatively high costs of labour, land and other inputs in many cases put the sector at a competitive disadvantage against cheap imports.
    - Strong markets, based on high-quality local supply, have been achieved, as in FR. This suggests that RASs and IMTA, perhaps aquaponics, should have a good impact.
    - HU and PL intend to strengthen fish farming in recirculation systems of species such as eel, sturgeon, tilapia and perch.

In 2017, the NGO Seas At Risk [160] noted that European policy-makers were still to address key points in making use of IMTA, including the needs for:

- clear definition of IMTA that is understood by consumers;
- clear labelling of products from IMTA production systems to create a market;
- definition of standards to develop a label;
- development of markets for seaweed cultured in the EU;
- recognition that IMTA is not zero-waste, therefore defining the environmentally acceptable thresholds of waste outputs from IMTA.

A year later, Seas At Risk noted that Members of the European Parliament (MEPs) had failed to develop a new vision for European aquaculture. Instead, they had adhered to the *status quo,* rather than adopting an approach to reduce the administrative burden for aquaculture producers and promote coordinated spatial planning to define new areas for aquaculture farms, to increase the competitiveness of European aquaculture and create a level playing field between domestic and imported aquaculture products. They also pointed out that MEPs were still recommending funding of pilot projects, not moving forward to support EU-wide implementation of systems such as IMTA and aquaponics[161].

In 2014, the European Commission and nine EU MSs (CY, ES, FR, GR, HR, IT, MT, PT, SI) set up the BLUEMED Research and Innovation Initiative[162] for blue jobs (now denominated "blue careers") and growth in the Mediterranean area. Their 2018 proposals include IMTA, widening aquaculture to include low trophic levels, expanding the range of species that are farmed, bringing in a circular economy to recycle wastes and combining aquaculture with other activities on offshore multi-purpose platforms[163].

The EU4Ocean Coalition[164] was launched in June 2020 with funding from the EU. It aims to actively enhance ocean literacy across all ages and societies in Europe, and increase the chances of responsible decision-making. The Coalition has three components: the EU4Ocean Platform for organisations and individuals working on and interested in ocean literacy initiatives, the Youth4Ocean Forum for 16–30-year-olds who want to be engaged in activities and projects, and a Network of European Blue Schools, with award schemes for recognition of outstanding contributions. IMTA could be considered a contributor to its Food from the Ocean, and Healthy and Clean Ocean themes.

The USA is also keen to see stimulation and rationalisation of fisheries and aquaculture activities and on 7 May 2020, an Executive Order was signed Promoting American Seafood Competitiveness and Economic Growth[165]. The policy points include:

- identifying and removing unnecessary regulatory barriers restricting American fishermen and aquaculture producers;
- facilitating aquaculture projects through regulatory transparency and long-term strategic planning;
- nominating NOAA as the lead for all off-shore projects;
- requiring that review of coastal and on-land projects be coordinated by a lead agency and determined within two years of announcing the go-ahead for an environmental impact survey (EIS); and
- requiring state and federal agencies to establish programmes by which to identify geographic areas potentially suitable for aquaculture and undertake EISs to evaluate and confirm this.

This may well give North American advocates of IMTA a strong opportunity for progress.

1.3.8 Integrated zoning, regulation and permits

> *We need a major rethinking regarding the functioning of an "aquaculture farm". It does not work only within the limits of a few buoys on the water, but should be managed using an Integrated Coastal Area Management (ICAM) strategy, according to the movement of the different elements considered. If organic particles released by the fed component settle quite rapidly, dissolved inorganic nutrients travel longer distances. This means that different strategies (in space and time) will be needed to recover these different nutrients, and that entire bays/coastal areas/regions should be the units of IMTA management[166].*
>
> Thierry Chopin, aquaculture champion, International Aquafeed interview (2020)

For sustainability, there is a need to integrate aquaculture activities with zonal planning and management. Certification of farms to a credible standard – such as the Global Aquaculture Alliance's (GAA's) Best Aquaculture Practices (BAPs), GlobalGAP or the Aquaculture Stewardship Council (ASC) – is important, but it needs to be combined with the zonal planning and management of entire aquaculture production zones for full sustainability. For example, GAA's BAP has developed a zone management standard, there is a proposed revision to the ASC standard to include area management, and area management has been added to the benchmarking tool used by the Global Sustainable Seafood Initiative (GSSI) [167].

Allocated Zones for Aquaculture (AZAs) – marine areas where the development of aquaculture has priority over other uses and will be primarily dedicated to aquaculture – would be legally established by the administrative bodies usually involved in licences and permits and setting policy identifying and agreeing on specific spatial areas within a region[168]. There is a Protocol on ICZM in the Mediterranean, two guidelines from the GFCM – Resolution GFCM/36/2012/1 on allocated zones for aquaculture, and the guidelines on a harmonised environmental monitoring programme for marine finfish cage farming in the Mediterranean and the Black Sea updated 2017 – and the EU's Marine Spatial Planning adopted in 2014.

AZAs could build on these and provide strong support for IMTA, which is regarded as having environmental, economic and societal benefits, especially if it is operated within an ICAM approach incorporating entire bays, coastal areas or regions as the IMTA Unit. This would need enabling regulations that recognise the ecosystem scales at which AZAs would operate.

Mariculture zonal management[169] and marine spatial planning are both methods of placing aquaculture in the marine setting. The IMTA community sees a need to embed these concepts into those of zone management and planning, whether marine or coastal.

The 2015 SARF report saw a need for legislative and regulatory tools to encourage co-location of mariculture with other offshore marine sector activities, such as offshore renewables or disused oil rigs[170]. Culture of extractive species with fed species in the same mariculture sites is encouraged in aquaculture development planning and zoning exercises in the European Union and North America[171], though this may not make the process much more rapid.

The EU MASP summary notes that most MSs acknowledge that aquaculture administrative procedures are long and cumbersome. Administrative complexity stems from the number of ministries involved, the different national and regional regulatory requirements impacting aquaculture activities based on national transposition of the Water Framework Directive (WFD), the Marine Strategy Framework Directive (MSFD), Bird and Habitat Directives, and the lack of communication between ministries and authorities on aquaculture issues. Table 1.11 summarises some of the initiatives that will favour aquaculture and, by implication, IMTA.

Table 1.11: Policy improvements proposed to in the EU's Multi-Annual Strategic Plans for Aquaculture

Initiative	States involved
Simplification of access for applicants as an overarching measure	Almost all
Setting up inter-Ministry coordination groups to review the applicable legislation, simplify it, and streamline application procedures	BG, DE, ES, FR, GB, GR, HR, IT, MT, RO, SK
Production of Guidelines to make the legislation and procedures more transparent, understandable and predictable	AT, CY, DE, EE, GR, HR, IT, PT
Improved involvement of stakeholders in the decision-making process to better inform authorities on technical and legal issues	BG, DK, IE, IT, FI, FR, GB
Strengthening or adopting a single-point submission process	CZ, IE, IT, FR, PT
Harmonisation of devolved legislation and procedures at national level	ES, UK

Achieving successful implementation of IMTA in the EU will be hampered by differing or non-existent legal frameworks for individual non-conventional species and certainly for combinations and complexity of regulation[172]. However, if there is an existing policy focus on environmental sustainability and technological innovation, this may be an incentive for IMTA. In the EU, national frameworks seemed permissive for experimental IMTA and for pilot schemes, but regulatory reform would be needed for commercial activity, especially in relation to the intersection between nutrient recycling and food safety.

The Centre for Environment, Fisheries and Aquaculture Science (Cefas) has produced a guideline for aquaponics activities in the UK that defines administrative procedures based on the size and purpose of the farm and the destination of produce[173]. This has led to several educational projects and some business activities such as BioAqua Farm, which says it has the longest thriving commercial aquaponic farm in the UK and the largest aquaponic trout farm in Europe[174]. Nevertheless, this does not guarantee success: A planning application for a land-based trout and vegetable farm in UK's Lake District was turned down in 2019 because it “contravenes a raft of policies,” according to one local councillor, and was also objected to by Friends of the Lake District and other local interests.

Licensing systems can be streamlined to some extent. In 2015, Norway announced a programme of free licences, intended to stimulate investment into new technologies, primarily looking at closed sea-based cages for salmon but also submerged, floating and other technologies[175]. Land-based, sheltered, exposed and open-sea projects were all eligible, and IMTA would not seem to be ruled out. Scotland provides a more typical picture. Here, there are five different authorities: planning permission from the local planning authority; a marine licence from Marine Scotland with a limit in 2019 of 2 500 tpa salmon per site; an environmental licence from the Scottish Environment Protection Agency (SEPA); an Aquaculture Production Business authorisation, also from Marine Scotland; and a lease from The Crown Estate, paying rent to install and operate the farm on the seabed, generally granted for a period of 25 years and dependent on securing planning permission.

The experience in the IDREEM project is not unusual. The Irish partner DOMMRS waited 4 years (2010–2014) to receive its requested licence to grow seaweed in an area of 6 ha, approximately 200–300 metres from a salmon site in which it would put 16 longlines [176]. This reinforces the need to streamline permissions and remove unnecessary bureaucratic obstacles caused by too many agencies involved in the decisions. Most SME partners experienced issues relating to the lack of an existing process for licensing IMTA sites, given the novelty and early development stages of establishing the practice of IMTA within Europe[177].

The first commercial permits for cultivation of seaweeds were granted in Norway in 2014, when public authorities created a specific interim licensing system for macroalgae[178]. The Ministry of Trade, Industry and Fisheries now coordinates the processing of seaweed farming applications and considers them according to the Aquaculture Act. The evaluation of applications involves several authorities, including the Directorate of Fisheries, Norwegian Coastal Administration, Norwegian Food Safety Authority, County Governor’s Environmental Department and Norwegian Water Resources and Energy Directorate, each one considering potential conflicts of the application within its area of responsibility. The concerned municipal authorities are involved in determining permits for fish and seaweed farms in concordance with coastal zone spatial plans.

Iceland’s legislation is permissive for IMTA but requires that the species to be used must be native to Iceland, and each requires an application to Iceland’s Environmental Protection Agency (Umhverfisstofnun), taking into account the requirements of the Nature Conservation Act and the Icelandic Food and Veterinary Authority (Matvælastofnun). Each permit is evaluated on a case-by-case basis and usually takes 6 months to process, including an 8-week period for public consultation. It can be modified to take account of public concerns, if needed[179].

For aquaponics, Joly *et al*. 2015[180] noted that this has no clear legal status and no unitary regulation in Europe. Companies have to take into account the differences and sometimes conflicts between agriculture, horticulture, aquaculture and urban legislation, and apply through separate channels for permits for different aspects of what they want to set up. This adds to the time, cost, complexity and risks, and ultimately impacts the commercial viability of aquaponics.

1.3.9 Biosecurity, diseases and food safety

As the world’s largest trading bloc for aquaculture produce, the EU has stringent requirements in place for approval of farms and processors intending to export to the EU, with quality management and process-oriented controls applied from farm-to-fork along the food chain[181]. Before a non-EU competent authority can export to the EU, it must receive official EU certification of its reliability with regard to food quality and safety, and to the health of the originating aquaculture establishment. Countries supplying fishery products must be on a positive list for the relevant product, with specific additional conditions for imports of bivalve molluscs, echinoderms and marine gastropods. Areas of concern are marine biotoxins that cause shellfish poisoning, and residues of veterinary drugs, pesticides, heavy metals and contaminants. The Directorate-General for Health and Food Safety of the European Commission (DG-SANCO) considers official requests from non-EU countries and determines if it will be listed. As part of IMTA's purpose is to extract nutrients from water, waste food and excreta, presumably IMTA produce will require every type of stringent testing for import.

To support IMTA, studies of transmissibility and relevance of diseases between the species chosen, and their potential to act as reservoirs, be a food safety hazard or a source of zoonosis must be undertaken. There are known biosafety and zoonosis hazards from shellfish farmed in coastal operations, with pathogens such as hepatitis virus, norovirus and *Vibrio* filtered out and transmitted from contaminated land run-off and rivers in the edible produce. In marine and land culture, aquaculture produce may be contaminated by agricultural effluents and toxins from microalgae and other plankton blooms. IMTA in pond-based land culture may be particularly exposed to transmissible hazards, and the products may need special attention with regards to biohazards. Previous studies found that workers and community members in contact with waste-fed aquaculture water were at an increased risk of acquiring diarrheal diseases, skin diseases and liver fluke infections. For example, all 27 ponds in 9 villages of Jiangmen City, China, were found to be contaminated with human and pig faeces, and exceeded the US limits for *Escherichia coli* counts[182].. Elsewhere, *Escherichia coli*, *Clostridium perfringens*, enterococci and faecal coliforms were found at potentially hazardous levels in ponds at 5/5 freshwater tilapia farms[183].

There is reassuring evidence for the food safety of produce from IMTA, in that harvest from the farms in the Bay of Fundy, Canada, were analysed regularly, and there was no evidence of unsafe concentration of heavy metals, environmental contaminants, fish disease treatments or microalgal toxins in mussels[184].

The IDREEM project investigated food safety aspects of the IMTA pilots around Europe, on the basis that the potential for accumulation of some contaminants might make co-cultivated species unsafe or reduce their food quality. Its final report[185] noted that fish, mollusc and seaweed samples from IMTA and control sites were collected from all the farms, and testing showed that all samples were well below EU-permitted limits for relevant contaminants such as heavy metals, Polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyl (PCB) and microbiological burden. There were a few cases of seaweeds with levels that marginally exceeded legislated concentrations for some metals, but this was more related to general environmental concentrations than the IMTA situation. In an IMTA-RAS study involving halophytes for nutrient retention, the plants were harvested and tested for microbial safety and were found to conform to acceptance standards for human food[186].

1.3.10 Stakeholder beliefs and Social Licence to Operate

> *"If SLO does become a deciding factor, then the public perception aspect of developing an SLO may become important for the industry. Most salmon companies would have a direct interest in increasing SLOs for their development and activities."*[187]
>
> Adam Hughes, SAMS, Scotland (*pers. comm.* 2020)

SLO indicates the attainment of community and stakeholder acceptance and approval for an industry's operations. The public perception of the aquaculture industry, especially mariculture, is that it performs badly in terms of taking care of the environment and respecting local communities. Work on SLO in the EU-funded AquaSpace project showed that all finfish farms are judged by those companies and sites reported as having the lowest operating standards at any given time[188].

SLO began as a concept related to activities of the mining industry, and has come to be regarded as part of the social sustainability of any enterprise. The ISO standard – ISO 26000:2010 Social Responsibility – concerns the SLO concept.

Seafish, the UK public body which supports the seafood industry, held a workshop on SLO in 2016, introducing the concept and helping establish it in the UK aquaculture and fisheries sectors[189]. Social licencing is a continuous activity and it requires positive action and communication to build strong relationships with local stakeholders, more than simple press releases, as seen in Figure 1.3[190]. The existence of social licence is shown by subsequent community support for aquaculture activities, a positive reputation for companies, few or no objections to business expansion, frequent and productive communication between local stakeholders, and few or no issues requiring formal resolution.

One aspect of the SLO process is to bring local community and industry into discussions at an early stage and share the expected or hoped-for positive impacts on communities in which the aquaculture activities will take place which, in turn, helps explore and foster a shared commitment. Social sustainability of aquaculture is not easy to measure, compared with environmental or economic impacts, but SLO is seen as increasingly important, although without a full understanding of how to cultivate, promote, nurture and measure it in the aquaculture context[191].

Figure 1.3: Engagement with stakeholders as part of gaining Social Licence to Operate

Inform	Consult	Involve	Collaborate	Empower
To **provide balanced info** to assist understanding of problems, alternatives &/or solutions	To **obtain feedback** on analysis, alternatives and/or decisions	To **work directly with stakeholders** throughout to ensure concerns/ issues are addressed	To **partner with stakeholders** to identify alternatives and preferred options	To **place a substantial part of decision making in the hands of stakeholders**
Promise to Participants				
Will keep you informed	Will keep you informed, listen to and acknowledge concerns and provide feedback	Will ensure concerns are addressed in alternatives and provide options	Look to stakeholders for direct advice in forming solutions and will incorporate input into decisions	Will implement what stakeholders decide.
Example of tools				
Fact sheets, web sites, displays	Public comment, focus groups, public meetings, open houses.	Workshops deliberative polling	Citizen advisory committees, consensus building	Citizen juries, ballots, delegated decisions

Source: Brooks, 2016

Consumer opinion about the produce of IMTA is not, strictly speaking, part of SLO, but it will still be an important factor for IMTA to be accepted in society. A survey of 649 New York seafood consumers in August 2007 found an 88% preference for integrated multitrophic aquaculture over monoculture, once the IMTA concept was explained. Also, in tasting panels, IMTA produce performed at least as well as monoculture produce[192]. In terms of the total output of Atlantic salmon in Canada, when the waste-reduction aspects of IMTA were explained to a sample of 525 Canadian consumers and their buying preferences tested, the increase in consumption due to IMTA was estimated at CAD 280–1 500 million a year[193]. Clearer labelling and information on IMTA production were also regarded as helpful in raising consumer awareness.

1.3.11 Life cycle analyses

Paradoxically, an LCA of IMTA and nutrient cycling has shown that the CO2-equivalents and other emissions of seaweed production do not compare as favourably with finfish cultivation when expressed according to nutrient content instead of product mass. For monoculture versus IMTA, it cannot be safely said that emissions are lower for IMTA. Thus, the essential question is: at which point do the trade-offs between nutrient bioremediation and emissions of CO2-equivalents tip the balance in favour of IMTA? A corollary is that the carbon footprint per unit nutrition of seaweed – rather than the C footprint per unit biomass – is higher than that of finfish."[194].

Steven Prescott, AquaBio Tech Group, Malta (*pers. comm.* 2020)

There are only a few detailed LCAs of the impacts of IMTA, partly because of the lack of full commercial-scale demonstration/experimental farms where different systems can be explored. All work has been done so far at a scale that does not translate into industrial reality, so the practicalities of large-scale deployment cannot be investigated, optimal mixes of species cannot be adequately investigated and, more importantly, neither LCA nor economics of full IMTA can be assessed in real life[195].

Hughes and Kelly (2011);

Alejandro Buschmann, Universidad de Los Lagos, Chile (*pers. comm.* 2020)

In applying the concept of LCA in aquaculture, and particularly to IMTA, it is important to recognise that environmental impact shifts – which occur when reductions in environmental impact of one stage either displace the impact to another stage or create an adverse impact on other environmental parameters – may exist (Prescott 2017[196]). LCA had not been fully applied to the environmental impact modelling of open-water IMTA systems at the time of Prescott's work, which used comprehensive datasets acquired from Chilean salmon monoculture, the salmon-feed industry and salmon-seaweed-mussels IMTA. The species involved were *Salmo salar*, *Macrocystis pyrifera* and *Mytilus chilensis*. See Table 1.12 for a summary of findings.

Table 1.12: Impact contributions of different species in IMTA, Chile

IMTA component	IMTA aspect	Impact share
Salmon smolt production – land RAS	Feed inputs	12%-37%
	Salt	5%-67%
	On-site diesel power	4%-29%
	Electricity supply	2%-27%
Salmon grow-out mariculture	Feed inputs total	71%-98%
	of which: oilseed crops	31%-87%
	fish-meal & fish-oil	0.13%-11%
	Smolt supply	3%-18%
Seaweed mariculture	Infrastructure	14%-89%
	Diesel for maintenance boat	1%-89%
	Production of seeded cartridges on land	9%-49%
Mussels mariculture	Infrastructure, of which	25%-99.5%
	provision of cotton mesh bags for seeding onto ropes	37%-99%

Source: Prescott 2017; the wide ranges are the results of different inputs and efficiencies at different sites

All aspects of the IMTA had environmental impacts, though seaweed and mussels provided benefits in terms of nutrient or nitrogen removal. For example, harvesting 200 tonnes a year of seaweed achieved >375 kg of phosphorus out-take equivalents. There was a potential for shifting of impacts, especially when calculated on mass-adjusted economic value, and it was not possible from LCA to conclude that

IMTA was overall more sustainable than monoculture. Of the eutrophication potential of salmon growing, 64% came from feed nutrients and 32% from the fish excreta, but even if adding seaweed and mussels reduced the eutrophication potential, it did so at the expense of other parameters such as depleting the ozone layer, because of the greater output of greenhouse gases by seaweed, on a nutritional content/weight basis. Using sunflower oil in salmon feed has a higher adverse impact than using rapeseed oil, and moving from 50:50 mixes to 100% rapeseed (Canola) oil would reduce the contribution of feed to unfavourable impacts by 6-24%. However, on an equal weight basis, the contributions of fish oil are still 18–99% lower than those from rapeseed oil (an interesting finding, given the move away from use of anchoveta oils and meals in fish feeds).

The IDREEM project noted that IMTA production created additional environmental impacts due to the add-on infrastructure required, such as ropes, buoys, extra diesel for boats and new offshore infrastructure for co-culturing, all with associated LCA implications including disposal[197].

1.3.12 Economic efficiencies

> *"The major challenge for IMTA is economic: industry in Europe, North America and elsewhere outside Asia is not willing to take up a diversion from the main business of finfish production. IMTA has not been adopted by the Norwegian (salmon) industry to a large extent, mainly because the salmon industry does not want additional work- and space-demanding activities nearby the fish farms, and they do not need it. The profits in the salmon industry are huge and any other business must compete with their salmon-revenue. (This position is corroborated by almost all interviewed contacts.) As long as the list of contras are longer than the list of pros, IMTA will not develop unless the industry is regulated to adopt it. Those few that are having kelp- or mussel farms close to their sites argue mainly in terms of increased sustainability and thereby societal acceptance."*[198]
>
> Kjell Emil Naas, Special Advisor Research Council of Norway (*pers. comm.* 2020)

One of the most important parameters for uptake and establishment of new approaches in an industry is the economic efficiency of the changes, innovations, new procedures and adaptations that need to be put in place. The prevalent view from many commentators is that "IMTA is going nowhere"; that it has no real economic driver and the concept clashes too much with the monoculture model, which predominates in the industry. Although RAS and IMTA may seem more attractive, the changing opportunity costs of land and water have an immediate impact on viability and investment[199]. In Atlantic salmon farming, for example, working capital requirements have steadily risen, from around €2.2/kg harvest in 2014 to >€3.0/kg by end 2018. Based on figures from Norway where licences cost €15 million per establishment and salmon sales prices are €5.7/kg, the payback period is at least 11 years (Mowi 2018). This militates against trying something new and potentially more costly and risky, such as IMTA. Nevertheless, there are tantalising glimpses of economic benefit to be had from IMTA at scale, if industry can be persuaded to invest enough either in full-scale demonstration sites or jump to commercial implementation.

Given labour costs and the type of marine aquaculture already in place in Europe and the Americas, the goal is less labour intensiveness, more automation, and easing of maintenance, monitoring and harvesting. Although CTAQUA from Andalucia has tested pilot-scale IMTA of gilthead bream, oysters in mesh bags on long-lines with floats, and seaweeds *Ulva* and *Gracilaria* on long lines or in floating net cages in saltwater tidal channels in Spain, the system is relatively labour intensive, which will prevent easy uptake of the approach. In Portugal, as part of the EU-funded project GENIALG, the ALGAplus combination of macroalgae and IMTA in tidal channels and saltwater ponds is also manual, although it will be possible to automate it. The organic certification and higher price for ALGAplus's sea bream (*Sparus aurata*) and sea bass (*Dicentrarchus labrax*), which started with juveniles in September 2018, will help offset the production costs[200]. There also may be added-value in the higher protein content of the macroalgae as a result of additional nutrient absorption and improved growth rates, if there is sufficient light[201].

Discounted cash flow analysis using 10 years of production data from a salmon-mussel-kelp IMTA farm in the Bay of Fundy, Canada, found that the IMTA operation was more profitable than standard monoculture expectations and, if a 10% price premium could be obtained for the product, IMTA would produce a substantial increase in net present value[202]. Nevertheless, due to risks and uncertainties, IMTA would have to generate substantially greater profits than salmon monoculture to stimulate investment.

The IDREEM project showed that the footprint of an average salmon farm is enough to support benthic IMTA involving finfish, shellfish, the sea cucumber (*Parastichopus californicus*) and kelp[203]. There is closer to a 1:1 ratio of biomass needed for bottom feeders compared to 10–100:1 for water-column feeder like mussels. Results using *in silico* modelling suggested a possible sixfold increase in yield of deposit feeders below finfish and 150% if below shellfish, reductions in total load of particulate organic carbon of up to 86% for finfish culture and 99% for shellfish culture, and a 22%. contribution to additional kelp production. There are large biological and engineering challenges with putting this in place, as it would take £2–3 million and a willing salmon company to do a study and, for commercial application, availability of spawn might be a problem[204].

The EU-funded MERMAID project concerned aquaculture-wind energy multi-use platforms with salmon-seaweed-mussels IMTA in an array of 100 10MW wind turbine units[205]. The annual electricity production was estimated to be 3 300 GWh at an annual average wind speed of 9.2 m/s with the annual salmon production predicted to be 60 000 to 70 000 tonnes. The calculation of annual financial yield from integrating salmon production with off-shore wind power was €240 to €280 million at a price of €4/kg, equivalent to 73%–85% of the annual electricity yield (€0.10 /kWh), not counting the value of the mussels and seaweed biomass.

The economic efficiency of nutrient density is an important aspect of attractiveness of candidate IMTA species, just as much as the market price. One disincentive for investing in seaweed spatial IMTA is the area that would need to be planted to achieve economic impact. The chance to replace fish-origin components of salmon feed with seaweed-origin oils and proteins is one driver for increasing seaweed farming activities. Table 1.13 shows some published data for protein content of 13 types of seaweed[206,207]. Brown seaweeds, the fastest growing for Northern Hemisphere cooler waters, have the lowest ranges of protein, from 3-20%. The usual protein content of fishmeal is approximately 65% (63–68%), which means that 5–10 kg DW of brown algae would be needed to replace 1 kg of fishmeal, not taking into account differences in protein digestibility and amino-acid composition. Water content is 70%–90%, so each 10 kg DW is equivalent to about 35–100 kg WW.

Table 1.13: Ranges of protein content of seaweeds

Seaweed	Protein content (dry mass basis)
Porphyridium Red alga	56%
Porphyra spp Laver	29%-47%
Pyropia spp Nori	28%-44%
Palmaria palmata Dulse	8%-35%
Ulva pertusa Sea lettuce	20%-26%
Saccharina latissima Sugar kelp	6%-26%
Undaria pinnatifida Wakame	12%-23%
Ulva lactuca Sea lettuce	10%-21%
Gracilaria tikvahiae	11%-20%
Alaria esculenta Kelp	9%-20%
Laminaria digitata Kelp	8%-15%
Ascophyllum nodosum Knotted wrack	3%-15%
Fucus sp. Bladder wrack	3%-11%

Sources: Fleurence 1999, Wells et al. 2017

Each year around 5 million tonnes (mt) of fishmeal and 1 mt of fish oil are produced from about 20 mt of raw materials – 75% from anchoveta and other pelagic fisheries and 25% from by-products of the processing of wild and farmed fish[208]. By-products from processing may account for as much as 35% in some regions. In 2017, 70% of global production of fish-meal and fish oil was used in the aquaculture sector. Given that the usage of fishmeal for its protein content in aquaculture has been about 3.5–4 million tpa in the recent past (IFFO, EUMOFA), the amount of seaweed needed to replace this could be estimated at as much as 350–400 mt WW. Global production of seaweed in 2015 was about 30 million tonnes (FAO data), including just over 1 mt wild-harvested. Farmed seaweed is predominantly used for human food, so if seaweed were to be used for feeding animals, then there would need to be significant technical, management and logistics innovations to succeed. The World Bank has provided a conservative estimate of 1 000 tonnes DW yield/km^2 ocean, implying the need for another 35 000–40 000 km^2 of farming to achieve this volume[209]. In addition, there are variations in nutritional and functional composition according to seasons and different environmental conditions. This means that neither consistent, reliable and reproducible yields nor consistent end-product characteristics and performance can be guaranteed – another disincentive for commercial IMTA activities.

Nobre *et al*. 2010[210] noted that adopting an IMTA configuration on a South African abalone farm raised farm profits by 1.4 to 5%. The overall gain from using IMTA in the case study was several times larger than the net gain in profit, and was estimated at US$1.1–3.0 million a year.

Using IMTA for bioremediation requires careful calculation of all elements of cost. Extraction efficiencies and estimated costs have been analysed for mussels versus seaweeds as bioremediators in IMTA for fish farms[211]. The estimated costs for mussels were €11–€30/kg nitrogen removed (KNR) compared with €209-€672/KNR for *Laminaria digitata* and €1 013/KNR for *Alaria esculenta*, and €10-€38/KNR for *Saccharina latissima* from other sources.

Linking potential markets with economic justification for IMTA will also be difficult. As far as algae-based biofuels and bioplastics are concerned, the main industrial issue is what surface area would be needed for which economics. *In silico* modelling of economic benefits by institutions is very often too optimistic and scenarios from some companies seeking money are exaggerated[212].

The economic viability of aquaponics has recently been examined in the context of the EU-funded Inagro project. In this, a demonstration set-up of catfish and tomatoes in Germany produced 24 tonnes of fish and 11 tonnes of tomatoes a year in a 540 m^2 area of separate but linked growing systems. Though this was not profitable, it yielded enough data for modelling to show that scale-up to at least 2 000 m^2 would be needed for the economics to justify the cost of investment in the system[213].

1.3.13 Investment

Factors involved in lack of cross-EU investment in IMTA, or in aquaculture innovation in general, include the bureaucracy and time for the application process related to licencing, lack of incentives to build scale and a focus on diversification rather than specialisation and scalability[214].

The lack of dedicated and harmonised legislation for aquaponics in general, and urban aquaponics in specific, makes it difficult for entrepreneurs to formulate a business plan and address banks and investors in this particular IMTA sector[215].

Turnsek *et al*. 2020[216] noted that the small average size of aquaponics farms is due to the high initial investment required coupled with the novelty of the technology. The fact that only small-scale facilities can be afforded, but are expected to provide technological and commercial validation, leads into a "chicken and egg" dilemma: large-scale farms are not built because investors require comprehensive proof of concept, and the small-scale farms are not able to provide this, because they are simply too small. In addition, as aquaponics includes both aquaculture and horticulture, most investments are double the cost of competing enterprises that engage only in aquaculture or horticulture.

To date, these comments apply to all IMTA activities, as validation is hardly possible at small scale and double or more investment may well be required when dealing with two or more types of biomass. The uncertainty of the long-term robustness of IMTA means that investment is rather scarce. However, there is funding available – Agriloops, in Rennes, France, was successful in an initial funding round of €0.5 million in 2018[217] to start building an aquaponics farm for saltwater prawns, cherry tomatoes and mesclun (mixed salad leaves). It also received an additional €1.4 million from Oghi, BNP Paribas Développement and business angels in 2019[218], to build the pilot farm, supported technically by CNRS-Roscoff.

As with any innovation, particularly at small scale, failures occur. A relevant example is GrowUp Urban Farms in UK[219]. It had the social, nutritional and sustainable aims of producing tilapia and salad crops in combination in London's Beckton district, for local and restaurant supply. It was set up in 2013 and began producing in 2016, with the aim of harvesting 4 tonnes of fish and 20 tonnes of crops per year and using it as a turnkey module for 9 farms, each 10 times the size. By 2018, however, the unit had closed, as "it wasn't making enough money to cover its costs"[220] and the enterprise was sold to the Vescor Group, which invests in ecologically-interesting opportunities[221]. It has been renamed GrowUp Farms and briefly flared back to life in September 2020 to post on its Facebook page[222], though there has been no subsequent action.

1.4 Prospects for IMTA

According *to Beyond Fish Monoculture. Developing Integrated Multi-Trophic Aquaculture in Europe*, the final report prepared by the IDREEM project in 2016, the conditions were not yet fully in place in Europe for the wide-scale adoption of IMTA. Yet the report also determined "there is a growing commercial interest, consumer interest, an economic and environment case for adoption of IMTA, as well as clear policy drivers for its future development." [223]

1.4.1 IMTA value chains: ecosystem services and product opportunities

End-points for IMTA include ecosystem services and definable commercial products. In a 2020 interview with International Aquafeed, aquaculture champion Thierry Chopin called for the value of ecosystem services to be recognised, accounted for and used as financial and regulatory incentive tools, such as in the development of nutrient trading credits. Explaining that he prefers to identify credits instead of taxes for those implementing sustainable practices, he added, "*In the coastal environment, it is not only a carbon story; consequently, we have to enlarge the debate from carbon tax to nitrogen and phosphorus taxes*."[224]

No real system for recognising and rewarding ecosystem services is yet in widespread and robust practice. Establishment of nutrient and carbon-trading credits has been strongly suggested[225]. Although carbon-trading is the closest in concept, it could easily be extended in theory to cover other nutrients that are potentially damaging to the environment and their sequestering or even harvesting would be beneficial. Phosphorus and nitrogen come into the latter category: phosphorus because of widespread world shortage of this essential nutrient and nitrogen because of nitrification and eutrophication of waters. For example, in the mid-2000s, the town of Lysekil in Sweden valorised ecosystem services by paying around US$10 for each kg nitrogen removed to the farm Nordic Shell Produktion AB, which was using *Mytilus edulis* (the common or blue mussel) as the remediator[226].

Production of seaweeds for other uses, such as bioremediation or biofuel production via anaerobic digestion, is at the development stage[227]. An interesting analysis of the potential for seaweed to provide phenols for bioplastics production has suggested that in the period 2016–2050, when it is estimated that about 1 billion tonnes of bioplastics will be needed globally, using about 3.3 mtpa WW of seaweed a year as raw material input could provide a 25% reduction in the total estimated CO_2 emissions[228]. Though this is in the context of the coastline of Sabah, Malaysia, the analysis could usefully be applied to other sites in Europe and the Americas.

The environmental services provided by RAS-mollusc farming have been estimated using data from a South African abalone farm producing 240 tpa, grazing on wild kelp as the food substrate. Monoculture in flow-through, and RAS replacing seaweed with 10% or 20% farm-grown kelp were modelled and compared. On-farm kelp production reduced nitrogen discharges by 3.7–5.0 tpa, conserved 2.2–6.6 ha of natural kelp beds a year and reduced greenhouse gas emissions by 290–350 tpa CO_2 equivalents[229].

In the context of using nutrient trading credits – Nitrogen (NTC), Phosphorus (PTC), Carbon (CTC) – as incentives for establishing IMTA as a bioremediation tool, Thierry Chopin (2010)[230] noted that the cost of removing 1 kg of nitrogen ranged from US$3 to US$38 at sewage treatment facilities, depending on the technology used and the labour costs in different countries. It has been possible to derive estimates of the value of nutrient removal – nutrient eutrophication reduction services, NERSs) – that IMTA might provide, including a net value of €18–26 billion/year of NERSs provided by shellfish aquaculture in the coastal waters of the European Union; €0.1–1.1 billion/year in the Baltic Sea; and the annual harvesting of kelps from the Bay of Fundy area, Canada, would represent an NTC of US$0.36–1.1 million and a PTC of about US$16 000. The 1 million tonnes of *Ulva prolifera* removed from the bays near Qingdao, China, to allow the sailing events in the 2008 Olympic Games were equivalent to removing 3 000–5 000 tonnes of nitrogen, 400 tonnes of phosphorus and 30 000 tonnes of carbon, with an NTC value of US$30–150 million, PTC of US$1.6 million and CTC of US$0.9 million.

Seaweeds are likely to be the largest volume biomass type produced by either close-to-fish IMTA or spatial IMTA. Both the 2013 Bellona Report[231] and the 2015 SARF Report[232] identified a number of well-recognised end-products from growing seaweed (either in IMTA or monoculture) that could be justified from an economic point-of-view. The Bellona Report includes cuvie/tangle (*Laminaria hyperborea*) and Norwegian kelp (*Ascophyllum nodosum*) as sources of petroleum-replacement products, carbon sinks or biofuels. This is on the basis that the sequestration rate for carbon is around 9 tonnes/ha, which could then produce $\leq$7 500 litres of bioethanol, even without the greater growth produced by exposure to fish nutrient effluents. The maximum carbon capture of seaweed is 2 kg/m^2/year, 2–3 times more than sugarcane, which is considered one of the best bioenergy crops. Half the energy demand in the EU could be met with around 2 300 km^2 of kelp, according to SINTEF Norway. Seaweed can also be harvested to produce biogas or processed for dietary supplements, food components and bioactives.

Capuzzo and McKie (2016)[233] noted that multiple products can be obtained from seaweeds, ranging from food to chemicals and bioenergy. For the UK, a total of 27 seaweed-related businesses were identified, based on web searches – 16 of them use seaweeds harvested in the UK. The majority of UK seaweed-related businesses produce seaweeds for food ("sea vegetables") or condiments, and for cosmetics. Other products, based on seaweeds and produced in the UK, include animal feed and supplements, chemicals (e.g. hydrocolloids), fertilisers and nutraceuticals (e.g. nutrients and dietary supplements).

The Bellona report also noted that bioplastics derived totally from algae are environmentally benign – degrading within 180 days without leaving any harmful chemical residues behind. Combining seaweed-origin biopolymers with petroleum-based materials such as polyurethane and polyethylene reduces the quantity of petroleum and speeds up biodegradation. Green algae from the order of *Cladophorales* are particularly suitable for the production of hybrid plastic – while they are not grown in IMTA, the potential is there.

The following list identifies some of the current commercial activities and opportunities for petroleum-sparing bioplastics.

- Cereplast, a US company, manufactures several products that are 50% algae and 50% petroleum, with an ambition to use 100% algae in the future.
- Algal cellulose can be used to make plastic, and nuisance microalgae have been used in Venice and France for paper. It is also possible to make cellulose batteries from seaweeds and fibres for textiles.

- Algopack[234], a French company founded in 2016, uses brown algae grown in and harvested from the Atlantic Ocean with C-weed Aquaculture[235] as a partner to make 100% macroalgal-origin granules that can be turned into bio-based packaging. ALGOPACK is entirely bio-compostable and biodegrades within 12 weeks in soil and 5 hours in water. When its packaging life is over, it becomes a soil-fertiliser as it breaks down. A hybrid material, ALGOBLEND is a 50:50 mix with petroleum-based polymers. The company promotes the material as process-efficient, as it can be dropped into standard industrial plant, producing a 25% energy saving as it is processed at lower temperatures. Algopack has now been acquired by Corely of the Lyreco Group, with the expectation that its output will increase dramatically from 100 tonnes per year to 10 000 tonnes per year in the next 5 years.
- Skipping Rocks Lab, a young start-up from Imperial College UK[236], utilises marine hydrocolloids from brown seaweeds and plant celluloses to make Notpla[237]. Its major product is the material Ooho[238], which has been used to encapsulate sports rehydration drinks made by the Lucozade company.

Human food and animal feed are clear markets for establishing value chains for seaweed biomass. In Scotland and Norway, IDREEM's harvests of *Alaria esculenta* and *Saccharina latissima* were used for human food (dried and milled) and animal feed ingredients. Lerøy Ocean Harvest, in its spatial salmon-seaweed IMTA operation, has two value chains in place: one a niche market for seaweed preparations as speciality foods, e.g. dried seaweed flakes and toppings for human consumption, made in Denmark; the other is fermented seaweed as a feed ingredient for cows and pigs[239]. The animal feed product is prebiotic and alters the ruminal and gastrointestinal flora favourably, e.g. it reduces piglet mortality by 3%, a significant economic benefit for pig farmers. Currently, the company can produce about 150 000 kg WW of sugar kelp a season, planted in autumn and harvested after 6–8 months. The economic balance is interesting. The price differential is a disincentive, e.g. for farming seaweed for bioenergy or bioplastic, as well as scale-up. But it takes $\geq$3 years to take a salmon from egg to market weight, and there can be three seaweed harvests in that time. According to Lerøy Ocean Harvest, the animal feed market is enormous, so there is no need to think of bioenergy or bioplastics.

The potential of seaweed for correcting methane emissions in ruminant livestock is also being explored by Symbrosia in Hawai'i, which is using *Asparagopsis taxiformis* grown on prawn-tank effluent and returning the cleaned-up water to the prawn tanks[240]. Lerøy Ocean Harvests's and Symbrosia's value chains are built on a wide range of research, including findings in beef cattle in Australia, where 0.1% and 0.2% of *Asparagopsis* in the diet for 90 days reduced methane production by 40% and 98% respectively and increased weight gain by around 40–50%[241]. Bromoform, the active ingredient in *Asparagopsis,* alters ruminal flora and fauna. Symbrosia plans to sell the *Asparagopsis* to dairy feed producers, in the first instance, for US$2.5–3.0/kg, and the prawns into the US mainland organic market for around US$40/kg[242]. The work funded by Australia's national research agency, CSIRO, and Meat & Livestock Australia at James Cook University has led to a new company, FutureFeed[243], on the back of A$13 million (US$9.34 million) from CSIRO, supermarket chain Woolworths, commodities handler GrainCorp, agrifood group Harvest Road, and an agtech accelerator. CSIRO estimates that if 10% of the world's cattle operations included the material in their feeds, global methane emissions could be cut by as much as 120 megatonnes a year. However, supplying enough of the additive for just 30% of the around 2.5 million beef and dairy cattle in Australia would mean processing 25 000 tonnes DW a year of *Asparagopsis* and, with average seaweed production of 30–50 DM tonnes per ha, it would need around 2 000 hectares of seaweed farms (compared with around 900 ha of prawn farms in Australia). Sheep also respond to seaweed in the diet with a reduction in methane emission and better weight gain, as found in shore-grazing sheep in the Orkneys, Scotland[244].

Harvesting the nutritional content of seaweeds for human food and animal feed is somewhat problematic, because of the dilution effect of water content, the large quantities, the logistics of ensuring freshness between harvest and processing, and the costs of drying and valorising the biomass. Certainly, it is attractive to use seaweed nutrients as a replacement for fish-origin and land-crop-origin proteins and oils, which would serve to add value to the use of seaweeds in IMTA and make finfish production more sustainable. A driver for this would be the total volume of fish feeds produced, 1.1 bn tonnes in 2018, with 28% for carp, 18% for shrimp, 13% for tilapia, 10% for salmonids and 31% for other fish including freshwater (Mowi 2019[245]). Trends to plant-origin materials are most clearly seen in salmonid feeds. Table 1.14 shows how the proportions of sources for raw materials have changed over the past 20 or so years.

Table 1.14: Development of raw materials in salmon feed in Norway 2000-2018

Ingredient	2000	2010	2018
Fish meal	34%	25%	13%
Fish oil	31%	17%	10%
Plant-origin materials	36%	59%	77%

Source: MOWI, 2019

Value chains for seaweed that can be strongly developed are illustrated by the ways in which pilot-scale seaweed outputs from EU-funded projects have been used. In IDREEM[246], the 2013 and 2015 seaweed harvests at DOMMRS, were sent to an Irish horse feed company to use as a health supplement and also used within the Marine Station's own facility to feed sea urchins. In 2015, the sugar kelp harvest was sent to University College Cork for use in biogas research. The Scottish partners in the IDREEM project (Scottish Salmon Company, Loch Fyne Oysters and SAMS) harvested a total of 2.5 tonnes WW of *A. esculenta* in May 2013 and 2015, and 1.0 tonne WW of *S. latissima* in May 2015, selling them to a Scottish company that dried, diced and milled the seaweed for use as a food condiment. GIFAS in Norway grew *A. esculenta* with salmon, initially harvesting and using the seaweed in animal feed, but also identifying markets in human food, bioactives, addition to insect meal and as a fertiliser.

With respect to markets for seaweed, its use as nutritional ingredients for pet food has very good prospects. One commentator who was previously with a commodities crop producer confirmed that the pet food industry is always asking for new ingredients[247], and Lerøy's already sells its seaweed into the livestock animal feed market and sees an exponential growth possibility there[248].

In a more focused biomedical way, there is work on seaweed alginates and chitin nanofibers as biomaterials for medical use[249]. This would assist management of chitin from crustacea grown in IMTA as well. A possible new and exciting use for seaweeds is to produce sulphated polysaccharides that interfere with SARS-CoV-2 entry into cells, in this case *Saccharina japonica* fucoidans[250].

"Mussels could in theory be fed back to fish as a protein source but in Norway, this can't be done without processing them, and IMTA is not needed to do this anyway. In the EU it is technically illegal to feed one animal off the waste products of another – the animal-derived protein issue, and faeces and pseudofaeces are definitely rather dubious for marketing. The answer is also not yet clear on food safety[251]. With seaweed things are a bit more positive and Norway has done a good job with Ulva."
Rui Gomes Ferriera, CEO LongLine, UK (*pers. comm. 2020*)

The mussel industry in Chile might be a suitable candidate for IMTA, with an output of around 300 000 tonnes a year, but it would still be necessary to manage harvests and maintain routes-to-market for the outputs and end-products[252].

Alejandro Buschmann, Professor U de Los Lagos Chile (*pers. comm. 2020*)

Mussels and other bivalves are likely to be secondary in terms of IMTA biomass, though commercial activities already exist. For example, Danish Seaweed Seed Supply, bought by the Norwegian company Seaweed Energy Solutions (SES) in 2013, has been growing *Saccharina latissima* and blue mussels together at three locations in Denmark (Knebel Vig, Hou, Limmorden) for over 10 years, using long-lines with droppers. The same lines are used for mussels/seaweed co-culture, so in the UK, it is more likely that it will be mussel-seaweed IMTA rather than fish-seaweed IMTA[253].

A problem with making much greater use of molluscs and crustacea as components in IMTA is what to do with the shells. Although some value chains already exist – e.g. crushed mussel shells in vineyards, or crustacean chitin as an antifungal and precursor to chitosamine and glucosamine as health supplements – the volume available would indicate that there is a need to develop new end-products or build easy access to growing value chains. Bivalve shells are exploited in China as the building materials for artificial reefs for marine ranching. Mussels, mussel flesh and residual flesh in clean shells can be used to provide accessible food and feed proteins as well as hydrolysed proteins and amino-acids for foods and specialised nutrition. It has also been envisaged that sub-standard bivalves can be fed as they are to higher trophic levels in IMTA, thus reducing feed inputs and improving economic efficiency.

The IDREEM project also generated 60 000 kg of mussels as spat, which were then deployed at other locations around Scotland for on-growing, and >250 000 queen scallops, which were harvested and individually quick frozen as a high-value human food[254]. Once permits are received, IDREEM partner AQUA Srl in Italy plans to scale-up the sea bass, sea bream and pacific oyster IMTA to commercial scale, supplying oysters to local retailers and restaurants. In Scotland, FIA Aquaculture Ltd and SAMS grew *Ulva* sea lettuce onshore[255], in raceways of nutrient rich water coming from turbot (*Psetta maxima*), cod (*Gadus morhua*) and sea bass (*Dicentrarchus labrax*) tanks. The *Ulva* was then used to feed amphipods for fish fry feeding and edible sea urchins (*Paracentrotus lividus*). FIA plans to produce enough *Ulva* to grow 100–200 sea urchins/m^2 to commercial size.

There are also plentiful examples of successful aquaponics enterprises. Sweden's Peckas Tomatoes (Peckas Tomater och Regnbåge) uses rainbow trout and tomatoes in gravel beds in greenhouses[256]. Belgium's Aqua4c produces 200 tonnes of jade perch (omegabaars) a year using residual heat and rainwater collected by the adjacent horticulture enterprise Tomato Masters, and returns nutrient-enriched water for tomato growth, via reed beds[257]. The Recirculating Farms Coalition has established a programme called Better Fish Farming[258], including an aquaponics farm in New Orleans of around 4 050 m^2 (1 acre), growing catfish, koi, goldfish, herbs, tomatoes, peppers, lettuces, greens, cantaloupe and flowers in recirculated water, plus potatoes, broccoli, cauliflower, onions, carrots, watermelon, eggplants, tomatoes, cucumbers and flowers in soil watered and fertilised by fish effluents.

The choice of grey mullet as a detritovore in benthic IMTA is regarded by van Beijnen and Yan (2020)[259] as an "*excellent sustainable fish choice because they are primarily herbivorous, efficiently convert food to body mass and can handle a wide variety of culture conditions; a big plus is bottarga, the salted and dried roe of gravid females, which is a pricey and sought-after delicacy across the Mediterranean*." It is an example of an existing value chain into which an IMTA species can immediately be plugged.

Once famers are using IMTA, the question arises of how they organise their biomass into the appropriate routes to market, given the likelihood that the amounts and timings may be inconsistent. In this context, on-line platforms or mobile-phone-based apps that match supplies with demand might be useful. These already exist for small farmers in Asia and Africa – e.g. GeoFarmer, TruTrade and apps developed in FAO-funded projects such as AgriMarketPlace[260]. An attempt was made in Iceland to set up an online platform, Resource Square/Auðlindatorg, for aquaculture and fisheries. It was organised as an on-line sales house for non-food marine biomass so that producers and users could easily be put together, especially when the volume of biomass was insufficient to justify a contract for supply with large industries. Unfortunately, none of the original suppliers or buyers who had expressed early interest followed through when the platform was being developed further, so this initiative has stopped[261]. The concept could however be revived for edible and non-food biomass from IMTA.

1.4.2 Taking opportunities for the future

IMTA has obtained encouraging but not commercial-scale results in most of its work to date, and shown promising environmental and economic benefits. But difficulties remain in encouraging established mainstream producers, such as off-shore wind farms, to integrate the types of IMTA offered. A new direction needs to be taken – away from the classic model of finfish cage at top, bivalve lines or cages round-about or below, and seaweed on the sea bottom. The evidence for this model is excellent in research scale and *in silico* modelling but dubious or at least inconsistent and not robust enough in real life for industry to invest and undertake the additional operational complexities that would be needed.

Among the viable options for IMTA are those in which each of the elements has a specific market value that makes it feasible to bring them together from the product value chain point of view:

- on-land fish production integrated via RASs with suitable crops or macroalgae (i.e. aquaponics);
- marine benthic IMTA, where detritivores with a reasonable or high market value (holothurians, sea urchins) clean up the footprint of finfish farms, whether or not bivalves and/or seaweed are grown nearby;
- fish-seaweed operations where the seaweed is harvested, and partially or completely processed into inputs of fish feed and, if in sufficient quantity, for industrial uses.

There are other viable options in which the main benefit is in less measurable outputs, such as disease management, ecosystem services, employment or social licence to operate:

- spatial or ecological IMTA, where the different trophic levels are not co-located, but are encouraged or deliberately placed around fish farms in the wider aquasphere, at several kilometres distance, described by one commentator as "decoupled mass balance IMTA";
- freshwater fish production, where ponds are supplemented by edible or not-so-edible water plants that improve the aquatic microbiome and assist fish health and growth;
- use of filter-feeders, such as bivalves or sponges, where there is evidence that they might be able to trap disease organisms that are damaging to fish (such as salmon lice) or to food safety (such as *Escherichia coli* or *Vibrio fischeri*).

Perhaps the most promising early opportunity for IMTA biomass is use of seaweeds as petfoods, livestock feeds and fish feeds – once the most economically efficient harvesting and processing conditions can be established. The French company Olmix has created value chains from "green tide" seaweed, which are processed and formulated into products for farm animals that increase the immunity of the animals they feed, and decrease fungal toxin production in feedstuffs. Though seaweeds are not currently farmed, the fact this value chain exists makes it possible to see how seaweed farming might provide a more reliable and standardised source of raw material and also fit into the broader ecosystems concept of IMTA. Seaweeds could thus be farmed in areas of nutrient run-off from the land, crop and livestock agriculture, provided food and feed safety is not compromised.

> *It is important to note the potential of freshwater aquaculture, inland aquaculture with enclosed waters, integrated multitrophic aquaculture and recirculation systems or aquaponics in urban zones for the improvement of food security and the development of rural areas*
>
> European Parliament, 2018

Moving forward in Europe, the European Parliament report of 2018[262] is a key starting point for policy changes and actions that would aid aquaculture innovations, including IMTA. It specifically calls for pilot projects on IMTA, agreeing with the Food from the Oceans scientific report that the only way to obtain significantly more food and biomass from the ocean in a short period of time is to harvest organisms at the bottom of the food chain, such as macroalgae and bivalve molluscs[263]. Very important points are:

- a *one-stop shop* to be created as soon as possible, which would take on and exercise all responsibilities, allowing relevant documents to be submitted to a single administrative body;
- a *fast-track* licensing system, whereby the competent administration grants a provisional certificate permitting those operators who meet predefined criteria to commence their activities;

- *spatial planning maps* to be elaborated by the Commission and the Member States in order to identify possible areas where aquaculture and other activities may coexist.

These points all recognise that spatial planning and licensing conditions are the most likely reasons for the unwillingness of other important or powerful sectors to share space.

Certification and promotion by international bodies is a well-recognised route to international take-up of products produced in a sustainable, green or environmentally beneficial way. The Sustainable Trade Initiative (IDH) works with the private sector to make business better and has an active Aquaculture Program[264]. It has co-developed, with the Global Sustainable Seafood Initiative, the Seafood Measuring and Accelerating Performance of the global seafood supply (Seafood MAP)[265] and the Partnership Assurance Model (PAM)[266]. The Aquaculture Program concerns shrimp, tilapia and *Pangasius* (catfish, basa fish), the three groups most internationally traded from “the south” to “the north”, with monoculture as the most common system of production. The Seafood MAP, due to be finalised in late 2020, and PAM may well include considerations of IMTA, because they are designed to complement certification by giving farmers, investors and producers an explicit framework that gives confidence that the producer is making a sound transition to sustainable aquaculture, translate global sustainability standards into local conditions and encourage all stakeholders to work together.

The issue of certification is certainly part of market context, and presents a strong way of letting the market and consumers know about the benefits of products. The aquaculture multi-annual strategic plans of the EU MSs consider aquaculture certification to be important for market growth (supported strongly by MSs BG, EE, FI, GR, IE, IT, RO, ES, SE)[267], perhaps in the form of an appellation or certificate of origin (AT, CZ) or through a scheme in collaboration with established international certification bodies for species which are not being certified at present (NL). If these initiatives take place, it would be important for IMTA interests to lobby for IMTA to have a “green” or “eco-friendly” certification included in broader aquaculture certification developments.

On the other hand, Turnsek *et al*. 2020[268] noted that, although aquaponics in the USA can be certified as organic, aquaponics producers in Europe can’t benefit from an official label. Consumer surveys suggest that produce from IMTA may command a premium as being environmentally-beneficial, but the reality is that this is not a decision consumers make; it is one that food retailers make. Lerøy Ocean Harvest, for one, has discovered that neither its salmon nor the seaweed product can automatically gain a price premium in spite of the production’s IMTA background[269]. Cohesive lobbying will be required. Existing organisations that could move IMTA forward include those concerned with aquaculture, marine sustainability and seaweeds.

- *The Aquaculture Advisory Council (AAC)*[270] focuses on finfish and shellfish producers, but offers seats on the Executive Committee to organisations such as Seas at Risk and the Good Fish Foundation. AAC members face many of the same challenges and difficulties – e.g. onerous or unintegrated regulations, licensing and controls – that IMTA activities would face. From this point of view, AAC’s recommendations on the Future Strategic Guidelines for the Sustainable Development of EU Aquaculture[271] are relevant for IMTA. These include that EU MSs should set up aqua-environment schemes to support the delivery of the ecosystem services of pond fish, shellfish and algae farming, and promote short consumption chains of locally produced fish by integrating aquaculture into local economies.

- *Industry and sustainability associations*, such as the Aquaculture Stewardship Council, will have a role in assessment, agreement and decision on whether IMTA is something to be strongly taken up or not. They will be developing, establishing or lobbying for certification systems that might favour IMTA, with the acceptance of premium prices implied and thus an economic driver for uptake.

- *In terms of the remediation of finfish aquaculture and seafood production and sustainable intensification of aquaculture production*, organisations such as the Global Salmon Initiative (GSI), Aquaculture Stewardship Council (which already operates an ASC certification scheme), Global Sustainable Seafood initiative (GSSI), Sustainable Fisheries Partnership[272] and Seafood Business for Ocean Stewardship (SeaBOS) seem relevant on the international scale.

IMTA, as an ecologically- and economically-sustainable farming activity, could be applied to local management of aquaculture in marine protected areas. In doing so, it would provide local food and nutrition security, reduce poverty and contribute to the socio-economic resilience of local communities, and at the same time, increase biodiversity and the potential for aquaculture ecotourism as part of the public good[273]. For example, BLUEMED, a consortium of coastal EU MS interests, proposes[274] establishing innovative networks of marine protected areas, described as “cells of ecosystem functioning”, that take into account the connectivity among sites across the Mediterranean and the benefits of an ecosystem-based management approach, as well as promoting IMTA.

Grassroots and context activities are also very important, and incentives for IMTA could be provided via innovation prizes, similar to the UK-based Aquaculture Awards[275], which focus on the industry, research inputs and services. For context, especially to encourage others, a very useful activity would be to create and keep up-to-date maps, such as those established for aquaponics by CIRAD’s APIVA programme[276] and the EU Aquaponics Hub[277], that show, in one place, all the IMTA-related activities in Europe, including the fully commercial operations, those under consideration, investors interested in the opportunities, and institutions offering training and research facilities.

In sum, more work is needed if IMTA is to become a commercial reality, despite the large amount of research and field pilot work carried out to date and summarised herein. There are specific associations or policy organisations devoted to individual aspects of IMTA, such as aquaponics and RASs, but none that can lobby for the broad extent of IMTA possibilities across all relevant sectors or include stakeholders from the span of supply- and value-chains such as crop agriculture, human and animal foods and health, environmental policy-makers and ocean-power industries. Others may be supporting aquaculture projects that could lead to IMTA but, for example, the Sustainable Fisheries Partnership has confirmed that none of its partners are working on IMTA or even discussing it, because its retailer and supply chain partners are focused on improvement in commodity species such as salmon, trout and seabass/bream in Europe and shrimp from international markets.

According to Anton Immink, the Sustainable Fisheries Partnership’s Global Aquaculture Director, this indicates that “*IMTA will remain a niche subject with researcher support but little potential to scale in a meaningful commercial way.”* [278] And Rui Gomes Ferreira, of LandLine Environment, believes that “*For industry, IMTA is still a romantic idea. The scientific case and, above all, the business case and supply chain validation for IMTA are still lacking.”*[279].

Nevertheless, for the applications outlined above – spatial, benthic and land-based IMTA – there seem to be near-term opportunities to move forward constructively.

Annex I – Projects relevant to IMTA

Canada.

Projects funded by DFO and CIMTAN have included a very broad range of targets, and have helped clarify what might or might not work. They include:

- determining capacity of bivalves to reduce sea lice and salmon parasites (*Loma salmonae)* – not effective in the sea;
- undertaking further work on salmon or sable-fish and detritivores – positive;
- making a 10-year discounted cash flow analysis of salmon monoculture versus fish-sugar kelp-mussels IMTA – even without a possible 10% price premium, the IMTA was profitable, but uncertainty related to IMTA's financial and environmental performance, as well as IMTA's increased operational complexity, were thought to be barriers to IMTA adoption in Canada;
- experimenting with the bioremediation of halibut effluent in closed land-based systems by seaweeds Irish moss (*Chondrus crispus*) and dulse (*Palmaria palmate*) – 50% of the nitrogen output of Scotian Halibut Ltd's 100 tonnes of halibut could be processed by 100 tonnes of seaweed in winter and 600 tonnes of seaweed in summer;
- testing absorption efficiency of mussels next to salmon cages (Canada) or seabream (Spain)[280] – no evidence that proximity improved absorption by mussels, which seemed more related to amounts of natural suspended nutrient particles;
- measuring use of fish waste nutrients by mussels suspended near salmon cages[281] – though there was evidence of higher absorption in IMTA mussels than those in distant monocultures, and the condition index was higher, the variation was mainly due to natural nutrient variability;
- harnessing wave power to support a sustainable land-based IMTA system aimed at reducing energy costs for coastal settlements and producing fish, scallops and seaweeds;
- developing a biological filter to reduce nitrogen in American lobster tank effluent, using red algae (*Porphyra* spp, *Pyropia* spp.) that could be sold as nori, establishing operating costs, profitability and nutritional value of the seaweeds.

Europe

Table 1.15: Some EU-funded and national projects in aquaculture and IMTA

Project and years	Focus and targets
Feasibility study 2000–2001	Looked at the potential of multi-functional use of offshore wind farms with commercial marine aquaculture in the German North Sea, investigating culture species, biology, techniques, integrated coastal zone management issues, regulations and market conditions. Led by the Alfred Wegener Institute for Polar and Marine Research (DE-funded).
SEAPURA 2001–2003	Involved outdoor tank cultures of seaweeds *Falkenbergia rufolanosa*, *Palmaria palmata*, *Ulva* spp, *Hydropuntea cornea*, *Gracilaria bursa-pastoris* and *Chondrus crispus* on fish farms in ES, PT. Research also undertaken in DE and UK (Northern Ireland), looking at bioremediation capacity and environmental effects in dealing with effluents from fish farms and other waste sources, microbial impacts, and in FR on the potential for use in fish feed and cosmetics[282]. https://cordis.europa.eu/project/id/Q5RS-2000-31334; https://seagriculture.eu/matthew-dring/.
Open Ocean Aquaculture 2001–2004	Studied the potential of mussel & algae aquaculture in German waters. Led by the Alfred Wegener Institute for Polar and Marine Research (DE-funded).
REDWEED 2003	Focused on reducing the environmental impact of sea cage fish farming through the cultivation of seaweeds. (UK-funded.) https://www.findaphd.com/phds/project/establishment-of-red-seaweed-mari-culture-redweed/?p63705.
AquaLast 2004–2006	Established the technical feasibility of aquaculture constructions on windmill pylons. Led by the Alfred Wegener Institute for Polar and Marine Research (DE-funded)
BIOPURALG 2004–2006	Set up an IE-NO collaboration investigating land-based IMTA of rainbow trout and the seaweeds *Porphyra dioica* and *Ulva lactuca*, in a cascading tank system linked to the outflow from the fish, stripping 60% to 90% of the ammonia and nitrate, and 40% of the phosphate from effluents, with *Porphyra* effective from October to April and *Ulva* from May to September[283]. https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5caea4153&appId=PPGMS.
Coastal Futures 2004–2008	Studied policy and practicalities of Integrated coastal zone management in DE. Led by the Alfred Wegener Institute for Polar and Marine Research (DE-funded).
AquaInno 2007–2010	Investigated the feasibility of Pond-in-Pond system for nearshore environments in DE. Led by the Alfred Wegener Institute for Polar and Marine Research (DE-funded).
IRC-IMTA 2009–2012	Involved a company (NO), aquaculture farms (NO, CN) and research institutes (GR, NO, UK, CN), paving the way for projects such as IDREEM and the Urchin Project funded by the Northern Periphery and Arctic Programme. https://cordis.europa.eu/project/id/230803/reporting; https://urchinproject.com/.
Open Ocean Multi-Use 2009–2012	Developed systems for fish cage development within an offshore tri-pile wind farm foundation, including technology, biology, economy as well as social science. Led by the Alfred Wegener Institute for Polar and Marine Research (DE-funded).
MABFUEL 2009–2013	Supported the feasibility of using seaweeds and microalgae with high lipid and carbohydrate content, and fast growth rate in cost-effective cultivation for biofuels in TK and IE. A Madame Curie programme, it called for using hexane extraction, supercritical CO_2, organic solvents and/or pyrolysis. https://cordis.europa.eu/project/id/230598/reporting.
MACROBIOMASS 2010–2012	Created a knowledge base for large-scale seaweed biomass cultivation in Norway (NO-funded). http://www.seaweedenergysolutions.com/en/projects-research-and-development.
SEAWEED-STAR 2011–2013	Focused on offshore cultivation of seaweed (Eurostars project). https://www.eurostars-eureka.eu/project/id/6027.
MERMAID 2012–2015	Looked at technical and commercial constraints and economic potential of IMTA using salmon, seabream and seabass, mussels and seaweeds on multi-purpose offshore platforms in 4 sites – Baltic, Adriatic, Cantabrian Atlantic and Wadden Sea. https://cordis.europa.eu/project/id/288710/reporting.
Offshore Site-Selection 2012–2015	Defined criteria for offshore sites (site-selection) for multi-use including GIS, economy and especially IMTA concepts. Led by the Alfred Wegener Institute for Polar and Marine Research (DE-funded).
EXPLOIT 2012–2016	Studied exploitation of nutrients from salmon aquaculture, with salmon and kelp, showing seasonal mismatch between peak salmon output and growth season for kelp, and assimilation up to 200 metres away from sea cages. Supported decoupled mass-balance seaweed. (NO-funded.) https://www.sintef.no/globalassets/sintef-fiskeri-og-havbruk/nstt/handa-sats-marint-2015.pdf/.
IDREEM 2012–2016	Aimed to accelerate IMTA development across Europe (an output of IRC-IMTA). IMTA: fish (salmon, seabass, seabream) with one or more of grey mullet, bivalves (mussels, oysters, scallops), seaweed, sea urchins, sea cucumbers; in NW Europe and Mediterranean: CY, IE, IL, IT, NO and UK (Scotland). http://www.idreem.eu/cms/home/.

Project and years	Focus and targets
SEABIOPLAS 2013–2015	Investigated seaweeds *Gracilaria vermiculophylla* and *Alaria esculenta*, grown in IMTA systems with salmon (IE) and seabream (PT) as biomass for extraction of ulvan, agar and alginate for production of lactic acid, polylactic acid and bio-derived plastics, and use of residues for fish and animal feed. https://cordis.europa.eu/article/id/170424-seaweed-a-sustainable-source-of-bioplastics.
DIVERSIFY 2013–2018	Studied flathead grey mullet (*Mugil cephalus*), usable in benthic and detritivore IMTA. It was one of 6 being intensively studied for hatchery and farming improvement[284], along with meagre (*Argyrosomus regius*), greater amberjack (*Seriola dumerili*), wreckfish (*Polyprion americanus*), Atlantic halibut (*Hippoglossus hippoglossus*) and pikeperch (*Sander lucioperca*) for freshwater RAS. https://www.diversifyfish.eu/.
AQUASPACE 2015–2018	Examined the social acceptability of aquaculture using 16 case studies in each of the partner countries (AU, CA, CN, DE, ES, FR, GR, HU, IE, IT, NO, PT, UK, US), some involving IMTA, e.g. DE, CN. http://www.aquaspace-h2020.eu/
INAPRO 2016–2018	Focused on aquaponics, with commercial partners involved in systems development or already operating freshwater fish RASs and tomato-fish linkages. Demonstration sites developed in DE, ES, BE used tilapia, pikeperch and African catfish, and those in CN used murry cod, barramundi and crayfish providing nutrients and water for herbs, lettuce, tomatoes and ginseng. http://www.inapro-project.eu/.
RESTORE 2016–2019	Has developed restoration strategies for the European oyster (Ostrea edulis) in the German North Bight including offshore wind farm areas. Led by the Alfred Wegener Institute for Polar and Marine Research (DE-funded).
TAPAS 2016–2020	Has developed decision tools to help harmonise and improve the efficiency of EU MS regulatory actions concerning IMTA. The aim is to establish a coherent and efficient regulatory framework that implements the Strategic Guidelines for the Sustainable Development of European aquaculture[285]. http://tapas-h2020.eu/.
MACROCASCADE 2016–2021	Focusing on consistency and efficiency of seaweed farming for biorefinery systems, including strain selection and harvesting technologies, and reducing costs for processing, which may make seaweed as a component of IMTA more attractive. https://www.macrocascade.eu/.
GENIALG 2017–2020	Involves companies in large-scale integrated European biorefineries and experts in seaweed cultivation, genetics and metabolomics, working together to select and improve strains of the sugar kelp (*Saccharina latissimi*) and sea lettuce (*Ulva rigida*), and establish economic large-scale production. The project includes a social licence study at test sites to gather information for a Handbook for Seaweed Farms. https://genialgproject.eu/.
INTEGRATE 2017–2020	Focused on creating a strategy document and action plan for IMTA in the Atlantic region, this Atlantic Area Interreg project has 8 core and 11 associate partners. It established three pilot studies, covering *Porphyra*-oyster IMTA systems; alternatives to organic and inorganic extractive components in benthic IMTA; and enhanced management of land-based IMTA with fish, molluscs, invertebrates and seaweed/salt-tolerant plants. http://integrate-imta.eu/.
SEAFOODTOMORROW 2017–2020	Works with 34 partners in 15 countries, developing new environmentally friendly seafood production and processing methods that support European seafood security, quality and markets, such as factoring IMTA integrating seaweeds, selenised yeasts or microalgae into diets of salmon and seabream in marine waters, and carp in freshwater. Preliminary results found no negative effects and healthier salmon with fewer sea lice; and investigating and developing certification for fish produced using environmentally friendly systems. https://seafoodtomorrow.eu/.
Offshore-Co-Use 2018–2020	Studied the combination of aquaculture and Passive Fisheries in Offshore Wind Farms in the German Bight. Led by the Alfred Wegener Institute for Polar and Marine Research (DE-funded).
ADRIREEF 2018–2021	Developing and creating natural and artificial reefs in the Adriatic to strengthen both aquaculture and tourism and, in turn, the blue economy. Working with regional development agencies, environmental agencies, universities and institutes as partners, it is establishing innovative low-cost underwater monitoring technologies and producing a white paper for funding projects in the 2021–2028 programming period (Interreg Italy-Croatia). https://www.italy-croatia.eu/web/adrireef.
Blue Growth Farm 2018–2021	Establishing a multi-purpose floating platform for wind- and wave energy with fish farming; and designing surveillance, monitoring and control systems and multi-purpose docking, including a survey of social attitudes about multipurpose offshore platforms. https://www.thebluegrowthfarm.eu/.
IMPAQT 2018–2021	Developing remote sensing and management systems for IMTA in land, coastal and off-shore environments, looking at interactions with the environment on an ecological scale. https://impaqtproject.eu/about-impaqt/.
FANBEST 2019–2021	This aims at setting up a network of public and private funds for start-ups, small and medium-sized enterprises (SMEs), and a scale-up of blue bio and marine resource exploitation, involving ES, FR, IE, PT, UK. Funded by Interreg Atlantic Area project: although not initially focused on IMTA, this is not specifically excluded. https://fanbest.eu/.

Project and years	Focus and targets
SEABEST 2019–2021	Aimed at reducing cost of producing seaweed in Europe, from spores to food products, by over 50% and scaling up to 14 000 tonnes per year. An SME instrument project, it is based on a feasibility study funded by Innovation Norway (VIDAN – 2014/104777) http://www.seaweedenergysolutions.com/en/commercial-projects/seabest-sme-instrument.
AquaVitae 2019–2023	Established as an Atlantic Consortium project with 35 partners from 15 countries and five targets, of which one is IMTA and aquaculture: sustainable seaweed, sea urchin, shellfish and finfish production. https://aquavitaeproject.eu/.
ASTRAL 2020–2024	Aimed at building new value chains for IMTA in Atlantic countries of Europe, South America and Africa (Horizon 2020) https://cordis.europa.eu/project/id/863034

Source: project websites; note, countries are designated using ISO-3166 two-letter codes

Project involving aquaponics

- *EU Aquaponics Hub*[286] *2014–2018*, an EU-funded COST action, stimulated the formation of the Association of Commercial Aquaponics Companies (ACAC)[287] in 2016, and the European Aquaponics Association[288] in 2018, linking national associations in a network.
- *Aqu@teach*[289] *2017–2020,* supported by Erasmus+, is the first tailored aquaponics curriculum for university students, including agriculture, agronomy, horticulture, aquaculture, landscape architecture and ecological engineering. Universities in SI, ES, CH and UK collaborated in developing the kind of approach that could be rolled out across Europe if needed.
- *Aquaponie, innovation végétale, aquaculture (APIVA) formed 2014,* aquaponics programme founded by CIRAD, Montpellier (FR), with the Lycée de la Canourgue in Lozère, Institut Technique de l'Aviculture (ITAVI), which also does applied research and training in aquaculture, CIRAD Bangkok, and many fish farming professionals. APIVA has supported projects on aquaponics in South-East Asia.
- *BiOPONi, formed 2018*, as an advisory and engineering organisation to help move aquaponics forward, involved in realisation projects across Europe, in Ghana and Côte d'Ivoire in West Africa, and Guadeloupe and Martinique[290] in the Caribbean.
- *OSU AquaFish Innovation Lab* worked on low-cost aquaponic systems for Kenya with University of Eldoret[291], with training and extension activities for small-scale or subsistence African catfish, and kale and spinach production, 200 kg and 120 kg respectively, where water and land were scarce, in urban and semi urban areas.

Some projects of interest involving seaweed

- *The EXPLOIT project (Bellona, SINTEF, NTNU)* surveyed the spread of nutrients from salmon farms in Norway and looked at how well blue mussels, scallops and algae absorbed them[292].
- *Salmon Group AS* and *Sulefisk AS* (Norway) and *Hortimare* (the Netherlands), funded by *Innovasjon Norge*, determined that *Palmaria palmata* and *S. latissima* kelps grew 48% and 61% faster, respectively, when grown 100 to 200 metres from salmon cages, and removed 5% to 12% of waste nitrogen from the farm[293]. Modelling suggests that 220 ha of seaweed, yielding 12 to 16 kg kelp/m^2, could bioremediate 100% of the output from a 5 000 tonne salmon farm[294].
- *MACROSEA project* (NO-funded) developed efficient technologies to reduce the need for technical maintenance in mechanisation of seedling deployment, biomass harvest and crop handling logistics[10].

[10] https://www.sintef.no/projectweb/macrosea/

- *University of Exeter and University of Bath* in UK, *and the University of Baja California* in Mexico are going to process nuisance seaweeds such as *Sargassum* by using acid instead of drying them, alkaline hydrolysis in saline conditions for sugar release and hydrothermal liquefaction (HTL) for the residue[295]. Yeasts can ferment the sugars into fatty acid replacements for palm oil, and the bio-oil from HTL can be processed further into fuels and high-quality, low-cost fertiliser. Through the HTL, any marine plastic debris mixed with the seaweeds will also be convertible to fuel oil.
- *University of Exeter with Westcountry Mussels and the Cornish Seaweed Company*[296]are piloting kelp and mussel IMTA in Cornwall, UK, 300–500 metres from the shore, and assessing the practical biological and engineering criteria for successful near-shore cultivation. They established the first 150 long-lines seeded with *Saccharina* and local seaweeds in November 2019. Part of the harvest to-date has been supplied to a UK seaweed-extraction company for food, nutritional bioactives and bioplastics assessment[297].
- *Abreu et al.* 2009[298] demonstrated that, when sited near salmon cages, *Gracilaria* had double the growth obtained at distant sites, and that a 100 ha *G. chilensis* long-line system would effectively remove all the N inputs of a 1 500-tonne salmon farm. The findings and principles have been carried forward into the Portuguese company ALGAplus.

Annex II – Species used in IMTA in Europe

Table 1.16: Primary fish species in European aquaculture

Fed species	Latin name	Country	Land- or sea-based farming
Meagre	*Argyrosomus regius*	ES	S
Sea bass	*Dicentrarchus labrax*	CY, FR. GR, IT, PT, ES, UK	L&S
Sharp-snout seabream	*Diplodus puntazzo*	ES	S
Atlantic cod	*Gadus morhua*	UK	L
Atlantic halibut	*Hippoglossus hippoglossus*	UK	L
Ballan wrasse	*Labrus bergylta*	UK	L
Flathead grey mullet	*Mugil cephalus*	GR, IL	L&S
Mediterranean mussel	*Mytilus galloprovincialis*	ES	S
Rainbow trout	*Oncorhynchus mykiss*	DK	S
Atlantic salmon	*Salmo salar*	IE, NO, UK	S
Turbot	*Scophthalmus maximus*	UK	L
Gilthead seabream	*Sparus aurata*	CY, DK, GR, IL, IT, PT, ES	L&S

Source: Kleitou et al. 2018; note, countries are designated using ISO-3166 2-letter codes; S = sea-based farming; L = land-based farming

Table 1.17: Invertebrate species used in IMTA and stage of progress

Species group	Species	Country	Technique	Land- or Sea-based farming	Commercial or Experimental
Seston feeders					
Clams	*Ruditapes decussatus*	IL, ES	n/a	n/a	E
	Ruditapes philippinarum	ES	n/a	n/a	E
Mussels	*Mytilus edulis*	NO, ES, UK	Cages; Long-line; Smart farm system	S	C&E
	M. galloprovincialis	CY, DK, IT, ES	Long-line	S	E
Oyster	*Crassostrea gigas*	IL, IT, UK, PT	Lantern nets; SEAPA baskets	S	E
	Ostrea edulis	CY, IT, ES	Lantern nets; Ortac baskets; Stacked boxes (40x40x10cm)	S	E
Scallops	*Aequipecten opercularis*	UK	Collectors; Pearl nets; lantern nets	S	C&E
	Mymachlamys varia	ES	n/a	S	E
	Pecten maximum	NO	Cages	S	E
Sponges	*Spongia spp*	CY	Mesh quadrats	S	E
Detritivores and grazers					
Abalones	*Haliotis tuberculata*	CY, ES	Ortac baskets	S	E
Crab	*Callinectes sapidus*	CY, GR	SEAPA baskets; Tanks	L&S	E
Fish	*Mugil cephalus*	GR, IL	Cages	L&S	E
Polychaete	*Alitta virens*	UK	Tanks	L	E
Sea cucumber	*Hediste diversicolor*	FR	Tanks	L	E
	Holothuria forskali	ES	n/a	S	E
Sea-urchin	*Paracentrotus lividus*	CY, IL	Bottom cages; Ortac baskets; Oyster baskets; Pots	L&S	E
	Psammechinus miliaris	UK	n/a	S	E
Shrimp	*Lysmata seticaudata*	ES	n/a	S	E

Source: Kleitou et al. 2018; C = commercial, E = experimental; abalones are also suspension feeders

Table 1.18: Seaweed species used in IMTA and stage of progress

Species group	Species	Country	Technique	Land- or Sea-based farming	Commercial or Experimental
Brown algae	*Alaria esculenta*	IE, NO, UK	Hanging rope; Horizontal rope (Longline)	S	C&E
	Saccharina latissima	DK, IE, NO, PT, ES, UK	Hanging rope; Horizontal rope (Longline)	S	C&E
Green algae	*Ulva lactuca*	IL, UK	Tanks	L&S	E
	Ulva rigida	PT	Tanks	L	E
	Ulva rotundata	PT	Tanks	L	E
	Ulva sp	FR, UK	Tanks	L	E
Plankton	n/a	FR	High-rate algal ponds	L	E
Red algae	*Asparagopsis armata*	PT	Tanks	L	E
	Hydropuntia cornea	ES	n/a	n/a	E
	Palmaria palmata	IE, UK	Tanks; Horizontal rope (Longline)	L&S	E

Source: Kleitou et al. 2018; C = commercial, E = experimental

The range of species used outside Europe is much wider. D Soto (2009)[299] provides some useful information, and the Program Publications of Oregon State University's AquaFish Innovation Lab describe on-the-ground experiences with species involved in freshwater aquaculture, mariculture and IMTA in the developing world[300].

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2 AVAILABILITY AND UTILISATION OF REST RAW MATERIALS IN DENMARK

2.1 Scope and methodology

2.1.1 Study scope

This case study aims to identify the occurrence, availability and utilisation of rest raw materials (RRM) derived from fisheries and aquaculture products in Denmark. RRM is a literal translation of the Norwegian term "restråstoff" and comprises all the potentially useful material that is removed from a live/whole seafood resource, in the process of preparing a "main product" for food use.

The case study serves as a methodological pilot case in terms of assessing the availability of relevant data, level of details at hand, and their suitability as input for a data-driven methodology to get a structural overview of the occurrence and availability of rest raw material in Denmark. The case study would also be a pilot in order to assess the feasibility of information availability on utilisation patterns.

1) Is it possible to calculate the volume of available RRM in Denmark?
2) Is all, or only parts of the available RRM utilised?
3) Can an estimated utilised volume of RRM be split into the various processing types or major product categories or uses?

2.1.2 Methodology

2.1.2.1 Apparent available RRM

The total net volume of first-sale, aquaculture production and trade ("net quantity") measured in product weight can be interpreted as the sum of volume of i) Fisheries and aquaculture products (FAP) for consumption in Denmark and ii) available volume of RRM for utilisation in Denmark.

Net quantity is defined by the following equation:

$$\boldsymbol{Net\ quantity} = First\ sale\ + Aquaculture\ production + Net\ import - Net\ export.$$

First-sale data from Denmark includes first sale from both Danish and foreign fishing vessels. The foreign landings are registered as imports, so to avoid double counting, Net import is defined as

$$\boldsymbol{Net\ import} = Import - Foreign\ direct\ landings.$$

Furthermore, there are significant foreign landings by Danish vessels which are reported as exports. Foreign landings by Danish vessels are not producing or in the position for providing any RRM in Denmark. Again, to avoid double counting, Net export is defined as

$$\boldsymbol{Net\ export} = Export - Danish\ foreign\ landings.$$

For the calculations, the following sources have been used:

Table 2.1: Data and sources used for Net quantity calcuations

Data	Source
First sale	EUMOFA disaggregated data: First sale - (EU)
Aquaculture production	EUROSTAT (fish_aq2a)
Import/Export	EUMOFA/EUROSTAT monthly trade data at CN-8 product level
Foreign direct landings/ Danish foreign landings	Fiskeristyrelsen Danmark

As an example, the table below presents the calculation of net quantity for the main commercial species (MCS) mackerel and trout. The trade calculations are done on CN-8 product codes, but the results are aggregated to "trade" in the examples.

Table 2.2: Examples of net quantity calculations (tonnes)

MCS/data	First-sale	Aquaculture	Import	Export	Net Quantity
Mackerel					
First-sale in Denmark	26 029				26 029
Foreign direct landings			-19 473		-19 473
Danish foreign landings				-20 405	20 405
Trade			32 396	49 169	-16 773
Total Mackerel	*26 029*	*0*	*12 922*	*28 764*	*10 187*
Trout					
First-sale in Denmark	4				4
Aquaculture		28 280			28 280
Trade			2 684	23 398	-20 714
Total Trout	*4*	*28 280*	*2 684*	*23 398*	*7 570*

Source: Calculations by EUMFOA

Based on these examples, there is a net quantity of roughly 10 000 tonnes of mackerel and 7500 tonnes of trout. Summarising all relevant MCS results in the estimated total net quantity. By subtracting estimates on FAP for human consumption, the residual is interpreted as the available RRM in Denmark.

2.1.2.2 RRM occurred, landed and assumedly discarded in Danish fisheries

Calculations of the volumes of RRM occurred, landed and assumedly discarded uses EUMOFA disaggregated first-sale data and conversion factors (CF). A CF is a ratio between the weight of the product and the weight of the whole fish.

The basis for CF used in this study is EU Regulation No. 404/2011, Annex III. The CF are defined by three variables:

i) species (Alpha-3 FAO species codes)
ii) preservation (e.g. alive, fresh, frozen etc.)
iii) presentation (e.g. whole, gutted, gutted and headed, filleted, etc.).

The list of CF from EC Regulation No. 404/2011 is not complete and missing conversion factors have been added based on assumptions and the knowledge of EUMOFA experts.

The total volume of RRM assumedly discarded at sea is the difference between first-sale volumes in product weight (including by-products) and whole fish equivalents (WFE).

$$RRM_{discarded} = First\ sale_{WFE} - First\ sale_{product\ weight}$$

where

$$First\ sale_{WFE} = First\ sale_{product\ weight} * CF$$

However, by using the combination of CF and presentations per species (fillets, gutted and headed and gutted), it is possible to calculate the share of head, offal and trimmings[1] of the whole fish. This enables a detailed calculation of occurred RRM by the different RRM fractions. The table and calculations below show the CF for these three presentations of fresh cod.

Table 2.3: Conversion factors for fresh cod by presentation

Presentation	CF
Gutted	1.17
Gutted and headed	1.7
Fillet	2.6

Source. EC Regulation No. 404/2011, Annex III

Offal accounts for about 15% of a whole cod

$$1 - \frac{1}{1.17} = 0.145.$$

By the same calculations, offal and head accounts for about 41%

$$1 - \frac{1}{1.7} = 0.412,$$

while the head, offal and trimmings accounts for about 62%

$$1 - \frac{1}{2.6} = 0.615.$$

Hence, the head is about 27% of the whole fish $(0.412 - 0.45 = 0.266)$ and trimmings about 20% $(0.615 - 0.412 = 0.204)$.

Table 2.4: Fractions of cod

Fractions	%-share
Fillets	38 %
Head	27 %
Trimmings	20 %
Offal	15 %
Whole fish	100 %

Source: Calculations by EUMFOA based on CF from EC Regulation No. 404/2011, Annex III

2.2 Introduction

FAO have estimated that in 2015, fish[2] accounted for about 7% of all proteins and 17% of animal proteins consumed by the global population. Furthermore, for about 3,2 billion people, fish provided almost 20% of average per capita intake of animal protein[3]. However, it is estimated that up to 65% of all fish biomass is wasted throughout the value chain as a result of poor management of seafood resources[4]. Waste occurs as discards at sea, through primary and secondary processing of FAP for human consumption, spoilage during transportation and at the household consumption level[5]. Furthermore, it is estimated that 30%-70% of all fish that reaches a processor becomes by-product. When food is wasted, all the energy, resources, and money that went into producing, processing, packaging, and transporting it are wasted. The further down the supply chain the food gets before it is thrown out, the more resources are wasted to get it to that stage. If measures are taken to reduce food waste by improving storage and transport systems, generating public awareness, and changing consumer behavior, this solution could lead to substantial reductions in waste and carbon emissions

Rest raw materials (RRM) is a literal translation of the Norwegian term “restråstoff” and comprises all the potentially useful material that is removed in order to prepare biomass for food use. Traditional processing of finfish, such as Atlantic cod, produces only the fillets for human consumption. In the past, everything else, the RRM, was either used for animal feed or simply wasted. Increasingly, efforts are being made to utilise RRM and to retrieve as much value as possible by processing RRM for human consumption[6].

RRM occurs in the first parts of the supply chain for both fisheries and aquaculture, during production of FAP for human consumption. For fisheries, RRM occurs onboard the fishing vessels (primary processing), in port or at first-sale auctions, and in processing facilities (secondary processing). For aquaculture, RRM occurs on the fish farms, during transport, at slaughterhouses (primary processing) and in processing facilities (secondary processing).

Since 2012, an annual study financed by the Norwegian seafood research fund, has developed a methodology of assessing the total availability (potential amount) of RRM as well as the utilisation rate and type of uses in Norway[7]. Based on these projects, this study tries to adapt and use a similar methodology on the fisheries and aquaculture industry in Denmark.

2.3 Danish seafood production and trade

2.3.1 Fisheries – first-sale

In 2019, the total landing volumes in Denmark amounted to around 928 000 tonnes (product weight), of which landings for human consumption accounted for almost 251 000 tonnes (27%).

Concerning first-sale volumes for human consumption, the largest commodity group[8] was small pelagics with 56% of the total volume, followed by groundfish with 14%, bivalves and other molluscs and aquatic invertebrates with 14% and flatfish with 10%.

In terms of main commercial species[9], herring is by far the largest with 46% (114 500 tonnes) of the total first-sale volume in 2019. Herring is followed by mackerel and mussel Mytilus with 10% each, saithe with 6%, European plaice with 6% and cod with 5%.

Table 2.5: First-sale volume for human consumption in Denmark 2019 by commodity group (tonnes product weight)

Commodity group	Tonnes	%-share
Small pelagics	140 876	56 %
Groundfish	35 737	14 %
Bivalves and other molluscs and aquatic invertebrates	36 098	14 %
Flatfish	24 008	10 %
Crustaceans	10 037	4.0 %
Other marine fish	3 191	1.3 %
Other	564	0.2 %
Total	**250 510**	**100 %**

Source: EUMOFA

Concerning landings for industrial use, the largest species in terms of volume was sprat with 38% of the total followed by blue whiting (24%) and sandeel (18%).

Table 2.6: Landings for industrial use in Denmark 2019 by species (tonnes product weight)

Species	Tonnes	%-share
Sprat	255 100	38 %
Blue Whiting	165 300	24 %
Sandeel	124 100	18 %
Norway Pout	47 800	7 %
Other	85 526	13 %
Total	**677 826**	**100 %**

Source: Fiskeristyrelsen

2.3.2 Aquaculture

According to Eurostat, Denmark produced 32 000 tonnes (live weight) of aquaculture products in 2018 (the latest year available). The production consisted of rainbow trout (28 000 tonnes), blue mussel (3 000 tonnes) and salmon (1 000 tonnes). Denmark also have production of other species (e.g. eel, pike-perch, Arctic char and brook trout), but due to few producers and low production volumes they are not reported to Eurostat.

The salmon is produced in recirculation aquaculture systems (RAS). Around 75% of the rainbow trout is farmed in freshwater and over the past 15 years, about 50% of this production have introduced some form of RAS, recirculating the water and filtering out biological particles, e.g. faeces and uneaten feed.

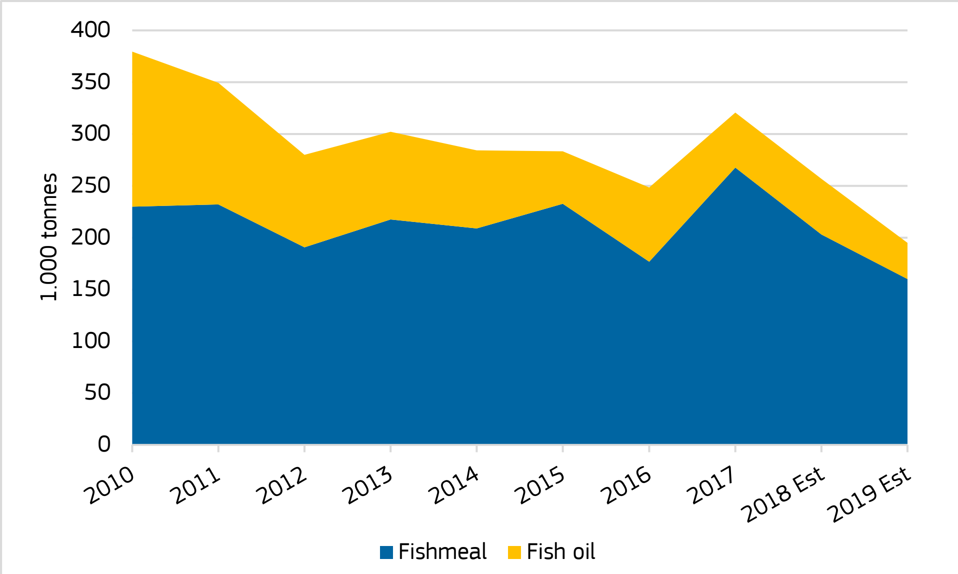
2.3.3 Processing

According to Eurostat data for 2018 (the latest year available), the Danish processing industry produced almost 90 000 tonnes (product weight) of FAP for human consumption. Fillets or fillet-like products, either fresh, frozen, smoked, dried, salted or in brine constitutes around 85% of this production, while whole fish (frozen, salted, dried or in brine) accounts for 8%. Frozen fish meat (whether minced or not) constitutes 4%, and livers, roes and caviar substitutes make up the remaining 3%.

Furthermore, Denmark is the EU's largest producer of fishmeal and fish oil, accounting for around 50% of the total EU production. Globally, Denmark ranked as the seventh largest fishmeal producer and the eight largest fish oil producer in 2018. Denmark is also a large importer and exporter of fishmeal and fish oil. In 2019, nearly 50% of the export of fishmeal went to EU-28 countries, of which more than 40% to Greece and the United Kingdom. Regarding fish oil, 20% was exported to EU-28 countries, of which 75% to the United Kingdom and Greece. Of the export to non-EU countries, Norway accounted for more than 50% of the fishmeal export and almost 100% of the fish oil export.

Due to significant variations in the quotas for the different species for industrial use, the availability in the fisheries vary from year to year and the fishmeal and fish oil production vary in line with available raw material.

Figure 2.1: Danish fishmeal and fish oil production 2010-2019



Source: FAO/IFFO, The Marine Ingredients Organisation

2.3.4 Trade

Denmark is a large seafood importer and exporter. With an import volume of almost 1.37 million tonnes, Denmark ranked 2nd in the EU in 2019. The Danish export volume amounted to almost 1.14 million tonnes, ranking 3rd in the EU in 2019. The Danish trade of FAP for human consumption accounted for 58% of imports and 68% of exports.

Table 2.7: Danish trade in 2019 of FAP for human consumption and non-food use (tonnes product weight)

MCS	Import	Export
FAP for human consumption	796 839	777 211
Fishmeal	86 300	189 505
Fish oil	116 123	146 474
Other non-food use	367 524	21 849
Grand Total	**1 366 786**	**1 135 039**

Source: EUMOFA

The MCS "other non-food use" mainly consists of three products: "Crustaceans, molluscs or other aquatic invertebrates, not for human consumption" (71%), "Fish waste, not for human consumption" (26%) and "Seaweeds and other algae" (2%). In 2019, Denmark reported a net import of 34 000 tonnes of these three products.

In terms of trade of FAP for human consumption, the four major commodity groups groundfish, salmonids, small pelagics and crustaceans accounted for 85%.

Table 2.8: Danish imports of FAP for human consumption in 2019 by commodity groups (tonnes product weight)

Commodity group	Tonnes	%-share
Groundfish	220 164	28 %
Salmonids	203 945	26 %
Small pelagics	165 579	21 %
Crustaceans	90 775	11 %
Flatfish	50 153	6 %
Other marine fish	30 444	4 %
Miscellaneous aquatic products	14 272	2 %
Tuna and tuna-like species	9 491	1 %
Freshwater fish	5 292	1 %
Bivalves and other molluscs and aquatic invertebrates	4 594	1 %
Cephalopods	2 131	0 %
Total	**796 839**	**100 %**

Source: EUMOFA

In terms of MCS, salmon was the main imported species with 25% of the total volume followed by herring (12%), cod (10%), blue whiting (7%) and coldwater shrimp (6%). Together, these five MCS accounted for 61% of the Danish imports of FAP for human consumption in 2019, while the top 10 MCS accounted for 83% of total imports.

In 2019, Denmark exported close to 780 000 tonnes of FAP for human consumption. The four major commodity groups salmonids, small pelagics, groundfish and crustaceans accounted for 80%.

Table 2.9: Danish exports of FAP for human consumption in 2019 by commodity groups (tonnes product weight)

Commodity group	Tonnes	%-share
Salmonids	197 184	25 %
Small pelagics	177 426	23 %
Groundfish	148 008	19 %
Crustaceans	100 885	13 %
Flatfish	56 072	7 %
Other marine fish	33 111	4 %
Bivalves and other molluscs and aquatic invertebrates	26 720	3 %
Miscellaneous aquatic products	20 498	3 %
Freshwater fish	13 159	2 %
Cephalopods	2 118	0 %
Tuna and tuna-like species	2 030	0 %
Total	**777 211**	**100 %**

Source: EUMOFA

In terms of species, salmon is the main exported species with 22% of the total volume followed by herring (14%), cod (11%), coldwater shrimp (7%) and mackerel (6%). These five MCS accounted for 60% of the Danish exports of FAP for human consumption in 2019, while the top 10 MCS accounted for 80%.

In terms of presentation, most FAP for human consumption are traded whole or gutted, followed by fillets. In 2019, there was a higher share of whole/gutted was higher for imports than exports, while the share of fillets was higher for exports than imports.

Table 2.10: Danish trade of FAP for human consumption in 2019 by presentation (tonnes product weight)

	Import		Export	
Presentation	**tonnes**	**%-share**	**tonnes**	**%-share**
Whole/Gutted	632 481	79 %	531 446	68 %
Fillet	75 451	9 %	120 378	15 %
Unspecified	48 782	6 %	58 692	8 %
Other cuts	33 872	4 %	58 386	8 %
By-products	6 253	1 %	8 310	1 %
Total	**796 839**	**100 %**	**777 211**	**100 %**

Source: EUMOFA

2.4 Occurrence and availability of rest raw materials

In this chapter, the availability of rest raw materials in Denmark is estimated. RRM occurs in all parts of the supply chain. For fisheries, RRM occurs aboard fishing vessels (primary processing), in port or at first-sale auctions and in processing facilities (secondary processing). For aquaculture, RRM occurs at the fish farms, slaughterhouses (primary processing) and in processing facilities (secondary processing).

RRM can also occur at the consumer stage, either in the HORECA sector or in private households, when FAP are sold either whole, with head, skin, bones or shell. The yearly volume of RRM at consumer stage is roughly estimated between 40 000 and 60 000 tonnes. However, due to lack of proper conservation and collection logistics of sufficient scale for further use, estimates of RRM at this supply chain stage are excluded in this report.

Chapter 2.4.1 estimates the overall apparent availability of rest raw materials from the FAP for human consumption supply chain, combining volumes of first sale, aquaculture production, trade, processing and apparent consumption. Chapter 2.4.3 estimates the RRM occurring in aquaculture production which does not enter the markets for human consumption (fish manure and dead fish). Chapter 2.4.2 estimates RRM occurred in the fisheries, but which are assumedly discarded at sea and hence currently not available for utilisation.

Chapter 2.4.4 summarises the volumes of available RRM and by-products, also taking into account the net trade of FAP for non-food use (ref. chapter 2.3.4, Table 2.7).

2.4.1 Apparent availability of rest raw materials

Following the methodology from chapter 2.1.2.1 and summarising all MCS for human consumption[10], the net quantity of RRM in Denmark in 2019 amounts to 292 000 tonnes. By subtracting apparent consumption, the residual is interpreted as the available amount of RRM in Denmark.

In 2018 (the most recent available figures), apparent consumption per capita in Denmark was 27 kg WFE. With a population of 5.8 million, the total apparent consumption is 157 000 tonnes WFE.

To estimate the apparent consumption in terms of product weight, two different adjustments have been made using the calculated net quantities: i) net quantity of fillets and ii) net quantity of the major prepared/preserved MCS.

i) Fillets

In 2019, Denmark imported (net imports) 75 000 tonnes of fillets and exported (net exports) 120 000 tonnes. In addition, the Danish processing industry produced around 75 000 of fillets and "fillet-like" products in 2018 (latest available data)[11]. Consequently, the apparent consumption of fillets in Denmark was roughly 30 000 tonnes (product weight) in 2019. With an average CF for fillets of 2, the apparent consumption in terms of WFE was roughly 60 000 tonnes.

ii) Prepared/preserved products

In 2019, the apparent consumption of prepared/preserved products (primarily canned products with or without oil or brine) of miscellaneous shrimp, tuna and small pelagics amounted to roughly 17 000 tonnes. Converted to WFE, this represents almost 25 000 tonnes.

Subtracting the 60 000 tonnes (WFE) of fillets from the total apparent consumption, a broad indirect assumption is that about 95 000 tonnes of fish is entering the consumption stage as whole. However, by also accounting for 25 000 tonnes (WFE) of prepared/preserved products, the apparent consumption of whole fish amounts to about 70 000 tonnes.

On this basis, estimates of the apparent consumption in terms of product weight range between 117 000 and 125 000 tonnes. Consequently, this corresponds with an apparent volume of available RRM of between 167 000 and 175 000 tonnes in 2019.

Table 2.11: Summary of calculations of apparent available RRM (tonnes product weight)

	Alternative 1	Alternative 2
Apparent consumption and available RRM (Net quantity)	**292 000**	**292 000**
Apparent consumption fillets	30 000	30 000
Apparent consumption prepared/preserved		17 000
Apparent consumption whole	95 000	70 000
Total apparent consumption	**125 000**	**117 000**
Apparent available RRM	**167 000**	**175 000**

2.4.2 Rest raw materials assumedly discarded

In terms of presentation, 74% of the first-sale volumes are sold whole, another 25% gutted, while other presentation forms represent 1%. Of the volumes sold gutted or of other presentation forms, groundfish is the largest commodity group with 59% of the first-sale volume, followed by flatfish (33%) and other marine fish (5%).

Table 2.12: First-sale volume not sold whole in Denmark in 2019 by commodity group (tonnes product weight)

Commodity group	Tonnes	%-share
Groundfish	35 707	59 %
Flatfish	19 925	33 %
Other marine fish	2 900	5 %
Crustaceans	435	1 %
Other	1 075	2 %
Grand Total	**60 042**	**100 %**

Source: EUMOFA

It is reasonable to assume that the by-products derived from primary processing of the fish aboard fishing vessels (primarily gutting) is discarded at sea.

Using the calculated conversion factors (methodology description in chapter 2.1.2.2), the estimated total volume of occurred RRM amounts to almost 118 000 tonnes. However, more than 109 000 tonnes of these rest raw materials are landed and sold, implying that about 8 500 tonnes of RRM are assumedly discarded at sea.

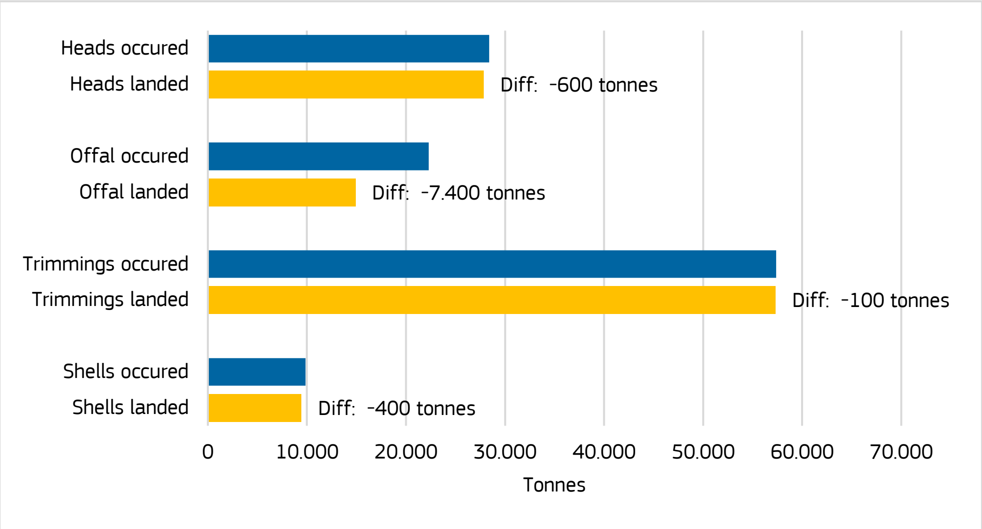
Table 2.13: Estimated volume of RRM occurred, sold and assumedly discarded at sea in 2019 (tonnes)

Commodity group	RRM occurred	RRM sold	RRM assumedly discarded
Small pelagics	64 000	63 800	200
Groundfish	25 500	19 400	6 100
Flatfish	13 800	12 500	1 300
Bivalves and other molluscs and aquatic invertebrates	9 100	9 100	0
Crustaceans	5 200	4 400	800
Other	200	100	100
Total	**117 800**	**109 300**	**8 500**

Source: Estimates calculated by EUMOFA

Most of the RRM assumedly discarded at sea consists of offal (guts) followed by heads and shells (crabs for which only claws are sold at first-sale stage). There is a very limited amount of first-sale of fillets, leading to a low estimated volume of trimmings assumedly discarded at sea.

Figure 2.2: RRM occurred and landed in 2019 by RRM fractions (tonnes)



Source: Estimates calculated by EUMOFA

In other words, most of the RRM from fisheries (93%) is landed in Denmark and potentially available for further utilisation.

2.4.3 By-products from aquaculture production

Aquaculture production results in two primary by-products that never enters the supply chain for human consumption: self-dead fish and fish manure[12].

In 2018 (the latest available data) there were 3 340 tonnes of self-dead fish from Danish aquaculture[13].

Over the past 15 years, about 50% of the Danish freshwater aquaculture production has been transformed from typical pond aquaculture to RAS with different technologies and levels of water filtering and recirculation.

With the transition to RAS technology where feed residue and fish faeces are filtered out of the water, the volume of fish manure has increased substantially. The Danish aquaculture producer organisation (Dansk Akvakultur) have estimated that Danish aquaculture produces 23 000 tonnes of fish manure, consisting of about 2 300 tonnes (10%) dry matter.

2.4.4 Summary of occurred and available RRM

Table 2.14: Occurred and available RRM and by-products

	Available RRM from human consumption supply chain		Net trade fish waste	Fish manure and deadfish*
	Low estimate	High estimate		
Pelagics	60 000	80 000	345 000	17 740
Salmonids	30 000	45 000		
Whitefish	30 000	45 000		
Shellfish	1 000	5 000		
Total	**167 000**	**175 000**	**345 000**	**17 740**

** Fish manure from RAS and self-dead fish utilised in biogas production (ref. chapter 2.5.3).*

2.5 Utilisation of rest raw materials

According to estimates from 2015, around 95% of FAP for non-food use are utilised in animal feed or pet food production, either directly or after being processed to fishmeal and fish oil. The remaining 5% is used for indirect human consumption as food additives or supplements (e.g. oil in Omega-3 capsules).

According to industry stakeholders, RRM achieves highest prices when utilised for indirect human consumption products, followed by pet food, animal feed and fishmeal and fish oil production. RRM not suitable for any of the above utilisations are used in biogas production which pays “little to nothing”[14].

Also, in the high-value category are RRM (or fractions or derivates of such) that are used for medical or health-enhancing purposes, cosmetics or certain food additives. These utilisations are however represented by marginal volumes.

2.5.1 Fishmeal and fish oil

Due to yearly variations in quotas and industrial landings, 10-20% of the fishmeal and fish oil production in Denmark is based on raw material from trimmings, offal and other marine by-products. Based on landings for industrial use in 2019, this would correspond to a utilisation of between 75 000 and 170 000 tonnes of trimmings, offal or other by-products in the Danish fishmeal and fish oil production.

According to estimates from 2015, between 80 000-100 000 tonnes of RRM are utilised in the Danish fishmeal and fish oil production.

2.5.2 Animal feed

Denmark is the world's largest producer of mink skins with approximately 1 500 farmers who produce around 19 million mink skins yearly.[15] Fish constitute around 40 % of the mink feed, so the Danish mink industry is a large consumer of industrial fish.

The mink feed production in Denmark is organised under "Dansk Pelsdyr Foder a.m.b.a", a cooperative of the mink farmers. They have 10 production facilities in Denmark, including one on the island of Bornholm. As the quality of the fish is important to produce high quality feed, mink feed producers are willing to pay a slightly higher price compared to the fishmeal and fish oil industry.[16]

According to industry stakeholders, RRM from the whitefish processing industry are mainly utilised for mink feed production.

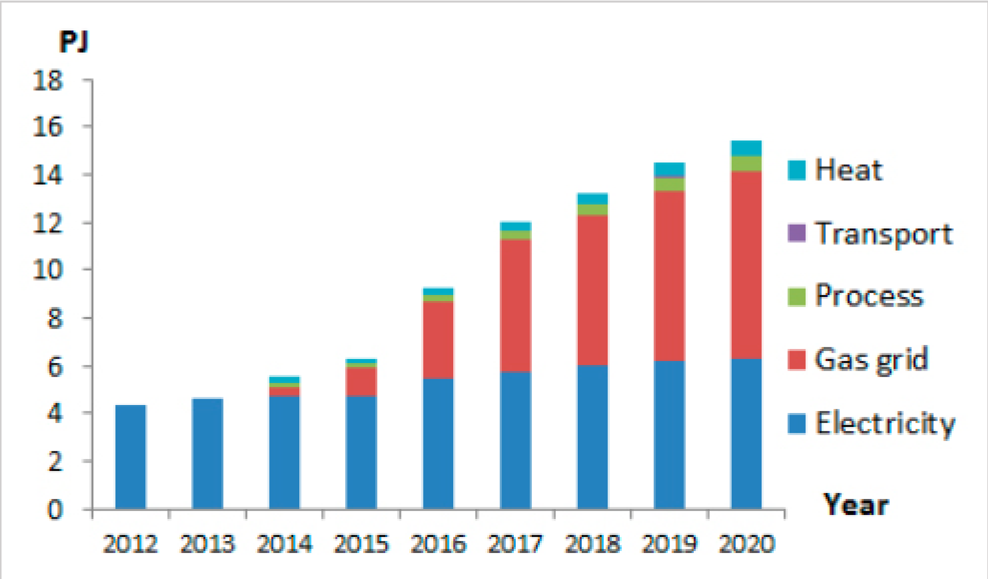
According to estimates from 2013, between 50 000-60 000 of RRM are utilised in feed production for the Danish fur industry.

2.5.3 Biogas

Biogas production is a combined energy production and waste treatment technology. It is produced by anaerobic digestion of organic material and suitable feedstocks are manure, sewage sludge and other organic waste types from both industries and households. A by-product from biogas production is high quality natural fertiliser[17].

Production of biogas in Denmark is rapidly increasing. The total production of around 4 petajoules (PJ) in 2012 is expected to triple and reach 16 PJ in 2020. The production is spread around the country and the majority of biogas plants are manure-based agricultural plants located near farms (see Annex I for a map of biogas plants in Denmark). They are often privately owned by a cooperative of 10-15 farmers.

Figure 2.3: Historical and expected biogas production and its use in Denmark 2012-2020



Source: Danish Energy Agency

Excrement of fish does not fall under the definition of "manure" in the European Union's animal by-product regulation (Regulation No. 1069/2009) and cannot be utilised as a natural fertiliser. Currently, the most viable utilisation of fish manure is biogas. Fish farmers have no income on the fish manure and sometimes even cover the transportation costs of the collection.

According to the latest available data (the 1-year period from 1st August 2017 to 31st July 2018), Danish biogas plants utilised 14 400 tonnes of fish manure from Danish freshwater aquaculture in their production[18].

According to The Danish aquaculture producer organisation (Dansk Akvakultur), biogas plants in Denmark also utilise all the self-dead fish from aquaculture (3 340 tonnes in 2018). Often, fish farmers have agreements with the same biogas plant for collection of both fish manure and self-dead fish.

According to the Danish Energy Agency, marine RRM is well suited for biogas production. However, with the current reporting scheme for biogas plants and the use of raw material in their production, they don't have any data of the volumes of RRM utilised for this purpose.

However, a rough estimate, considering the estimated ranges for both available RRM, utilisation in fishmeal and fish oil production, animal feed and products for human consumption, the utilisation of RRM in biogas production ranges between 20 000-60 000 tonnes.

2.5.4 Summary of utilisation of RRM and other by-products

Table 2.15: Utilisation of RRM and other by-products by product groups

Utilisation	Available RRM from human consumption supply chain		Net trade fish waste		Fish manure and deadfish
	Low estimate	High estimate	Low estimate	High estimate	
Fishmeal and fish oil	80 000	100 000	50 000	70 000	
Animal feed (incl. pet feed)	50 000	60 000	30 000	40 000	
Biogas	20 000	60 000	230 000	290 000	17 740
Indirect human consumption	5 000	10 000			

2.6 Conclusions

Denmark is a big seafood nation in the EU in terms of both fishery, aquaculture, fish meal/oil production, and trade. Based on the methodology for this study, between 167 000 and 175 000 tonnes of RRM occurred from the FAP for human consumption supply chain in 2019.

In addition, Danish fishers assumedly discarded about 8 500 tonnes of RRM at sea, which has a potential of entering the economy, when brought ashore in future. From aquaculture production, almost 18 000 tonnes of by-products (fish manure and self-dead fish) were utilised in the Danish biogas plants. Furthermore, Denmark had a net-import of 345 000 tonnes of other marine by-products. In other words, the total available volume of RRM in Denmark in 2019 was between 530 000 and 540 000 tonnes.

The utilisation of RRM and by-products is more difficult to estimate but several industry stakeholders claim that close to 100% of the materials are utilised. RRM and by-products achieve highest prices when utilised for indirect human consumption products (food additives or supplements (e.g. oil in Omega-3 capsules)) followed by pet food, animal feed and fishmeal and fish oil production. RRM not suitable for any of the above utilisations are used in biogas production which pays "little to nothing".

This case study was a methodological pilot case in terms of assessing the availability of relevant data, level of details at hand, and their suitability as input for a data-driven methodology to get a structural overview of the occurrence and availability of rest raw material as well as its utilisation patterns in Denmark.

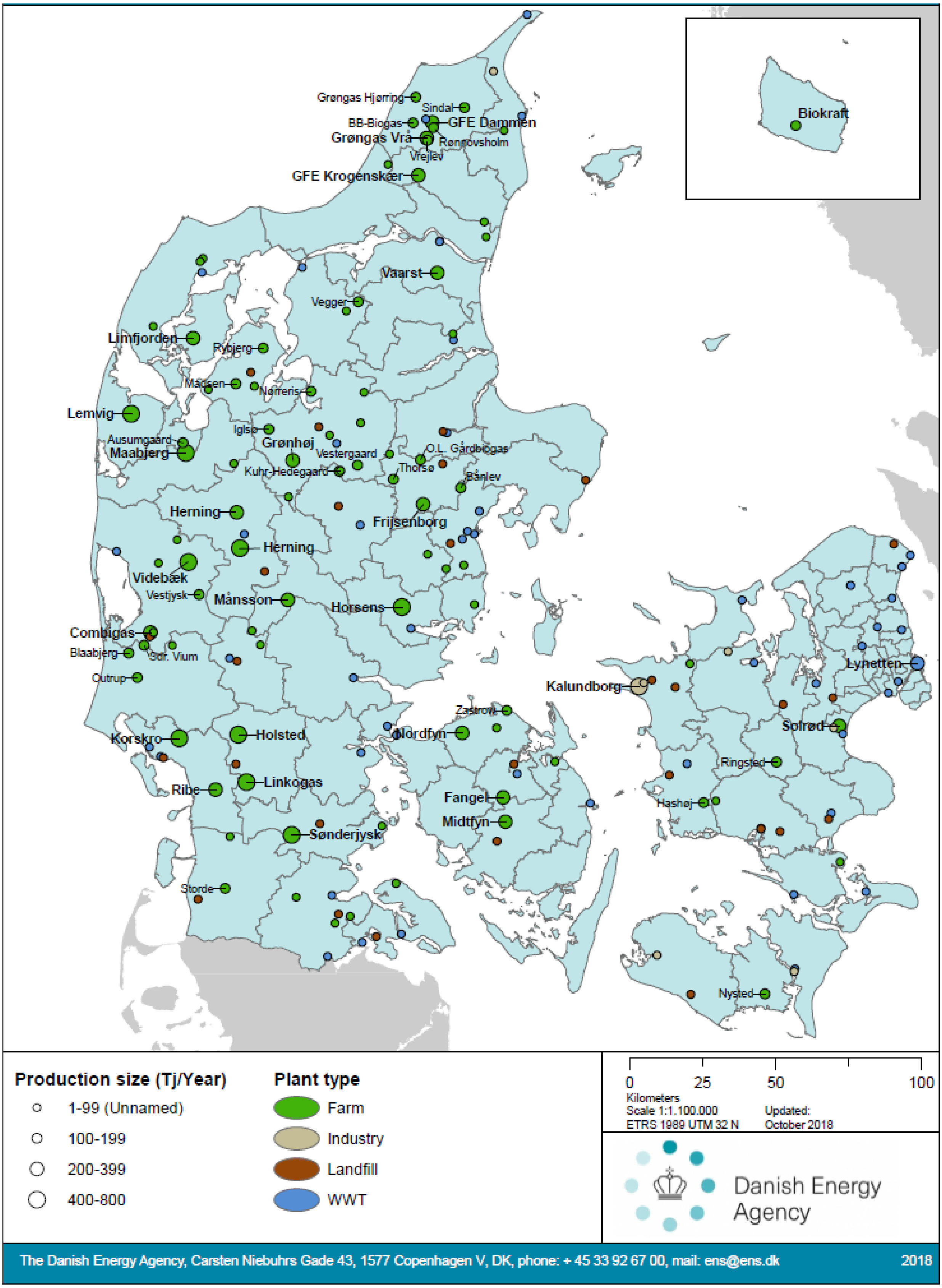
In general, the availability of public data is good in Denmark. However, for a study like this, detailed data needs to be available throughout the supply chain. This case study has revealed several missing data points, especially concerning detailed consumption data, volumes of RRM and by-products from the Danish processing industry and traceability of utilisation of these raw materials.

Estimating these missing datapoints is even more challenging considering Denmark is a central hub for seafood trade and processing of FAP for human consumption, as well as a large importer/exporter and consumer of FAP for non-food use (including RRM, by-products, fishmeal and fish oil).

This case study has revealed that a descriptive study of the occurrence, availability and utilisation of RRM is not possible through only a data-driven methodology. Even for Denmark, where data availability is relatively good, there is a need for comprehensive qualitative input and private data from industry stakeholders.

Consequently, and based on this case study, the feasibility of upscaling or repetitive use of this methodology on other Member States is uncertain.

Annex 1 – Map of Biogas Plants in Denmark



[1] In this report, trimmings include all parts of the fish other than the fillets, head and offal.

[2] Here, the term fish includes shellfish, crustaceans and cephalopods.

[3] The state of world fisheries and aquaculture, FAO 2018, ISBN 978-92-5-130562-1.

[4] Ghosh PR *et al*. (2016) *Progress towards sustainable utilisation and management of food wastes in the global economy*, in *International Journal of Food science,* 2016, e3563478, Doi: 10.1155/2016/3563478.

[5] EUMOFA (2018) *Blue Bioeconomy: Situation report and perspectives*, ISBN 978-92-79-96713-9

[6] Ibid.

[7] Project 900855 (2012-2014) https://www.fhf.no/prosjekter/prosjektbasen/900855/, project 901197 (2015-2016) https://www.fhf.no/prosjekter/prosjektbasen/901197/, and project 901336 (2017-2019) https://www.fhf.no/prosjekter/prosjektbasen/901336/.

[8] In EUMOFA, data are harmonised into 108 main commercial species (MCS) and 12 commodity groups (CG): https://eumofa.eu/harmonisation

[9] In EUMOFA databases, data are harmonised into 108 main commercial species (MCS) and 12 commodity groups (CG): https://eumofa.eu/harmonisation

[10] Three MCS (Fishmeal, Fish oil and Other non-food use) are excluded from these calculations.

[11] EUROSTAT ProdCom

[12] Fish manure is often also referred to as aquaculture sludge.

[13] Danmarks Statistik

[14] The Danish Seafood Association

[15] https://agricultureandfood.dk/danish-agriculture-and-food/mink-and-fur

[16] DiscardLess – D6.5, chapter 3.4

[17] Danish Energy Agency, https://ens.dk/en/our-responsibilities/bioenergy/biogas-denmark

[18] Danish Energy Agency, “Biomasseopgørelse 2017/18”

3 CELLULAR MARICULTURE AND PLANT CELL TECHNOLOGY

*Chapter authored by Pierre Erwes and Nicolas Erwes

3.1 Introduction

By 2050 the world population will reach 9.7 billion people. To date there are already 7.7 billion people on earth, meaning that the population will increase by 2 billion within the next 30 years[1]. To keep up with increasing demand, it is estimated that agricultural production must increase by 70%[2], although 33% of the world's arable land has highly degraded over the past 40 years[3].

Additionally, climate change impacts including draughts, cyclones, and extreme weather conditions are dramatically reducing the cycles and the spaces dedicated to land-based agriculture. At the same time, the large amount of resources consumed by livestock agriculture is reflective of its large environmental footprint. Approximately 25% of the earth's surface is taken up for livestock farming, which is approximately 70% of all land used for agriculture. More importantly, the production of meat, eggs and dairy constitute about 30% of all freshwater usage.

The most alarming fact about livestock agriculture, however, is that the greenhouse gas emissions generated by livestock farming alone are 18% of all emissions[4], a share higher than the emissions from all modes of transport (12%). Considering the effort that has been done in the automotive industry to reduce carbon emissions, it is surprising how livestock farming contributes such a significant proportion of all greenhouse gas emission with little done to reduce it.

Despite the fact that aquaculture is not as bad as conventional agriculture, there are several concerns about sustainability and best practices. Low trophic species and / or multi trophic aquaculture is one appropriate answer to this issue but it is not very well developed as a commercial model.

In spite of the sustainability, health, and animal welfare issues associated with the industrial production of animal products, global demand for animal protein is still rising. Despite limited consumer awareness and acceptance to date, plant-based alternatives to animal proteins are becoming more available with higher quality, but for many applications they are not currently able to fully replace the sensory and functional properties of animal proteins.

Substantial progress has been made towards exhaustive plant protein characterisation to identify plant-based alternatives that replicate animal proteins properties and cellular mariculture and agriculture seek to solve this problem directly by producing genuine animal proteins through fermentation or more sophisticated industrial and biotechnological processes.

Cellular mariculture focuses on the production of aquaculture products from cell cultures using a combination of biotechnology, tissue engineering, molecular biology, and synthetic biology to create and design new methods of producing proteins, fats, and tissues that would otherwise come from traditional agriculture.

This chapter on cellular mariculture will look at the different views on the matter, on its market potential, trends and carbon footprint evaluation. Furthermore, it will also expand on the concepts of cell plant factory (plant or seaweed) and of animal plant factory, by looking into legal and regulatory issues, existing production systems, leading technologies, markets, key players, consumer acceptance, blocking factors, EU role.

3.2 Plant cell technology

3.2.1 Definition

This first part aims to describe new technologies that can transform plant science to address the challenges of new biology for human nutrition, environment and commercial uses.

100 years ago, fossil oil-based solutions, plastics and modern comforts were not an option. Today, thanks to science and technology, there are much more possibilities, yet it is important to know the difference between natural, synthetic and naturally derived ingredients. This key question can be answered by looking at either:

- the molecular structure of a raw material (when the molecule is present in the natural environment);
- or at its origin, whether it is from plant materials found in nature.

The industry has been mainly using the second approach, and in view of that, the definition of a natural ingredient is of a plant compound that retains its natural structure without any chemical transformation. Natural ingredients include plant, animal, mineral and/or microbial ingredients present in (or produced by) nature. Natural ingredients may also be directly extracted using simple methods or they may be the result of naturally occurring biological processes. In order to retain their structure, natural ingredients are obtained via physical processes, such as distillation, maceration, solvent extraction and squeezing.

As the type of ingredients obtained via simple natural ingredients are limited, chemistry has been used to modify natural ingredients to create entirely new molecular structures, allowing increased performance and new sensorial effects.

Synthetic ingredients are substances derived from petrochemical sources. These ingredients tend to be readily available and low cost; however, their long-term availability and environmental impact also happen to be well-known challenges.

The major three challenges for humankind in the 21st century are food, energy, and the environment, including climate change and sustainability. To produce the necessary significant quantities of natural ingredients, it is not possible to rely only on traditional agricultural technology to provide sufficient raw plant materials. In addition, the following challenges should also be considered;

- Rare plants are not easy to cultivate and their growth might be very slow;
- The development of more plant species will require more time and have a very high failure rate;
- Increasing agricultural production will face an important lack water, scarce lands and expensive labour costs;
- Hydroponics is an interesting option but will need a source of light, and it is not suitable for all plants cultivation;
- Chemical synthesis is becoming a challenge due to severe pollution, and single molecule development which is not adapted to molecular nutrition;
- Genetically modified plants are also vulnerable to the impact of sudden outbreak and will face opposition from civil society.

Plant cell culture (PCC) is a well-established technology platform for the synthesis of natural products (NPs). Large-scale plant cell culture technology platform for Plant cell / tissue materials could become a mainstream solution.

Plant life plays an essential role in all the three sustainability challenges. All of our food and the majority of our energy are produced by photosynthetic plants. Plants are major players in determining our climate, and agricultural expansion is a major factor in habitat deterioration and pollution of waterways by fertiliser application and runoff.

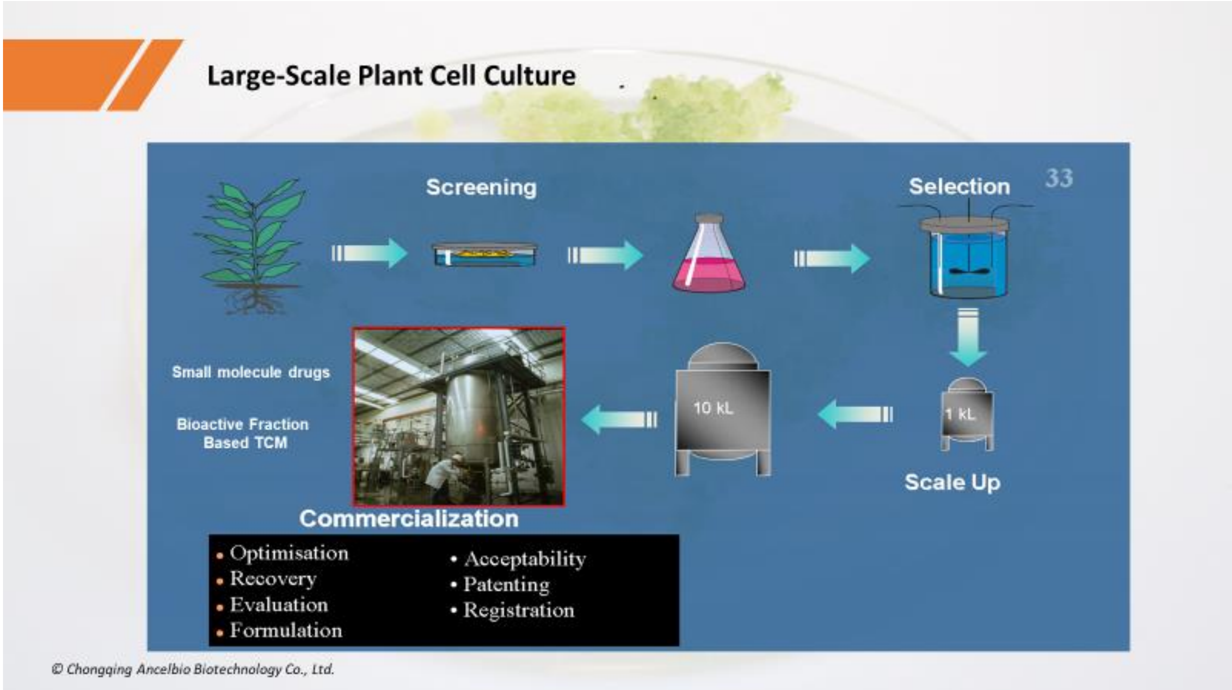
A plant, as an immobile organism, develops a series of defence measures against predators and harmful environments. Using these properties, it is possible to force a plant to synthesise a specific metabolite by mimicking a stress. Only a small amount of the plant is needed to produce large quantities of the molecule of interest.

Plant cell cultures provide an attractive route to obtain highly valuable plant-derived products, such as flavours, fragrances, alkaloids, pigments and pharmaceuticals that are expensive to synthesise chemically and that naturally occur only at low concentrations. Plant cell cultures are a potential source for the production of high-value secondary metabolites.

In the past few years, there has been some significant success for the production of valuable second metabolites. Apart from plant cell culture-mediated metabolite production, there is also the opportunity to identify cell lines that can produce amounts of compounds equal or even higher than those in the plant. In addition, certain compounds that are not present/synthesised in plants can be produced by cell cultures.

Plant cell culture techniques have been used to overcome problems in manufacturing nutraceuticals, cosmetic and pharmaceutical products, with the benefit of higher and better production of active concentrations[5]. This technology involves complex methods that ensure growth of plant cells, tissues or organs in the environment with microbe-free nutrients. It also allows synthesis of biologically active compounds that exist in plants but that are either not usually available in the natural environment or are difficult to obtain by chemical synthesis. The extracts obtained through plant cell technology are currently used for production of both regular consumer or professional products and ingredients. The steps in the extraction process involve selection of best plant material candidate and its sterilisation, callus induction and sub-cultivation on commercially available plant tissue culture medium.

Figure 3.1: Large-scale plant cell culture



The development of powerful new "omics" technologies has provided exciting opportunities for PCC. In this context, the number of patents related to PCC products has risen to a total of 28,000.

Table 3.1: Examples of generation of natural products using Plant Cell Culture

Industry	Products	Species	Manufacturer	Notes
Food	Anthocyanins	*Euphorbio milii*	Nippon Paint Co. Ltd, Osaka Japan	Textile dye
		Aralia cordata	Nippon Paint Co. Ltd, Osaka Japan	Coloring agents
	Arbtin	*Catharanthus roseus*	Mitsui Chemicals Inc., Tokio Japan	Pigments
	Betacyanin	*Beta vulgaris*	Nippon Shinyaku Co., Ltd	Pigments
	Carthamin	*Carthamus trinctorius*	Kibun Foods Inc., Tokio Japan	Pigments
	Geraniol	*Geraminea spp.*	Mitsui chemicals., Inc	Essential Oils
	Gingseng	*Panax gingseng*	Nitto Denko Corporation, Osaka, Japan	Dietary supplements
		Wild gingseng from CMCs	Unhwa Biotech Corp., Jeonbuk, South Korea	Dietary supplements, cosmetic and medical products
	Shikonin	*Lithospemum erythrorhizon*	Mitsui Chemicals., Inc	Red pigments
Pharmaceuticals	Alginates	*Lessonia trabeculata*	Fraunhofer	Anticancer
	Berberines	*Coptis japonica*	Mitsui Chemicals, Inc.	Anticancer
		Thalictrum minus		Antibiotic Anti-inflammatory
	Echinacea polysaccharides	*Echinacea purpurea*	Diversa, Ahrensburg, Germany	Immunostimulant
		Echinacea angustifolia		Anti-inflammatory
	Paclitaxel	*Taxus spp*	Phyton Biotech., Inc Germany	Anticancer World
			Samyang Genex., Seoul, South Korea	Anticancer
	Podophyllotoxin	*Podophyllum spp*	Nippon Oil, Tokio, Japan	Anticancer
	Rosamarinic acid	*Coleus blumei*	ANattermann & Cie. Gmbh, Cologne, Germany	Anti-inflammatory
	Scopolamine	*Duboisia spp*	Sumitomo Chemical Co., Ltd, Tokio, Japan	Anticancer World, also Used in treatment of motion sickness, nausea and intestinal cramping
Cosmetics	Atropine, Gingsenosides, Coumarines, Flavonoids, Alkaloids, Camptothechin, Anabasine, Nicotine	Hairy roots from *Atropa belladonna Carlina acaulis Nicotiana glauca Panax gingseng*	Rootec, Witterswil, Switzerland	A wide range of products for beauty health and nutrition
	About fifteen active ingredients for cosmetic use	Cell suspension cultures and hairy roots cultures, different species	Sederma, Le Perray-en-Yvelines, France	Develop of cosmetic active ingredients
	Active ingredients for cosmetic use	Suspension culture and hairy roots *Malus domestica Solar vitis*	Mibelle, Switzerland	Develop of cosmetic active ingredient
	Human Glucocerebrosidase (GCD) enzyme	Carrot suspension cultures	Protalix BioTherapeutics Karmiel, Israel	ELELYSO Plant cell-expressed form of the glucocerebrosidase enzyme for treatment of Gaucher disease

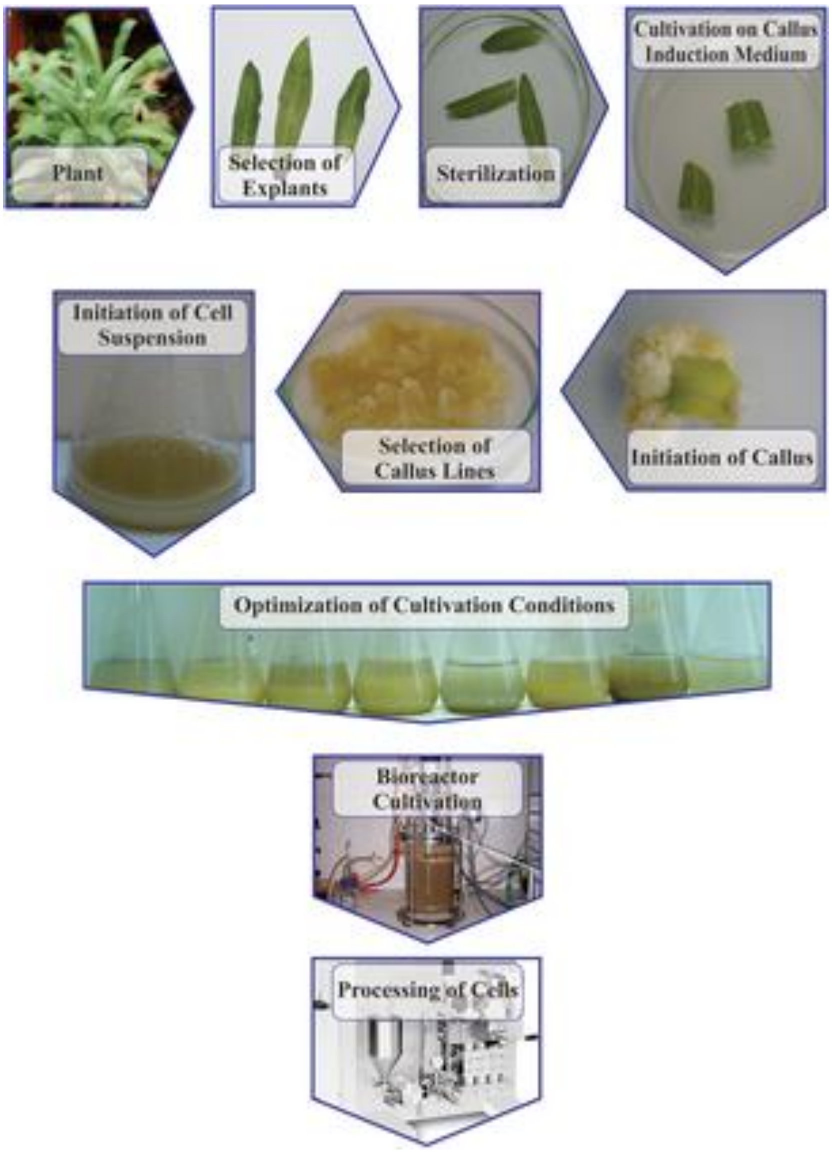
Industry	Products	Species	Manufacturer	Notes
	Vaccine against Newcastle disease virus (NDV)	Tobacco suspension cultures	Dow Agrosciences, LLC, Indianapolis, USA	First tobacco cell-based vaccine approved by the FDA against Newcastle disease virus in poultry
	Sodium Alginates	*Lessonia trabeculata*	Penn State University	Human biomaterials 3D printing
	Human proteins	*Physcomitrella patens* suspension cultures	Greenovation Biotech BMBH Freiburg, Germany	α-galactosidase for Fabry disease and βα for Gaucher disease. Both are in phase 1 of clinical trials
	Glycosylated recombinant proteins	Hairy roots	Root Lines	Rhizo prot platform

Source: Plant cell culture strategies for the production of natural products, Marisol Ochoa-Villarreal, Susan Howat, SunMi Hong, Mi Ok Jang, Young-Woo Jin, Eun-Kyong Lee, and Gary J. Loake

The cell culturing technique includes several steps that are always followed during in vitro propagation of different plants[6]:

- Isolation of the plant cell from (mechanical method/enzymatic method) the cultured tissue. The selection of the appropriate cell line can be based on the highest biomass production and shortest doubling time.
- Growth and subculture of suspension cultures (batch and continuous cultures). Suspension cultures are those cultures in which cells are suspended in a liquid medium and mixed at a certain speed to expose the cells to uniform nutrient media from all directions, which could prevent the aggregation of cells and eventually increase the absorption of nutrients by promoting the growth of the cells. These cultures are maintained by the sub-culturing of the cells in the early stationary phase to a fresh medium.
- Selection and optimisation of culture medium for cell suspension culture.
- Synchronisation of suspension cultures. Established suspension culture can be processed with high pressure homogenisation to break the suspended cells completely and entirely release the active ingredients. Some research in the past few years has demonstrated plant cell culture technology as an effective method for extraction of stem cells in the development of novel plant derived actives.
- Physical (selection by volume and temperature shock) and chemical methods (starvation, inhibition, mitotic arrest). Culture parameters including levels of phytohormones and components within the media can be optimised more rapidly by employing a statistical design of experiments approach.
- Measurement of growth in suspension cultures. The use of a non-invasive, in-line system to monitor cell biomass during culture can be an important step to maximise product yield and quality, while improving culture nutrients.
- Cell counting, packed cell volume, cell fresh, and dry weight.
- Viability of cultured cells (phase contrast microscopy, reduction of tetrazolium salts, fluorescein diacetate method, Evans blue staining).
- Culture of isolated single cells (to culture isolated single cell), filter paper raft nurse technique, microchamber technique (to culture low-density cell cultures), and scale-up technique (bioreactors are used for large-scale cultures).

Figure 3.2: Schematic presentation of technological steps in development of InnovaStemCell Calendula active cosmetic ingredient



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Source: https://www.researchgate.net/figure/Schematic-presentation-of-technological-steps-in-development-of-InnovaStemCell-Calendula_fig1_325929060

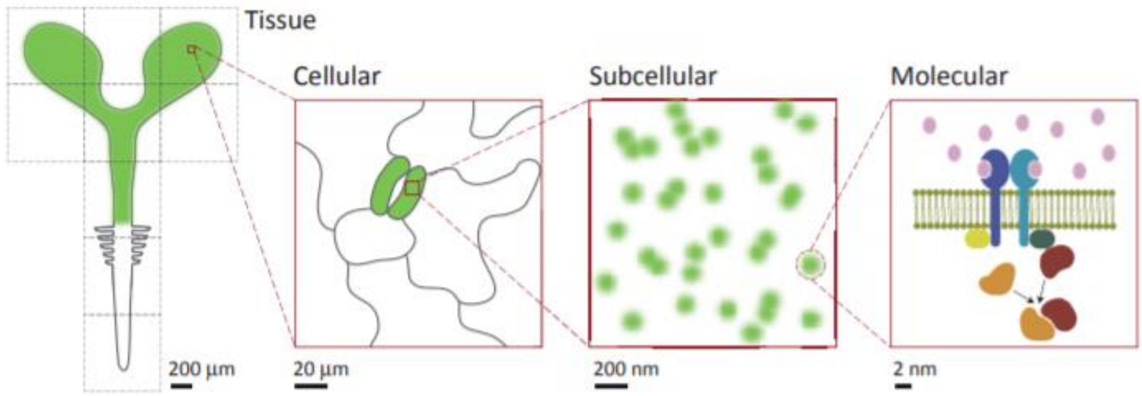
3.2.2 Plant Cell Atlas

A comprehensive understanding of plant cell structure and function at a molecular level is essential to uncover the mechanisms that plants use to produce the services we depend upon. Advances in genetics, molecular biology, biochemistry, and microscopy have produced detailed pictures of important cellular components, pathways, and mechanisms in higher plants, but many structural and functional features of plant cells remain to be understood at a molecular level, and it is highly likely that important features and compartments remain to be discovered and elucidated.

If we wish to accelerate the development of plant cell technology there is an urgent need for building a Plant Cell Atlas (PCA), with the goal of creating a community resource that comprehensively describes the state of the various cell types found in plants and that incorporates information on nucleic acids, proteins, and metabolites at increasingly higher resolutions.

A PCA will facilitate the elucidation of basic, longstanding questions in biology that relate directly to grand challenges in food security and climate change. For example, how do we get the maximal output of specialised plant cells that produce useful products (e.g., nutrients, oils, natural products) while reducing environmental impact? In addition, a Cell Atlas can provide insights into how viral or bacterial pathogens change cell properties.

Figure 3.3: Various scales of the plant cell components that need to be mapped and integrated in the plant cell atlas



Source: https://www.cell.com/trends/plant-science/fulltext/S1360-1385(19)30021-4

A PCA could help developing a community resource and will accelerate synergies between private and research community. It would also raise public awareness on the alternative to produce high-value compounds without depleting Cell wild stocks. A PCA would also facilitate the understanding of important questions related to food security and climate change.

3.2.3 Market potential and key players

Cell Plant based ingredients have emerged as alternative high-value compound sources, thus encouraging manufacturers to experiment and develop alternatives to plant-derived ingredients. It is a very fast-growing sector for the development of new organic cosmetics, nutraceuticals and pharmaceuticals. Cell plant-based ingredients are a high source of essential amino acids, minerals and vitamins which are required by the body to prevent dangerous diseases and promote a healthy lifestyle. Rising consumer awareness regarding artificial mixtures and chemical composition which may further prefer products containing natural plant sources are likely to stimulate cell plant-based ingredients market growth. The market of plant-based ingredients was worth over USD 8 trillion in 2018 and industry expects consumption at over 4.5 billion tonnes by 2025. Cosmetic raw materials accounted for USD 21.9 billion in 2017[7]. With an annual growth rate of 4.43%, the market will reach USD 31.8 billion by 2023

But what are the global motivations behind plant-based ingredients? The consumer values that are leading the wants and trends around cell plant-based nutraceuticals, cosmetics and personal care products include:

- The rise in selective way of consuming: some plant protein consumers are forced into this way of buying through restrictions such as allergies and diseases. Others are following self-imposed organic rules, such as "vegan keto"[8], or simply want to be a part of a circle: #vegan has 83 million mentions on Instagram.
- Growing awareness of ethical and environmental issues: many plant-based products /ingredients have a strong sustainability story and claim lower carbon footprint than traditional

ingredients sources. Health and sustainability are big drivers, due to a perception that plant protein products are gentler on the environment.

- Mounting concerns over health: plant-based products give the perception of providing consumers with a healthier alternative to traditional products. Over half of ingredients users want natural ingredients in their product, reflecting growing consumer demand for recognizable, simple ingredients.

Beyond these primary motivations, consumers are also attracted to plant-based ingredients for the following reasons:

- Novelty: the biggest cohort in the plant-based alternative market are flexitarians who are interested in trying new things which are novel or innovative, such as through exciting flavours and formats.
- Diet: in many regions, plant-proteins have a ‘better-for-you’ halo and are perceived to be a healthy way to add vegetables and grains and potentially help with weight maintenance or loss.
- Cultural tradition: some cultural and religious traditions lean towards a vegetarian behaviour. For example, some Chinese consumers never use animal products on specific days of the lunar calendar. Mixing cultivation, incorporating seaweeds into echinoderms and molluscs mariculture systems has long proven to be the most promising approach for mitigating the pollution of the surrounding environment by aquaculture operations. Accordingly, seaweed cultivation has been carried out for decades and has grown rapidly in China and other countries[9].
- Trend and influence: as consumers in developing nations see the rise of plant-based ingredients in more prosperous countries, the trend is gaining traction. Western countries also tend to import natural and organic food trends from other regions. Seaweed is becoming a very trendy sector.
- Food Safety: Some consumers—especially those in Asia—perceive plant proteins as being safer than animal proteins.

The sections below look into the new areas that plant-based ingredients companies are exploring.

3.2.3.1 Nutrition and nutraceuticals

Plants have always been a rich source of compounds to maintain or improve human health. Historically these were compounds that occurred naturally in plants, but with the introduction of new plant biotechnology at the end of the last century, the possibility emerged to engineer plants to manufacture new compounds, including small molecules and biologics that originate from non-plant sources. Very rapidly, the technology to genetically modify almost any plant species was developed, including all of the world’s major food and feed crops, and with that arrived the prospect of delivering recombinant compounds of potential medical benefit, by the oral route.

This boom in plant biotechnology occurred at the same time as the explosion in university enterprise activities. A number of new companies including spin-offs were established to take advantage of growing interest in the field of ‘molecular pharming’. Although most of these ventures were clearly developing pharmaceutical drug targets, for some the regulatory path was not so clear and alternative routes for commercial development became of interest. For example, it was considered that some products could be developed as nutraceuticals (or food supplements), cosmetic ingredients or medical devices, the regulatory path for which are different than for medicines.

Spending on agricultural and nutrition research and development has increased recently but the rate of growth is slow than expected. As of the present market scenario, products with plant stem cells with key ingredients are rare as against supplements with key nutrient ingredients that boost body stem cell regeneration. Affordability associated with these processes is in the capacity of the nutrition companies, where research in academia is restricted to funding and donations. As a result, the end-products thus introduced in the market are high priced.

The plant stem cell market for nutrition is observed as the most diversified and competitive market comprising large number of players. The market is dominated by several players, depending on their major competencies.

3.2.3.2 Cosmetics

Active cosmetic ingredients, obtained by the plant cell culture technology are often called "plant stem cells". Plant cells have the potential to express the full genetic machinery coded in the nucleus. Plant cells are suitable to good manufacturing practice procedures and can be easily propagated by using large volume bioreactors independently on climate or soil or field management practices. Moreover, in vitro cultured plant cells are characterised with fast growth, and the ability to accumulate large amount of uniform biomass for a short period of time. This is very important advantage especially for the production of rare bioactive compounds, as resveratrol, paclitaxel or terpenoids, which are usually found in low concentrations in plants and their isolation and purification requires the processing of large amounts plant biomass. Additionally, plant cell culture technology offers a reliable and powerful production platform for continuous supply of contamination-free, phytochemically uniform biomass from herbal, aromatic, medicinal, and even from rare and threatened plant species.

The perspective to obtain natural phytochemicals by using an environmentally sustainable biosynthetic platform made plant cell culture technique exceptionally attractive for the production of active ingredients for high added values "green" cosmetic formulations.

The cell plant industry highly depends on research work. Scientific evidence supports substantial anti-oxidant and anti-inflammatory compounds found in botanicals, such as grapes, lilacs, Swiss apples but also in seaweeds. Consequently, cosmetic products containing such extracts have the ability to exert very interesting properties such as anti UV or antioxidant. Many cosmetic companies are promoting their products with the claim of utilising stem cell technology. The market is diversified and competitive with North America and Europe being major consumers of cosmetics. Asia is emerging as a leading market for global skincare as well.

Figure 3.4: Taxus cell culture vs extraction of plant materials for paclitaxel production

	Extraction from Taxus plant materials	Taxus cell culture production via 1000L bioreactor
Content	~0.1mg/g	~10mg/g
Growth cycle	100 years (3-5 years at least)	30 days
Land requirement	~3000 square meter	~60 square meter
Output	0.01%×10KG bark/Spec 100 years Taxus×3000 Spec =3KG/100 years	300ml/L×1000L×(300day/year÷30day) =3KG/year
Production cost (US$)	40,000/KG	14,000/KG

Source: Ancelbio Biotechnology 2019

3.2.3.3 Pharmaceuticals

Plant-derived pharmaceuticals are about to become the next major commercial development in biotechnology[10]. The advantages they offer in terms of production scale and economy, product safety, ease of storage and distribution cannot be matched by any current commercial system; they also provide the most promising opportunity to supply low-cost drugs and vaccines to the developing world.

However, despite the promised benefits, the commercialisation of plant-derived pharmaceutical products is overshadowed by the uncertain regulatory terrain, particularly with regard to the adaptation of good manufacturing practice regulations to field-grown plants. The success of such products also depends on careful negotiation of the intellectual property landscape, particularly the achievement of freedom-to-operate licenses for use in developing countries.

According to Newman and Cragg 2012, the utility of natural products as sources of novel structures is still alive and well. Up to 50% the approved drugs during the last 30 years are from either directly or indirectly from natural products and in the area of cancer, over the time frame from around the 1940s to date, of the 175 small molecules 85 actually being either natural products or directly derived there from. It is only recently that biotechnology has been used to generate plants that produce specific therapeutic proteins, products that are traditionally synthesised using recombinant microbes or transformed mammalian cells. The first of these plant-derived pharmaceutical proteins (PDPs) are now approaching commercial release.

3.2.3.4 Key players

Latest research trends in the cosmetics industry are based on the use of biotechnology-based ingredients and a study of their effects on cell biology. Biotechnology has had a significant impact on the cosmetics industry in many ways. Companies use this technology to discover and develop components of cosmetic formulas. Many active ingredients are being made using this technology (source www.grandviewresearch.com and Biotech Ingredients Market Size, 2019 - 2025).

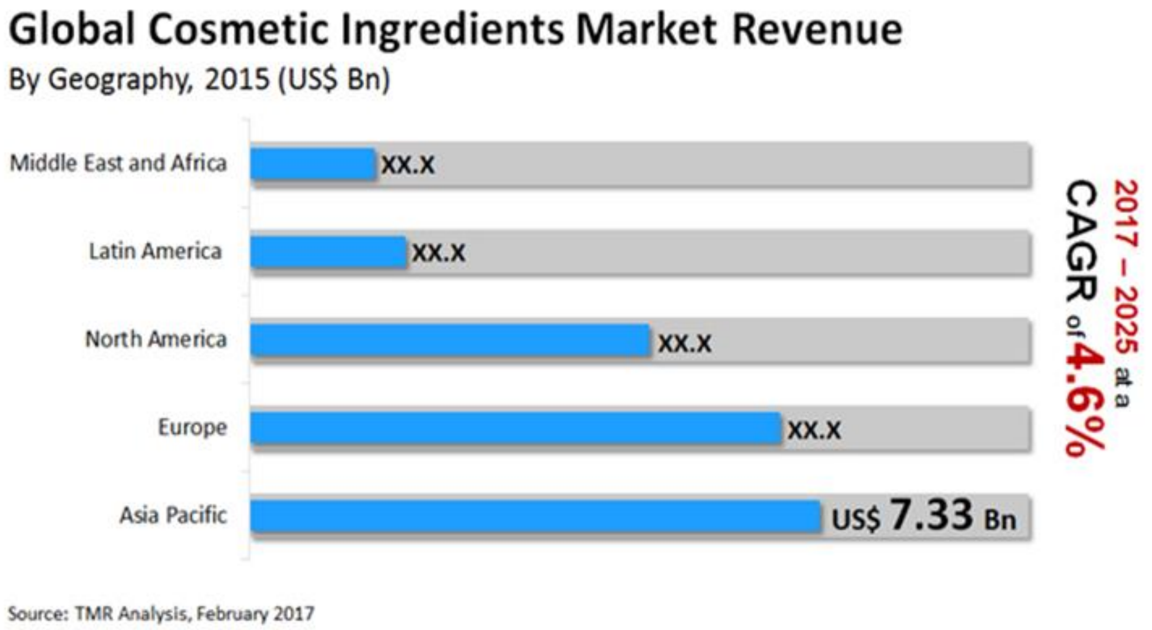
In 2017, Europe emerged as the leading market for biotech ingredients in cosmetics and fragrances. This growth can be attributed to development of innovative value chains for producing bio-based ingredients, government initiatives, and increasing production capacities of bio-based chemicals. Business sustainability programs, along with potential investors in the industry, are projected to drive market growth over the forecast period.

North America emerged as the second-largest market for biotech ingredients. Increasing R&D activities to develop innovative bio-based routes are likely to contribute to market development. Early adoption of the product, along with presence of potential industry participants, is likely to drive market growth over the forecast period. Increasing consumption of personal care products, flavouring agents, and fragrance products is likely to create potential opportunities for this regional market. Moreover, advances in metabolic engineering, bio-transformation, and microbial biosynthesis is projected to drive the market.

Key players in the biotech ingredients market have been developing flavours using microbial processes such as biosynthesis or biotransformation using bacteria, yeast, or fungi. Companies have been focusing on R & D activities based on biotechnology in order to invent novel microbial fermentation processes to manufacture natural vanillin.

Sollice, Givaudan, and Novocap Group are some of the pioneering players in the market for biotech active ingredients. Business partnerships are projected to foster market growth in the North American region. Companies such as Hallstar Company and Deinove SAS have been working on developing stable oily active ingredients for personal care and beauty industries.

Figure 3.5: Global Cosmetic Ingredients Market Revenue



The global biotech ingredients market size was estimated at USD 1.50 billion in 2018 and is expected to register an estimated CAGR of 8.0% from 2019 to 2025 (source www.grandviewresearch.com/industry-analysis/biotech-ingredients-market).Even though the main cosmetic players are positioned on this market, it appears that they are just testing the R&D capacity and will not likely become the future main players in the field.

The key players (alphabetic order) in this market are:

Active Botanicals Research (ABR), Italy:

Products: Echinan 4P, Teupol 10P and Teupol 50P, Acetos 10P

Applications: food supplement ingredient

AgBiome Inc, US: Gene and Strain Identification System. Their innovative platform allows to efficiently capture and screen the most diverse and unique microbial collection for agriculturally relevant applications.

Products: synthetic pesticides.

Applications agriculture

Ancelbio, China Ancelbio has world leading research and development capacities of plant cell lines and banks, hyper-production technologies by integrated manipulation of biosynthetic and post-biosynthetic pathways, and proprietary scalable and modular bioreactor systems for commercial-scale production.

Products: more than 30 Products and over 70 cell lines – ex European Edelweiss, Snow Lotus, etc.

Applications: cosmetics, cellular immunity and accelerate self-repair of damaged cells, skin regeneration,

Belgis Biotech Laboratories, Belgium: the company is committed to biotechnology excellence by providing with exclusive tissues culture techniques and easy to operate know-how, Plantlets of a wide range of floriculture, fruit and vegetable varieties.

Products: plant stem cell.

Applications: agriculture and floriculture

BiotechMarine by Seppic, France: BiotechMarine, a subsidiary of Seppic, part of wesource™, is specialised in active ingredients extracted from seaweeds or maritime plants, maritime plant cells and macroalgae cells.

Products: Celtosome (from seaweed)

Applications: Cosmetics, skin rejuvenation and care

Diana Plant Sciences, France: select raw materials including fruits, vegetables, meat and seafood to offer clean label solutions, standardised nutrition actives and functionalities enabling impactful product claims.

Products: Cocovanol

Applications: Food supplement ingredient

Innovacos, Spain: Innovacos designs and manufactures innovative cosmetic ingredients to fulfil the needs of formulators in their quest of developing sophisticated products. Our highly trained group of chemists and cell biologists have undertaken the task of investigating the benefits of various biomasses collected from around the World & Earth.

Products: Plant C-Stem Vigna radiata

Applications: Cosmetics, skin rejuvenation

In vitro Plant-tech, Sweden: it offers raw materials and extracts from plants produced in a controlled, clean room laboratory environment. To ensure maximum effectiveness, they select the most potent plants. This enables them to provide a constant supply of consistent, high-quality, customised plant material with full traceability for the cosmetic, food and pharmaceutical industries.

Products: Stem cell extracts from: roseroot, greater plantain, milk thistle, Aloe vera

Applications: Cosmetics, skin rejuvenation

Institute of Biotechnological research (IRB) by Sederma, France: Sederma is a world leader in the field of active ingredients intended for the Cosmetic industry. They have developed a unique range of biochemical actives, with substantiated efficacy. Sederma became a member of the Croda International Group in 1997. Located near Paris, all Sederma activities, from R&D and manufacturing to administration and warehousing, are gathered in a 11 000 m² complex.

Products: Stems GX products: Buddleja Stems GX, Echinaceae Stems GX, Gardenia Stems GX, Lenontopod Stems GX, Resistem, Marubium Stems GX

Applications: Cosmetics: treatment of rosacea, acne and sebum related disorders,

Lida Plant Research S.L., Spain: Lida Plant Research is a biotechnological company based on the development of new solutions and products for improvement of yields and crop protection against different types of biotic and abiotic stress.

Products: plant vaccine, biostimulant, phyto vaccine.

Applications: agriculture and biotechnologies.

Lonza, Switzerland: Lonza combines technological innovation with world class manufacturing and process excellence. Together, these enable customers to deliver their discoveries. Lonza is a preferred global partner to the pharmaceutical, biotech and specialty ingredients markets. Their solutions improve life quality by preventing illness, enabling healthier lifestyles and supporting a safe environment. The company works to prevent illness and promote a healthier world by enabling our customers to deliver innovative medicines that help treat or even cure a wide range of diseases. The company also offers a broad range of microbial control solutions, which help to create and maintain a healthy environment.

Products: ReGeniStem Brightening.

Applications: skin bringhtening.

Lumene, Finland: they use handpicked Nordic botanicals, allowing Nature to regenerate and remain in balance. Thoughtfully selected not only for their ability to nourish the skin but also for their local origin and sustainable source.

Products: stem cell culture extract from arctic cloudberries-

Applications: cosmetics: skin rejuvenation and care.

Lipotec, Spain: founded in 1987 in Barcelona, Spain, and acquired in 2012 by Lubrizol (Berkhshire Hathaway company), Lipotec SAU is a well-known worldwide expert in advanced active ingredients for application in cosmetics.

Products: peptides, biotechnological molecules, botanical extracts.

Applications: cosmetics: skin rejuvenation and care.

Mibelle Biochemistry, Switzerland: Mibelle Biochemistry Switzerland designs and develops unique, high-quality actives for the beauty industry which are based on naturally derived compounds and extensive scientific expertise. This independent business unit within the Mibelle Group was founded in 1991 by Dr. Fred Zülli in Buchs, Switzerland. In a short period of time, Mibelle Biochemistry has developed an excellent reputation throughout the world as a creator of innovative active ingredient concepts as well as being a real expert in the fields of biotechnology and biochemistry. Its broad line of actives is available in more than fifty different countries around the globe.

Products: PhytoCELLTECH actives from argan tree, apple, alpine rose, soapwort, comfrey and grapes.

Applications: cosmetics, skin rejuvenation and care.

Naolys, France: Naloys actives, holding a world patent, are produced from an innovative and unique biotechnology process based on an industrial scale production of active plant cells.

Products: Rose roots, Mexican poppy, Poet's narcissus, Edelweiss, Curry, sequoia, etc…

Applications: cosmetics, anti-aging, anti UV, skin regeneration.

PhytoScience SdnBhd, Malaysia: it is a global health & wellness company stands at the forefront of product innovation and committed to helping people take control of their health, both physical and financial well-being. Founded in 2012 on little more than dreams and hard work, PhytoScience is now a multi-million-dollar company, based in Kuala Lumpur.

Products: Triple Stem Cells™.

Applications: nutrition and skin care.

Sandream Enterprises, Thailand: part of Aakash Chemicals, which is a vertically integrated manufacturer of specialty chemicals for colorant applications. They are specialised in organic pigments, dyes, liquid colorants, slip additives, and specialty resins.

Products: callus stem cell extracts from: orchid, lotus, tomato, rice, grape, carrot, green tea, ginseng

Applications: cosmetics, skin rejuvenation and care

Vitalab, Italy: Vitalab was established in 2010 as a joint venture between Arterra Bioscience srl and Intercos SpA/CRB SA. The strategic combination of Arterra scientific know-how in plant science, human skin cell biology and drug discovery with the experience in the global cosmetic market of Intercos/CRB allows the identification and development of innovative active compounds for cosmetic use. Vitalab collaborates with prestigious national and international research institutions to take advantage of the most recent discoveries in life sciences for the development of new active ingredients.

Products: stem cell culture extracts.

Applications: cosmetics, skin rejuvenation and care, skin brightening and firming.

Vytrus Biotech, Spain: Vytrus Biotech develops high added value natural active ingredients on an industrial scale through an innovative and unique process in the biotechnology field which obtains the real power of nature. They developed and produced the first Spanish active based on plant stem cells.

Products: Plasma Rich in Cell Factors (PRCF) products.

Applications: cosmetics: skin rejuvenation and care, skin whitening and air loss.

3.2.4 Carbon footprint evaluation

Agriculture, forestry and mariculture are fertile grounds for applying biotechnology: they are not just major contributors to climate warming but also play a potential role in reducing emissions. Agriculture generates more than a quarter of global greenhouse gas emissions, while the combined impact of forest fires and deforestation accounts for another 20%[11] (). Vice versa, forests (land- and sea-based) are major carbon sinks and have a lot of potential to sequester CO_2 from the atmosphere. The production of 500 million tonnes of seaweed would absorb 135 million tonnes of carbon, about 3.2% of the carbon added annually to seawater from greenhouse gas emissions, offering the potential for using carbon credits to improve the profitability of seaweed businesses[12]. Agriculture and mariculture will have to play a crucial role for sustainable energy production.

Crop biotechnology has significantly reduced agriculture's greenhouse gas emissions by helping farmers adopt more sustainable practices such as reduced tillage, which decreases the burning of fossil fuels and retains more carbon in the soil. Had biotech crops not been grown in 2015, for example, an additional 26.7 billion kilograms of carbon dioxide would have been emitted into the atmosphere, which is the equivalent of adding 11.9 million cars to the roads.

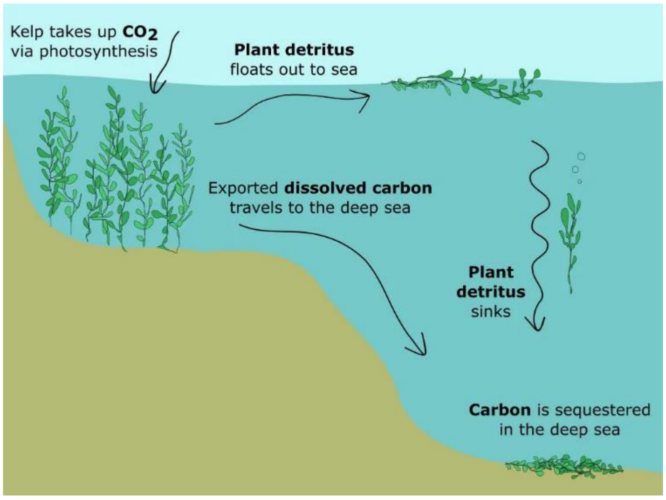
From 1996 to 2015, crop biotechnology reduced the spraying of crop protection products by 619 million kilograms, a global reduction of 8.1 per cent. This is equal to more than China's total crop protection product use each year3. As a result, farmers who grow biotech crops have reduced the environmental impact associated with their crop protection practices by 18.6 percent[13].

Coastal ecosystems sequester away large amounts of carbon – they can sequester up to 20 times more carbon per acre than land forests. Studies are currently being developed to assess the real potential of seaweed and kelp carbon sequestration, such as:

- Substantial role of macroalgae in marine carbon sequestration. (https://www.nature.com/articles/ngeo2790)
- Installing kelp forests/seaweed beds for mitigation and adaptation against global warming: Korean Project Overview (https://academic.oup.com/icesjms/article/70/5/1038/644026)
- Development of a Methodology for the Quantitative Assessment of Ireland's Inshore Kelp Resource (https://oar.marine.ie/bitstream/handle/10793/702/Quantitative%20Assessment%20Methodology%20for%20Inshore%20Kelp%20Resource.pdf?sequence=1&isAllowed=y)
- Sustainable Seaweed Biotechnology Solutions for Carbon Capture, Composition, and Deconstruction (https://www.sciencedirect.com/science/article/pii/S0167779920300901).

Marine plants that contribute to carbon sequestration, such as mangroves and seagrass, live in rich soil (the case of seaweed is explained below). When these plants die, some of the leaves, branches, roots, and stems get buried underwater in the soil, and because of low oxygen concentrations, the plant material can stay buried for decades or longer before breaking down and releasing carbon dioxide. Unfortunately, because the carbon is stored close to the shore, it can be easily disturbed by runoff, human activity, or storms and released back into the atmosphere sooner than it otherwise might have.

Figure 3.6: Substantial role of macroalgae in marine carbon sequestration



Source: Dorte Krause-Jensen & Carlos M. Duarte https://www.nature.com/articles/ngeo2790

Unlike mangroves and seagrass, macroalgae such as kelp usually grow near the shore in rocky and eroding conditions where plant materials cannot get buried. Instead, parts of macroalgae get exported to the deep sea, where the carbon can be sequestered. Because the carbon from macroalgae is stored far away from the shore, it is less likely to be disturbed and returned to the atmosphere. With the development of offshore seaweed aquaculture – which may benefit from synergies with the offshore wind energy industry – sequestration ratios are linked to the final use of the product. If the production is dedicated to bioplastics, the carbon remains sequestered in the product itself; if the final product is nutrition or feed, the carbon is released very quickly and in this case the ratio is neutral.

A paper published in 2016 in Nature Geosciences[14] compiled data from previous studies in order to provide an estimate of how much atmospheric carbon is being removed by macroalgae. Their rough estimate suggests that around 200 million tonnes of carbon dioxide are being sequestered by macroalgae every year –almost the annual emissions of the state of New York. These estimations, however, rely on indirect calculations. To improve the numbers on how much carbon is being sequestered by macroalgae, one would need to measure how much of it ends up in the deep sea, and how much gets captured if the seaweed is left untouched (marine permaculture) or if being transformed/processed. Of course, one also needs to consider that the calculations are likely to be very different from one species to another. Kelp is the best-case scenario, whereas some Atlantic species might make a lower contribution.

Plant cell Contribution to carbon sequestration: if one considers the overall activity of the sector, it can be argued that the carbon footprint will remain marginal. Meanwhile, plant cell technology generates a minimal impact on ecosystems, as the technology remains independent from natural resources cycles. It is also considered as a highly eco-sustainable technology because (i) there is no need for arable soil, (ii) there is a drastic reduction of water use, (iii) it is herbicide- and pesticide-free, (iv) it is volatile organic compound- free.

3.2.5 Legal and regulatory issues

The situation in the EU. New Plant-Breeding Techniques (NBTs) are methods allowing the development of new plant varieties. They are called 'new' because these techniques have only been developed in the last decade and have evolved rapidly in recent years. Moreover, as these practices are still continuously evolving, there is no limited set of techniques that can be put under the 'umbrella term' of NBTs.

Seeds, the main focus of New Plant-Breeding Techniques which aim at improving their genetic characteristics, are regulated in the EU by 12 Directives: Directive 2002/53/EC on the common catalogue for varieties of agricultural plant species and 11 sectoral Directives that govern the seeds of specific crop species (for beets, cereals, fodder plants, forest material, fruit plants, oil and fiber plants, ornamental plants, potatoes, vegetables, and wine). The legislative framework for seeds is based on two elements:

- Registration of the seed varieties.
- Certification of the seed varieties before they can be sold on the EU market.

The general principle is that companies can register their new seed varieties in the national catalogue of one of the EU Member States, which needs to notify the European Commission, after which the seed variety will be registered in the Common Catalogue of the EU. Before registering the variety, the seed needs to be tested for 4 elements:

- Distinctiveness: it needs to differ clearly on, at least, one important characteristic from another registered seed variety.
- Uniformity: all resulting plants should be identical.
- Stability: the plant characteristics should remain in place over generations.
- For agricultural crops, the 'Value for Cultivation and Use' needs to be proven.

The European Union GMO regulatory framework dates back almost three decades. It was set up in 1990 just after the development of recombinant DNA technology (directive 90/220/EEC was replaced by the current directive 2001/18/EC in 2001). At that time, experience with recombinant DNA technology for crops was limited. The extremely cautious approach taken in the EU has resulted in one of the most severe sets of GMO regulations in the world. Strict safety assessments, cumbersome bureaucracy and activism against GM organisms have almost chocked research and release of GM crops in Europe. Almost no significant quantities of GM crops are cultivated on the continent.

Scientists, breeders and seed producers are afraid that gene-edited crops, plant or seaweed will be placed under the same onerous GM regulations, which would make the technology too expensive and too slow for competitive agricultural biotech. The question at stake is: do gene-edited crops fall under EU Directive 2001/18/EC?

In regards of the cosmetic regulation, the European Commission through the EU Cosmetics Directive has overall responsibility for cosmetic legislation with the EU. Each member state designates a competent authority that enforces the legislation. Here are some of the relevant issue to be considered:

- There are no requirements for registration of manufacturers or importers or premarket approval. The relevant member state authority must be notified of the place of manufacture or of initial importation. Belgium, Denmark and Spain request a notification of products prior to marketing There are 1 233 121 prohibited substances and another 97 subjects to restrictions in the use of cosmetics manufacturing.
- Positive lists permit the use of a number of cosmetic colourants, preservatives and UV filters. Inclusion of new substances in the list is subject to scientific evaluation.
- General labelling requirements exist, including the address where product safety information is kept within the EU. Warning statements are required in the respective national languages for products containing certain ingredients.
- The safety of cosmetic products placed on the EU market is the responsibility of the person who places the product on the market, assured through in-market surveillance by competent authorities designated by each member state.
- The 7th Amendment to the Cosmetics Directive introduced a ban on animal testing of cosmetic products from September 2004 in the EU. A ban on animal testing of ingredients within the EU and on the marketing of cosmetic products tested on animals and products containing ingredients tested on animals, within the EU or elsewhere, is effective not later than March 2009.
- Other product categories are medicinal and biocidal products regulated under separate directives.

Figure 3.7: Summary table: legislation and requirements for GMOs, seeds and novel foods in the EU

	GMOs	Seeds	Novel foods
Main legislation	Directive 2001/18/EC on the deliberate release into the environment of genetically modified organisms Regulation (EC) 1829/2003 on genetically modified food and feed	Directive 2002/53/EC on the common catalogue for varieties of agricultural plant species 11 sectoral Directives GM seeds also need to follow the GMO legislation: Directive 2001/18/EC and Regulation (EC) 1829/2003	Regulation 258/97, which will be replaced by Regulation (EU) 2015/2283 from 2018 onwards Does NOT apply to GMOs, which are subject to Regulation (EC) 1829/2003 on genetically modified
Requirements	For cultivation: assessments of the environmental risks, monitoring of the GMOs after their release, labelling and registration requirements, and public consultations. For food and feed: authorisation; supervision; and labelling (if they contain more than 0.9% of GMO	For registration: ** DUS tests: identification and description of the seed variety.* ** VCU trials (for agricultural crops): to test the agronomic performance of the plants resulting from the* For certification: inspections verifying and guaranteeing the identity, health and quality of the seeds; labelling; and tests of samples.	Safety assessment and authorisation, requiring data on the compositional, nutritional, allergenic and toxicological characteristics of the products, as well as information on the production process and the
Average costs for approval	Registration fee: up to € 90 000 Total costs of €6.8 million on average for the required data collection (has varied from €3.8 million to €10.3	Registration: *DUS tests: €90 – €2000 per year ** *VCU tests: €1000 – €2550 per year ** Certification: 1 –2% of total seed production * mostly shared or even fully paid by the public authorities	€20 000 – €40 000 (but can vary from a few hundreds to one million euro) For the simplified procedure of novel foods similar to existing products: between €900 and €2000
Average duration for approval	For cultivation: 3 years* For food and feed: 3 to 4 years	Registration: – DUS tests: 2 years – VCU tests: 2 to 3 years Certification: at least 2 years	2 to 4 years

Source: https://www.farm-europe.eu/travaux/new-plant-breeding-techniques-what-are-we-talking-about/

The Pegasus Report[15] notes that although European marine flora displays one of the highest species-diversity levels in the world, its commercial production is still in its infancy, with only 1% of the world's production, from which less than 1% was coming from aquaculture in 2016. Interest in seaweed-based industrial applications is on the rise, and seaweed are a promising bioresource for the future, with demand for high-value seaweed-derived compounds (cosmetics, food) growing in Europe. However, the European production lags behind Asian countries, despite a large exclusive economic zone, high seaweed biodiversity, and international leadership in fundamental research on seaweed genomics, genetics and cutting-edge techniques.

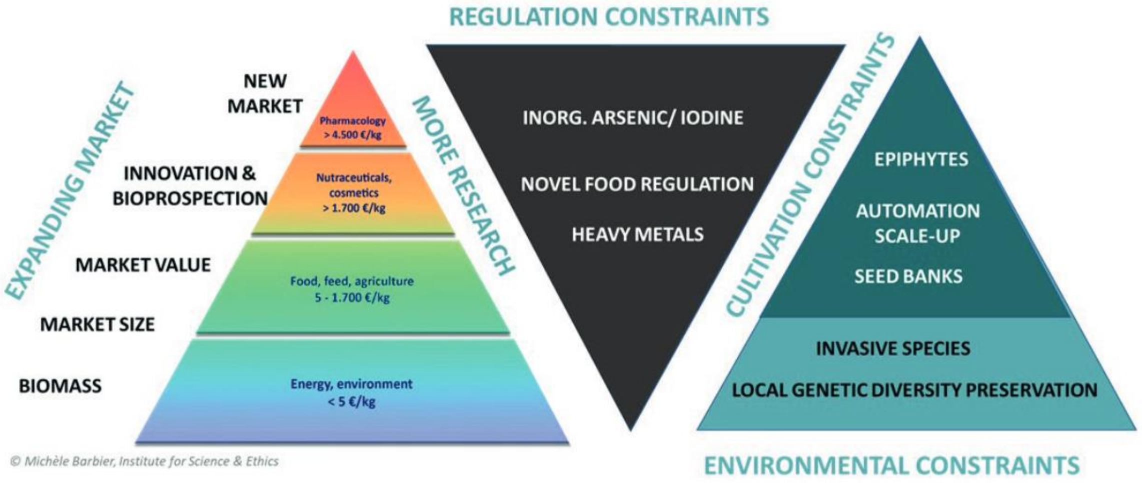
Even if the Pegasus report does not take into account the potential of cell plant technology, it is important to note that there might be a special direction to look at:

1- Environmental issues regarding invasive species: a list of alien species of economic interest in Europe should be established as well as their risks for the environment (update the Annex 4 of EU Regulation 708/2007). In this case the development of cell plant technology using confined production methods for non-local stem cell species would become an interesting approach.

2- Traceability and organic certification: the notion of local strains for a specific market requires appellation of controlled origin. Traceability would define these applications. Certification procedure must be implemented. It is obvious that the cell plant technology will allow a full traceability and certification and it follows strict industrial production protocols.

3- Food safety: bottlenecks that hamper market development have been identified in European legislation. Legislation on contaminants such as heavy metals and issues on iodine and inorganic arsenic should be addressed in seaweed "as food". The monitoring of heavy metals, iodine, arsenic etc. could remove market barriers and provide clear updated regulation on the threshold values of different contaminants. In this case also the cell plant technology will offer all warranties of traceability and purity for the stem cells that will be developed and produced.

Figure 3.8: Bottlenecks hampering seaweed market development



Source: Pegasus report (http://www.phycomorph.org/doc/PEGASUS_KEY-FACTS.pdf)

The main regulatory trigger for subjecting organisms to regulatory oversight is safety. Most of the cells used in plant cell technology are considered as natural ingredients. However, if the stem cells have been modified or improved with CRISPR[16] they fall under the specific regulation of GMOs. To follow the fierce debate about the legal status of gene-edited crops, it is important to check the basis for regulatory oversight in different countries.

The situation outside the European Union. The US Department of Agriculture regulates solely based on the presence (or absence) of DNA derived from plant pests, not on the basis of the trait or product qualities. So, it did not signify a change of heart, when the USDA announced in March 2018, that it would not regulate gene-edited plants. Gene-editing researchers hailed the announcement as it affirmed that gene-edited crops are not riskier than any other new plant varieties.

The agency basically acknowledged gene editing as a much faster form of traditional breeding. So, as long as the genetic changes could have been bred in a plant — say a simple deletion, base pair swap, or insertion from a reproductively compatible relative — it would not be regulated. However, most plant genome editing experiments use Agrobacterium-mediated transformation to deliver genome editing nucleases into plant cells[17]. If gene-edited plants contain 35S promoters, T-DNA or similar they will still require regulation. Also, if one uses gene-editing technology to introduce genes from distant species, they still have to jump through all the regulatory hoops[18].

More importantly, the Food, Drugs and Cosmetics Act regulates cosmetics in the US and remains largely unchanged since its introduction in 1938. Cosmetics can be categorised as cosmetics, drugs or both, in which case they must meet the requirements of both. Characteristics of the US market include:

- Cosmetic products are not subject to pre-market approval and companies are not required to submit information on their products or to register cosmetic manufacturing establishments. The safety of cosmetic products is the responsibility of the manufacturer and is supported by an in-market surveillance system.
- No approval is required for the use of any new ingredient in a cosmetic, but a small number of ingredients are strictly regulated or prohibited. All colour additives must be tested for safety and approved for their intended use by the FDA before they can be marketed.

Canada regulates the introduction of "novel traits" into crops. Its biotechnology regulatory framework dates back to 1993 and is not triggered by the use of a certain technology, but by the novelty of the final plant product. Therefore, it is not expected to require any amendment to accommodate case-by-case decisions on products derived from gene editing.

Latin America incorporates gene editing in its current biosafety governance. Most countries in Latin America established governances on biotechnology that rely heavily on principles and concepts established in the Cartagena Protocol on Biosafety (CPB). The CPB is an international agreement that aims to ensure the safe handling, transport and use of GMOs (called LMOs – living modified organisms – in CPB). LMOs are defined as "any living organism that possesses a novel combination of genetic material obtained through the use of modern biotechnology". Argentina, the world's third-largest producer of GM crops, is not among the 170 countries that have ratified the CPB. Yet, it defines GMOs in provision no. 701-2011 exactly as the CPB.

In 2015, Argentina extended its regulatory framework and published the world's first regulation for new breeding technologies including genome-editing. In resolution No. 173/2015a, the Secretariat of Agriculture, Livestock and Fisheries outlines the procedure for a case-by-case assessment to determine whether a crop will be regulated as GMO or not. In a nutshell, gene-edited crops will not be subject to GMO regulation if no transgene is inserted.

Chile and Brazil followed Argentina's lead. Chile signed a normative resolution in 2017. Brazil published a resolution in January 2018. Both regulate gene-edited product case-by-case and exempt them from regulation when there is no insertion of transgenes.

There is optimism that other South American countries will adopt similar regulations. The Colombian government recently announced that it would not regulate gene-edited cacao developed by researchers at the University of California, Berkley with money from Mars Inc., one of the world's biggest chocolate producers.

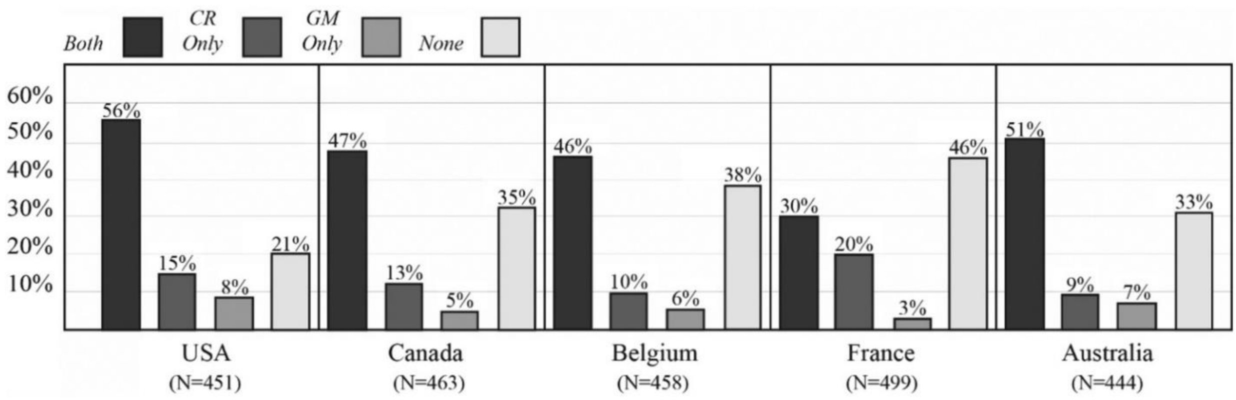
3.2.6 Consumer acceptance

There is no study conducted so far on consumer acceptance regarding the new plant cell technology, so it is difficult to predict the consumer perception. It is important to note that the debate could be easily influenced one way or another if the industry does not communicate clearly on the non-GMO approach.

In 2008, Mibelle Biochemistry successfully launched plant stem cell culture extracts into the cosmetics industry. The company launched PhytoCELLTECH Malus domestica, the first commercially available plant cell culture extract whose effect was studied on human skin cells and which claims to be derived from plant stem cells. The ingredient has been used by leading cosmetics brands such as Dior, Lancôme, Guerlain, and La Prairie in their cosmetic formulations. This high value market is expanding fast in the consumers category of average and high incomes. Under the growing demand of the consumers the cosmetic brands are increasing the demand on ingredient providers and tend to develop their own R&D. Unless the stem cells are not genetically modified the consumer demand will probably grow steadily.

Meanwhile, in the last 20 years, numerous studies have measured consumers' perception for genetically modified (GM) food products and subsequently discussed market and policy implications for such products (Chern et al., 2002, Huesing et al., 2016, Huffman, 2003, Li et al., 2002, Lusk et al., 2005, McFadden and Lusk, 2016, Nayga et al., 2006, Wunderlich et al., 2017). CRISPR is another innovative technology that may not result in the permanent introduction of foreign DNA into the host organism for some applications (Huang et al., 2016, Wolter and Puchta, 2017). Given the differences found in other studies (Delwaide et al., 2015; Shew et al., 2017), it is possible that CRISPR will also be valued differently compared to conventional and transgenic GMO foods.

Figure 3.9: Respondents CRISPR and GM-derived plant by country



Source: https://www.sciencedirect.com/science/article/pii/S2211912418300877

In the USA, Canada, Belgium, France, and Australia, 56%, 47%, 46%, 30%, and 51% of respondents indicated they would consume both GM and CRISPR plants, respectively. In all countries except for France, more people said they would consume both GM- and CRISPR-derived plant than those who said they would consume neither product. Moreover, among the participants who would only consume food and plant produced with one biotechnology, respondents were more willing to consume food and plant produced with CRISPR compared to those who said they would eat food and plant produced with GM. At the same time, a Eurobarometer survey from 2019 revealed that concern about genetically-modified ingredients in food or drinks is highest in Lithuania (45%), Bulgaria and Greece (both 42%) and Latvia (41%), while respondents express the lowest levels of concern in Malta (12%) and Finland (13%)[19].

Meanwhile, the EU ruled in July 2018 that CRISPR gene-edited crops of all types and applications must be labelled and regulated in the same manner as transgenic GMOs. If plant cell technology is to improve stem cell using any GM or CRISPR method, then there is a risk of consumer non acceptance especially in view of the fast development of the natural cosmetic trends. If plant cell technology focuses on selection of natural cell before industry production, the technology will not fall under the GM and CRISPR regulation and would be more likely accepted by consumers.

3.3 Cell-based seafood

3.3.1 Definition

Back in 2002, a group of NASA-funded bioengineers succeeded in producing the first cell-based fish fillet[20]. Although the government ultimately decided that there were more efficient ways of feeding its astronauts, Benjaminson’s research instigated the development of the cell-based meat industry. Although the term cellular mariculture does not exist in the literature, the more commonly referred concept of “cell-based seafood” can be defined as the production of seafood products from seafood cell cultures rather than from whole animals[21]. This industry is the latest trend in the emerging biotechnology field of “cellular agriculture” which emerged around 2013[22]. Cell-based products offer an innovative method of reconciling the increasing global demand for protein with the various health, environmental, economic, and ethical issues linked with animal farming industries. Back in 1930, the British Prime Minister Winston Churchill envisioned such a future, in which humans would “escape the absurdity of growing a whole chicken in order to eat the breast or the wing, by growing these parts separately under a suitable medium”[23].

The emergence of cellular mariculture in particular is intimately linked with the shift in global protein consumption from land-animals towards seafood or plant-based products. The new technology provides a promising approach “for alleviating pressure on both wild fisheries and aquaculture systems” which are increasingly unable to meet the growing demand for seafood products.[24]

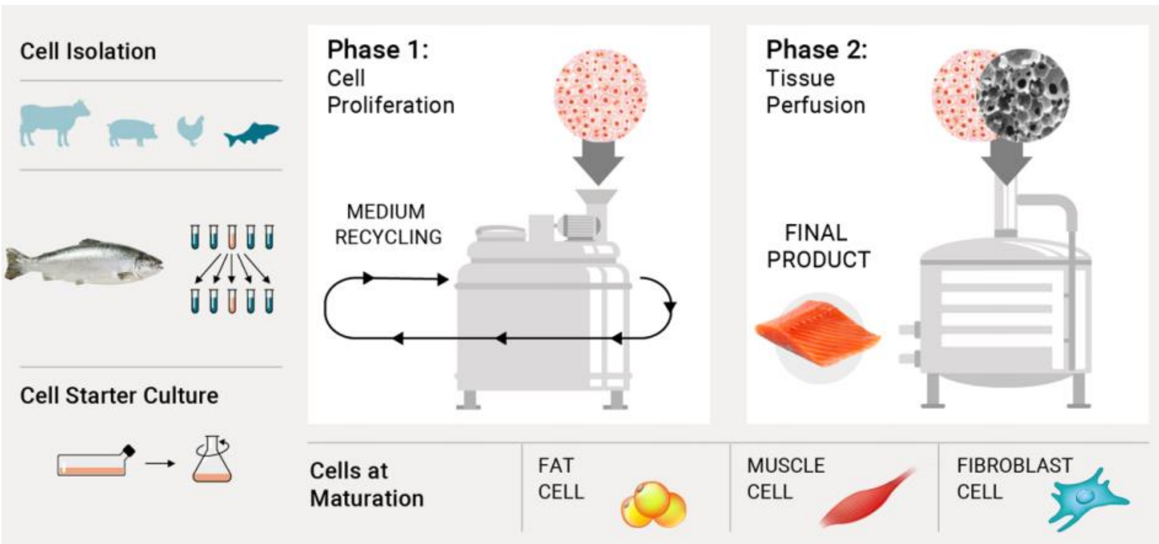
3.3.2 Existing production systems

The fundamental biological requirements of all cell types are largely similar across all species because they share identical development pathways, which were acquired with evolution[25]. These similarities in cell production methods should instigate cross-industry innovation as the knowledge acquired in the cell-based meat industry can transfer into the seafood industry[26]. Even so, modifications to the general process are necessary due to the variety of growth factors and the precise nutriments required by different types of cells.

The production of cell-based seafood can be broken down in three steps[27] :

1. The identification of an appropriate cell line from the tissue of interest: the results yielded by genetically modified fish in close aquaculture systems[28] are laying the groundwork for cell-based fish production research and development. There are two starting points: primary cells or cell lines. Primary cells are biopsied from a mature tissue of the animal. Cell lines are established either by inducing immortality and indefinite proliferation through an induction or by selecting cells with spontaneous mutations resulting in these traits[29]. Each stem cell can produce billions of cells related to the targeted tissue.
2. The creation of a medium which will provide the nutrients necessary for the proliferation and the differentiation of the cells: stem cells are then isolated and grown in a plant-based medium full of nutrients which stews in a bioreactor while the cells grow and multiply[30]. The cells are "tricked" into thinking they are still inside a body and therefore continue doing their work to create tissue. The nutrient solution contains elements required for cellular growth: amino acids, fatty acids, sugars, salts, and vitamins. Nevertheless, there are certain limitations to the number of cells that can be placed in the bioreactor: if the concentration is too high, the cells become stressed and they can turn "suicidal"[31].
3. The design of a bioreactor which will provide a growth-friendly environment for the cells: bioreactors are complex closed-system environments for producing biomass that require constant monitoring, maintenance and optimisation[32]. The solution is agitated in a bioreactor to keep the cells in suspension and avoid clumping. Cells are then inserted into a centrifuge and applied to a collagen scaffold, which facilitates adhesion and muscle tissue growth. Without the scaffold, only unstructured products such as ground meat is possible, which severely limits the potential of the industry. A nutritious liquid called "bio-ink" is then added, which will help 3D print the product into the desired shape[33].

Figure 3.10: Cell-based seafood production



Source: GFI report

3.3.3 Market potential and key actors

3.3.3.1 Trends in the global protein market

According to the Food and Agriculture Organisation (FAO), the market base for alternative proteins is only worth about EUR 2 billion, or around 13% of the global meat market worth approximately EUR 1.57 trillion[34]. Even so, demand shifts are playing a critical role in shaping the future evolution of animal-protein markets[35]. Existing protein sources are unlikely to quickly disappear from global diets, but the protein market is shifting due to four main factors: (i) health considerations, (ii) ethics, (iii) environmental constraints, and (iv) technological innovations. A McKinsey report stated that "changing consumer behaviour and interest in alternative-protein sources – due in part to health and environmental concerns as well as animal welfare – have made way for growth in the alternative proteins market."[36] This echoes a study conducted by the global market intelligence company Mintel, which quantified this growing consumer consciousness and found that "approximately 80% of Millenials in the US ate meat alternatives, compared to 50% of non-millenials"[37]. The aftermath of the COVID-19 crisis may equally accentuate ongoing trends with regards to meat consumption: China, a country which accounts for 33% of all global meat consumption, may be begin to invest in alternative protein sources to avoid future health crises. The state-backed national nutrition association has advocating such change since 2016, pleading for a 50% reduction of meat consumption per year[38]. Despite the ongoing crisis, cell-based industries raised EUR 166 million in the first 3 months of 2020. As Craze explains,

> "the resilience of 'future foods' industry to the spread of the panic in the world economy from coronavirus may be down to the fact that it is billing itself as a solution to the root cause of the virus. Scientists said the virus can be tracked to a traditional Chinese market in Wuhan where animals are slaughtered on-site to ensure freshness of the meat. Phasing out [these practises] has become part of the future food companies' rhetoric"[39].

Nevertheless, projections expect global demand in animal proteins to double by 2050. This suggests that, despite increased awareness about the issues linked with the animal protein industries, consumers are not yet willing to eliminate the consumption of animal meat from their diets. Cellular agriculture perfectly addresses consumers' conundrum for real animal protein without all the negative health, environmental, and ethical externalities associated with the traditional consumption of animal proteins. This explains why the growth of non-traditional proteins (insects, microalgae and cell-grown meat) is expected to grow by nearly 870% before 2025, dwarfing plant-based products (14%) and aquaculture (74%). This niche industry however will only represent 1% of the global protein market by 2025 – a drop in the ocean when compared to plant-based proteins, expected to amass 66% of the market[40].

The seafood industry is also impacted by these market trends. Although 69% of global animal protein consumption came from land-based sources, production levels will eventually peak due to the limited availability of land. The seafood industry will likely be solicited to help meet growing global demand for animal proteins. Moreover, the consumption of fish is increasingly promoted as part of a healthy diet. In addition to having higher protein contents than terrestrial animals, fish have a lower feed conversion rate than land animals[41]. The implications in terms of global food security are important, as more protein can be produced through seafood. The cultivation of seafood, especially through aquaculture, constitutes a viable solution to meet global protein demand "at a fraction of the environmental costs of land-based proteins"[42]. The intensification of aquaculture however poses several challenges similar to the intensification of land animal husbandry: environmental pollution linked with nitrogen and phosphorous waste, risk of pathogen spread from farmed fish to native fish, and unclear ethical implications for the welfare of farmed fish[43]. Cellular mariculture thus presents itself as a solution to the aforementioned issues by developing products which are healthy, environmentally friendly and ethical.

3.3.3.2 Key actors in the cell-based seafood industry

The cell-based seafood industry is embryonic. Nonetheless, the absence of real supply chains, the uncertainties associated with various industrial processes, and persistent knowledge gaps have not deterred opportunistic start-ups from emerging across the world. The cell-based seafood industry is now thriving with new companies eager to adapt their technology on a particular species. Europe has not yet managed to enter this high potential market.

Table 3.2: Existing cell-based seafood companies as of March 2020

Company	Year founded	Location	Product	Capital raised
Wild Type	2016	San Francisco (USA)	Salmon	EUR 11.5 million (Series A)
Finless Foods	2017	Berkely (USA)	Blue fin tuna	EUR 3.2 million (seed funding)
BlueNalu	2017	San Diego (USA)	Mahi Mahi	EUR 22.6 million (Series A)
Seafuture	2017	Calgary (Canada)	Unspecified	Research funded by New Harvest (NGO)
Shiok Meats	2018	Singapore (Singapore)	Shrimp, crab, and lobsters	EUR 4.9 million (seed funding)
Avant Meats	2018	Hong Kong (China)	Fish maw (croaker and sturgeon)	Unspecified seed funding
Cell Ag Tech	2019	Toronto (Canada)	Unspecified	Unspecified

Source: own elaboration

- **Finless Foods**, which was the first company to develop cell-based fish products, is developing a blue fin tuna that can be used in sushi rolls. The first kilogram of product produced by the company in 2017 cost approximately EUR 7930. The company seeks to reduce that price to regular market prices (around EUR 16,8 per kilogram)[44].
- **BlueNalu** is concentrating on high-value fish species that cannot be farmed through aquaculture such as mahi-mahi and Patagonia toothfish. They expect to have fillets packaged up for distribution by 2021, depending on the US Food and Drug Administration (FDA) clearance[45]. BlueNalu is more advanced than its competitors by virtue of being actively involved on different fronts: legislation, research and development, and supply chain. Moreover, they recently unveiled plans to build a 14 000 m^2 facility which could produce 8,2 tonnes of product per year[46]. Finally, new investors which partnered with the company in January 2020 will provide range of expertise and infrastructure support for matters relating to the supply chain, operations, sales, marketing, and distribution[47].
- **Wild Type** produced its first cell-based salmon in June 2019. It was the first company in the industry to complete a Series A funding in 2018. The first salmon roll which was produced in 2019 cost EUR 184 a unit. The product they have developed however can only be served raw for the moment as it cannot withstand temperatures above 100°C[48].
- **Avant Meats** has focused on fish maw (a delicacy in China based on croaker fish) because of its simple composition. This facilitated research and development efforts and enabled the produce to enter the market at a lower price point that other cell-based seafoods[49]. Although their primary target demographic was initially China, the company announced that their next product would be a fish filet intended for both Western and Eastern consumers[50].
- **Shiok Meats** produced the first cell-based crustacean in 2019. In March 2019, the price of a shrimp dumpling was around EUR 400 – in beginning of 2020, the price dropped to around EUR 100 per dumpling[51]. The company believes that Singaporeans will be able to eat their products, and possibly buy their own bioreactors within ten years[52].

- The first Canadian cellular mariculture company, **Seafuture**, has focused on developing a serum-free medium that is specific to fish. Unlike its competitors which are currently using a plant based medium, Seafuture is identifying "the core set of fish proteins necessary for a healthy cell culture"[53].

3.3.3.3 Market potential for cellular mariculture

Comparative advantage over aquaculture and fisheries

Although aquaculture systems are considered as more efficient than natural fishing, the scientific literature has yet to compare the effectiveness of cell-based seafood over aquaculture[54]. Nevertheless, cellular mariculture possesses four characteristics which provide a key comparative advantage over the aquaculture and fishery industries:

1. Cell multiplication: the production of seafood from cell cultures only takes a couple of weeks or months at most, much faster than natural or aquaculture-bred fish. Indeed, by comparison, a genetically modified salmon grows to market size in approximately 18 months, which is already half the time of a normal salmon[55]. According Finless Foods, bioreactor cells double every 24 hours and the scaling is much faster than in aquaculture[56]. This behaviour is linked to the muscle hyperplasia which many fish undergo as juveniles, leading to the rapid increase of the number of muscle cells[57]. Finally, "many fish and crustaceans retain high expressions of the enzyme telomerase in multiple tissue types, which may enable long-term proliferative capacity or facilitate the establishment of immortalised cell lines for research use and, ultimately, commercial cell-based seafood production."[58] The use of this enzyme will ultimately enable cell-based seafood to provide more seafood products than the aquaculture and the fishery industries.

2. Waste reduction and increase in product life: Spoilage is a major concern in the seafood industry because consumers prefer fresh products which have not been frozen[59]. According to Branigan et al, nearly half of the edible US seafood supply was lost from 2009 to 2013 due to consumer food waste, discarding of by-catch, or distribution spoilage[60]. Although the seafood industry already uses low-value by-products to create minced products, one of the main advantages of the entire cell-based industry is that it will drastically reduce waste across the entire food system. Indeed, unlike aquaculture, cell-based fish has the distinct potential to "alter many of the fundamental parameters considered immutable in food cultivation, including the production of inedible excess tissues such as bone, skin, shells, and scales."[61] The technology will encourage the production of high-quality products from the desirable cuts of different species without needing to monetise low-value waste products.[62] This process is also more energy-efficient as all the energy is devoted to the creation of the fish meat (as opposed to real fish who must "divert" energy to keep other organs functioning). Furthermore, by virtue of being produced in aseptic cultivators, the shelf-life of cell-based seafood products may greatly increase without needing to freeze the product. This may reassure many consumers who do not feel comfortable assessing whether seafood is fresh and safe to eat.

3. "Footloose" infrastructure: Unlike the fishing industry, cell-based seafood is not limited by natural resource availability or geographic restrictions. The Global Food Initiative perfectly expands on this point:

   > "These production platforms rely on consistent manufacturing and raw material inputs with robust supply chains and unconstrained supply. [...] Manufacturing facilities for [...] cell-based seafood need not be constructed near sensitive, expensive, and overburdened coastal areas and can instead be situated for most efficient logistical access for raw materials and final product distribution. [...] Cell-based seafood producers are able to generate products in direct response to consumer demand rather than being dictated by availability, in sharp contrast to both wild-caught seafood and farmed seafood."[63]

   Hence, the "footloose" nature of this industry means that it can theoretically emerge anywhere (as attested by the rise of start-ups in Calgary and Toronto). This phenomenon will be accelerated by the high turnover rate of biotechnology companies, with new companies learning from the mistakes made by declining companies[64]. Despite this advantage over water-based aquaculture and fishery industries, cell-based seafood start-ups tend to agglomerate in the same regions. This is due to start-ups' willingness to acquiring knowledge and capital through cooperation, creating a gravitational pull towards regions with already existing resources.[65]

4. Greater variety of products: The infrastructure required for different cell-based seafood species are virtually the same because "fish muscle cells grown in cultivators will exhibit essentially the same metabolic requirements regardless of the species of origin."[66] This eliminates the need to develop infrastructure adapted to the needs of one particular species – the only differences between the production processes of marine species "reside in subtle changes in the formulation and manufacturing process to develop unique flavours and textures mimicking each species."[67] This will enable the cellular mariculture industry to develop on certain exotic species which cannot be efficiently grown through aquaculture.

Indeed, all the species selected by the aforementioned cell-based seafood companies are driven by market size and environmental impact, and not necessarily the suitability of cells for *in vitro* cultivation[68]. The targeted species only represent a small proportion of the multi-billion market across all marine animals. This developing market provides a first-mover advantage for early entrants "because the procedures for producing cell-based seafood products should be relatively transferable across species once optimised."[69] Cell-based seafood is thus appealing from a business perspective because it is more adapted than aquaculture to meet consumers' increasing demand for higher-value species like predatory fish[70] and can therefore make low volume products a possibility[71]. Even in the long run, Rubio et al suggest that cell-based production allows for a greater variety of seafood products. Indeed, "large cell cultivations can result in a large mass of seafood relevant cells that could have implications in processed foods such as surimi. Three-dimensional tissue cultivation on the other hand, can result in structured products more akin to fillets."[72] Cell-based seafood products are therefore more controllable and predictable, enable a faster response to shifting demands, and provide customised end products that precisely meet these demands. More valuable cuts, product formats, and species of seafood products could be produced without generating low-value byproduct waste[73].

Comparative advantage over cell-based meat

By comparing the characteristics of mammalian and fish muscle tissues, Rubio et al suggested that fish tissues are more suited for bioreactor cultivation. The unique characteristics of fish-cell tissues provide acute advantages over those of mammalian cell structures, with energy and cost considerations for the mass production of cell-based seafood. According to the authors:

- fish cells can "endure hypoxic conditions, reducing the need for active oxygenation in oxygen-limited bioreactor environments."[74];
- fish cells can tolerate pH variations, thereby enabling a wider range of pH environments in which the cells can be optimised.
- in contrast with mammalian cell culture (conducted around 37°C), fish cell cultures can be performed at much lower temperatures (4 to 24°C for saltwater and 15-37°C for freshwater species)[75].
- the structure of fish muscle tissues is simpler than that of meat muscle tissues, making it easier to produce (absence of complex swirling of marble and fat which characterises high quality meat).

The cell-based seafood industry might exploit these advantages to become more competitive in a protein market which is slowly transitioning away from land-based animal meat. Nevertheless, the cell-based meat market is more mature than cell-based seafood. This difference is particularly salient when comparing aggregate investments in both industries. As of March 2020, the cell-based meat industry has secured EUR 221 million (mostly dominated by Memphis Meats), in comparison with the EUR 41.6 million obtained by the nascent cellular mariculture industry[76].

3.3.3.4 Challenges

Competition from other industries

All the seafood start-ups argue that "an all of the above solution" is needed to address current global security and climate issues. In other words, aquaculture, fisheries, and cellular mariculture need to work together to bolster innovation – for the time being. Yet market analysts underline that the structure of the seafood industry pay complicate cellular mariculture industry's attempts to obtain support from key stakeholders to influence the entire sector[77]. Indeed, the seafood industry is more disaggregated than the centralised land-based meat industry. While 13 companies control about 15% of the global seafood catch, just four companies control the production of 60% of world's pork and 70% of the world's cattle.[78] The involvement of existing industries in a shift towards cellular seafood is hampered by opaque supply chains caused by the geographical distance between the harvest area and the points of consumption. Moreover, despite claiming that cellular agriculture is not a "zero-sum game", the CEOs of cell-based seafood companies are aware that their disruptive technology will progressively nibble segments of the seafood market from traditional industries and, in so doing, become the sole source of animal protein in the future. Furthermore, the CEO of Finless Food has stressed that the cell-based seafood industry has more to gain from cooperating with established pharmaceutical industries than with aquaculture companies. Indeed, the production method, business models, and technology used by the aquaculture industry have little in common with those of the cell-based seafood industry. Aquaculture, on the other hand, can provide valuable insights with downstream processes such as sales, packaging, distribution, and marketing[79].

The founders of Finless Foods also indicated that it was not a priority for them to compete with other cell-based industries due to their "ideological alignment." Yet the enormous potential of the cellular mariculture market is attracting the more established industries working in cellular agriculture. Plant-based "seafood" industries, such as New Wave Foods, Ocean Hugger Foods, Good Catch Foods and Sophie's Kitchen appeal to the rising vegan market and by virtue of not using fish stem cells to develop their products[80]. Likewise, some companies in the cell-based meat industry, such as Impossible Foods, are looking to capitalise on their acquired infrastructure and knowledge to expand into the seafood industry. The absence of plant-based or cell-based seafood products on the market makes it difficult to forecast projections of consumer demand for these products with a high degree of confidence. Even so, cell-based meat lobbies, in coordination with meat and dairy industries, have begun to partner with cell-based seafood to compete against the rise of plant-based proteins.[81] The Alliance for Meat, Poultry, and Seafood Innovation (AMPS) for instance seeks to prevent plant-based industries from using animal related terms, such as "meat" or "seafood", to depict their products. This issue of labelling, which constitutes on the main legal issues currently facing the industry, is covered below.

Pricing

The main challenge confronting this new industry is its competitiveness, and more specifically its ability to scale-up production whilst reducing costs. The prices of cell-based products are mostly driven by the cost of the medium[82]. Van der Weeke wrote in 2014 that a fully defined serum free and animal origin free medium at a price of EUR 1 000 per m^3 would generate a product costing around EUR 391 per kilogram. The price of cell-based meat would only reach the price of conventional meat once the growth medium costs EUR 1[83]. Thus far, three solutions have been identified to reduce the cost of the growth medium:

i) reduce the cost of inputs (creating a cheaper feed);

ii) increase the efficiency of the cells by selecting those that work best, and thus maximise the number of cells that can be grown per litre of medium;

iii) recycle the growth medium[84].

Long-term returns and capital-intensive industry

A report written by PitchBook Emerging Tech indicated that venture capitalists had invested EUR 6.9 billion into foodtech start-ups in 2018 alone, of which EUR 38 million concerned the cell-based meat industry[85]. Analysts from Barclays investment bank predict that the alternative protein industry could be worth EUR 129 billion by 2029[86]. This data underlines the capital-intensive nature of this nascent industry, with large investments required to finance research and development, as well as infrastructure. More importantly, the very long-run return on these investments may offset certain investors. Indeed, the co-founder of Wild Type estimates that their company is "at least five to ten years from seeing actual cell-based seafood products on the shelves."[87] Nevertheless, the rise of cellular agriculture sparked the interest of venture capitalists, private funded business accelerators (such as IndieBio), and industrial protein corporations (mainly Cargill and Tyson Foods). Their investments seek to strengthen the legitimacy of this nascent and "disruptive" industry. Some of the abovementioned cell-based start-ups are considering joint venture partnerships with large companies to solve some of the technical challenges related to the scaling up of production[88]. Financial partners may therefore strongly influence these start-up's research and development and in the worst cases, constitute a barrier for effective collaboration.

3.3.4 Carbon footprint evaluation

Given that this nascent industry is still in the early stages of research and development, it is difficult to ascertain with precision its carbon footprint. Nevertheless, the technology behind cell-based seafood seems to perfectly address the issue of increasing protein production in accordance with global efforts to reduce greenhouse gas emissions[89]. More specifically, cell-based seafood will use resources more effectively to produce proteins, thereby indirectly contributing to the preservation of the environment and the reduction of the carbon footprint associated with distribution of seafood products.

The environmental externalities of this industry will be much smaller than conventional products in terms of the amount of land and water used throughout the product creation cycle[90]. As explained in the previous section, cellular mariculture will greatly reduce the creation of waste (and thus reduce the need for industries – and their respective energy consumptions – associated with recycling of these by-products). The CEO of BlueNalu expects that cell-based seafood "will have even greater resource efficiency, as we no longer need to grow the heads, tails, bones or scales that make up 40 to 60% of the fish. [Rather we can] focus resources on producing fish filets that are 100% yield."[91] A holistic evaluation of cellular mariculture's carbon footprint, however, would also require more research on the energy consumption and waste production associated with bioreactors. As the WWF points out, "we do not know the magnitude it takes to culture a specific alternative and there is no equivalency for greenhouse gas emissions vs an amount of wild fish captured." [92]

Technological improvements notwithstanding, cell-based seafood will indirectly promote the protection of the environment. Indeed, traditional seafood industries rely on the exploitation of land and oceans to ensure the production of their goods. Thus, cellular mariculture can gradually help to reduce this dependency, thereby reducing the carbon footprint of the seafood industry. Even so, the environmental gains linked with the shift towards cell-based seafood cannot disregard the aforementioned carbon footprint of the bioreactor technology.

Finally, the "footloose" nature of the cellular mariculture industry can offset the carbon footprint of traditional industries in terms of transportation and distribution. Indeed, products will no longer need to be frozen and shipped to markets of interest. As the technology continues to mature and become less costly, cell-based factories will be able to emerge anywhere to meet local seafood demand. Such a decentralised economic model will reduce the carbon footprint associated with the distribution of goods to different markets. A Japanese university even started to experiment with "home-grown cell-food" which would enable consumers to directly grow their own produce once equipped with a bioreactor.[93]

3.3.5 Legal and regulatory issues

3.3.5.1 Regulatory uncertainties

The development of cellular agriculture as a whole has raised various questions about their regulatory status, safety and labelling issues. In the US, the interest of regulators in cellular agriculture has steadily increased over the past few years. Although cell-based seafood has been under the jurisdiction of the US Food and Drug Administration (FDA) since March 2020, cell-based seafood production remains unregulated. Moreover, there is no clear timeline about when regulators will approve cellular agriculture products for sale. As a comparison, it took nearly a decade for the US Department of Agriculture, in November 2018, to announce that cell-based meat would be regulated under the same laws that govern regular meat[94]. FDA approval for cell-based seafood products, however, should be faster than with genetically modified aquaculture. As the CEO of BlueNalu explained, "the approval will be about whether this is safe, clean and the manufacturing processes are reliable and accountable"[95]. Leading American companies in this industry formed the Alliance for Meat, Poultry and Seafood Innovation (AMPS Innovation) to "create a pathway for cultured meat and seafood"[96]. Eager to maintain their global leadership position in this nascent industry, US companies are advocating for "swift regulatory processes" which will give them a competitive edge over their international competition[97].

Although no country has yet provided clear regulatory guidelines for cell-based animal protein products, the lobbying efforts of the American industry are more pronounced than in the EU.

In Europe, only the European Food Safety Authority's current legal framework could apply to the European cell-based seafood industry. These products would namely fall under the novel food category, in which companies have 18 months to prove that their products are safe to consume. Cell-based seafood would equally require a pre-market authorisation as well as approval by the European Food Safety Authority (EFSA). As Merten-Lentz explains, "it is not clear what type of nutritional and toxicological evidence EFSA would require to approve cultured meat"[98]. It is equally likely that any EU guideline on cell-based seafood products would subsequently require inspections and enforcements by Member States – thereby lengthening the regulatory hurdles facing the nascent industry. In contrast with their American competition, the absence of any trade association or lobbying group further hinders cell-based seafood companies from reaching out to lawmakers and the public.

3.3.5.2 Labelling

Labelling constitutes one of the main legal hurdles facing all of the cell-based industries. The EU's Novel Foods Regulation stipulates that "there can be requirements regarding labelling, in order to fully inform the consumer, for instance by describing the food or its composition"[99]. The EU Regulation on Food Information to Consumers (FIC) would then apply to cell-based seafood once it is authorised. This would mandate industry to label the denomination of a food – an issue which remains to be resolved for cell-based animal products as a whole[100]. Moreover, these products have no legal name due to the fact that they are not on the market. Cell-based meat products fail to completely comply with the current European definition of "meat". According to EU and US regulations, meat products must be derived from skeletal muscles and naturally adherent tissues. As Merten-Lentz explains, "probably only the submission of a novel food application to EFSA could start a process towards a regulatory framework"[101].

In the same way that the US Cattlemen's Association is lobbying for cell-based beef to not be called "beef", one might expect the seafood industry to lobby against cell-based seafood being called "seafood." Various terms are being used to describe the industry: lab-grown seafood, cultured seafood, clean seafood, cell-based seafood, slaughter-free seafood. BlueNalu applied to trademark the term "cellular aquaculture" but it is unlikely to be approved. Finless Foods prefers the term "clean seafood" but officially uses the FDA term of "cell-based fish"[102]. Cell-based meat has thus become the industry-preferred term for products made from animal cell culture. Indeed, this neutral term is more conducive to conversations with the conventional meat industry and with regulatory agencies.

Another legal conflict is developing with the plant-based protein industry. As explained previously, the meat, dairy, and cell-based meat industries will be looking to prevent the plant-based industry from labelling their products using animal terminology such as "meat" or "seafood". Indeed, the term plant-based seafood may be misleading for consumers in the sense that no parts of an animal were used in the production.

3.3.6 Consumer acceptance

3.3.6.1 The opportunities of cellular mariculture

The public relation issues facing cellular mariculture resemble those which aquaculture continues to face. In their article on European aquaculture, Kaiser and Stead pointed out how:

> "the goals to which aquaculture can make a substantive contribution in the long run are too important to be left to specialists from science and industry alone. An important prerequisite may be a change in attitude in the sector itself. It is no longer appropriate to try and avoid public controversies or to steer or even manipulate the public image, but rather invite broad sections of society to become part of the deliberations that will form future policies"[103].

Concerns surrounding the future development of the aquaculture industry are intimately related to the general issues of sustainability and food safety, which require ethical standards, clear guidelines, and strong core values. Gasteratos argues that cell-based agriculture can provide various long- and short-term benefits with respect to human health, environmental protection, social justice, economic development, and scientific progress. All of the following points[104] can be used in public relation campaigns to harness consumer acceptance:

- **Health Benefits**
  - Eliminate pathogen contamination or food-related illnesses (bacterial contamination would be better controlled)[105].
  - Increase food security with a new, stable, and unlimited source of protein.
  - Provide higher quality proteins (without any hormones, plastic, mercury or other dangerous elements).
  - Ensure greater product consistency.
  - Increase shelf-life of products and reduce the risk of spoilage.
- **Environment**
  - Reduce the use of land for seafood production (and therefore pollution associated with its industries).
  - Reduce water consumption related to the production of seafood.
  - Reduce the creation of waste associated with fishing and aquaculture (fish blood, by-products, excrements, etc). This will indirectly help to reduce plastic contamination as 46% of plastic contamination originates from the fishing industry.
  - Reduce the need to fish natural species and potentially make the fisheries industry less competitive (and thus reduce the overexploitation of depleted stocks and fishing by-catches such as turtles, dolphins, etc). It is important to point out however that aquaculture made the same claims decades ago. Farm-raised salmon did not reduce pressure on wild salmon stocks and simply ended up increasing overall salmon consumption[106].
- **Social justice**
  - Tackle slave labour in fishing industry and poor factory working conditions of certain employees.
  - Reduce post-traumatic stress disorders associated with the slaughter of animals.
  - Increase taxpayer savings by reducing the number of product recalls link with contaminations.
  - Reduce seafood product fraud with stricter appellation controls.

    - Provide more affordable seafood proteins (prices will continue to drop as the technology becomes more mature).
    - Provide ethical protein that no longer requires the killing animals.

- **Economic development**
    - Decentralise seafood production centres: the "footloose" nature of the industry allows geographically landlocked countries and markets to have access to seafood proteins. This reduces the cost and carbon footprint associated with the distribution of products from coastal areas.
    - Enhanced resilience of seafood proteins vis-à-vis natural disasters.
    - Enhanced financial resilience to economic crises.
    - Adapt to growing consumer demand for ethical products (consumers are more willing to pay a premium for high value animal-based products).
    - Increase taxpayer savings by reducing government subsidies or bailouts for dwindling industries.
    - Instigate change in the animal by-product market (use cell-grown technology to grow horns, skin, bones, etc).
    - Promote high-end skilled labour force and provide new job opportunities.

3.3.6.2 Challenges

The first obstacle for consumer acceptance of this new technology is taste. The "yuck" factor is quite pronounced and the industry will need to convince consumers that their product tastes just as good as natural seafood. This issue blends perfectly with the "unnatural" image which the product presents. Consumers are likely to associate bioreactor-grown proteins with genetically-modified organisms (despite it absolutely not being the case) and meat-related preservatives added by agribusiness. Cell-based seafood will also raise safety suspicions: food traceability and labelling will be crucial in swaying consumers in the right direction. Most of the identified issues are linked with operating in a low information environment. This new industry will need to promote transparency and convince consumers that their products are not another ploy carried out by transnational agribusiness corporations in alliance with Silicon Valley start-ups. The dangers of fake news will need to be taken into account as competition may attempt to lobby against this disruptive industry.

3.3.7 Perspectives for the EU

Despite its promising trends, the cell-based seafood industry is confronted to four major blocking factors: knowledge gaps, financial needs, inexistent institutional support, and insufficient trans-sectoral coordination.

3.3.7.1 Knowledge gaps

The growth of marine animal tissues *in vitro* remains overlooked in the scientific world. The field lacks established protocols and solid scientific data, which explains why start-ups require significant up-front investments in basic research and development. Indeed, cells from fish and other marine animals are not usually cultured in research laboratories. As such, sophisticated genome annotations for seafood-relevant species are limited compared to common laboratory species (rat, mouse, fly) and common livestock species (cow, pig, chicken)[107]. There is a crucial need to "develop the tools and resources that are already well established for mammalian cell culture – such as cell lines, robust protocols, commercial reagents, transformation vectors and reporters, full genomes sequences and biomolecular datasets for cells derived from marine species."[108] The majority of research on marine animal cell lines tends to focus on areas related to genotoxicology because of its implications for the aquaculture industry.[109] However, existing experimentations on harvested native muscle tissues from marine animals provide interesting insights into the potential of cell-based mariculture.

Obtaining cell lines thus constitutes the primary barrier for both academia and commercial activities. This obstacle points towards the need for a public repository of validated cell lines for all marine animal species. It can prove difficult however to obtain fresh tissue from exotic or deep-sea species, and "near impossible to obtain embryonic tissue – which is often desirable for high proliferative capacity and ability to generate all meat-relevant cells – for species that are not bred in captivity."[110] Obtaining such tissues may therefore require developing partnerships with marine research institutions, aquariums, aquaculture facilities, and industrial fishing groups. More specifically, the aquaculture industry has acquired extensive experience in "handling aquatic species at all stages of maturity including embryos and it routinely used fish cell culture for advanced breeding and to monitor stocks for pathogens"[111].

While the EU's Horizon 2020 funded various research projects focused on toxicity, the monitoring of stocks, the mapping of actors, cell-based seafood was not considered.[112] The European Collection of Authenticated Cell Cultures (ECACC) is one of the world leading cell-line depositories but fails to provide research support for industries outside of traditional fishing and aquaculture. Moreover, the Horizon 2020 Work Programme 2018-2020 on "Food Security, Sustainable Agriculture and Forestry, Marine, Maritime and Inland Water Research and the Bioeconomy" did not include any objectives related to cell-based protein research.[113]

Limited access to relevant cell lines hampers the development of this new industry, with each company having to invest in the creation of their own cell lines. The American company Kerafast has taken this gap into account and is currently developing the world's first online platform of industry-relevant protein cell-lines. [114] Seafood cell-lines will be made available to encourage the development of sustainable products. The EU could equally work in this direction by supporting the creation of a seafood relevant cell-line database. Such an endeavour should be founded upon transdisciplinary expertise (drawing from fields of regenerative medicine and bioengineering) and acquired knowledge should not be protected by IP laws at first to encourage further research.

3.3.7.2 Financial needs (research and development)

It has been repeatedly underlined in this report that academic research in the cell-based industry is capital intensive. Most academic research in the area has been funded by NGOS such as the Good Food Institute and New Harvest. This can be explained by the fact that available public funding requires companies to publish research findings. Such a requirement has deterred many start-ups from applying and thus getting access to research and development funds[115]. Furthermore, the private sector is dominating the investment landscape of the cell-based industry.[116] Companies must heavily invest in research and development in order to acquire sufficient knowledge on the different steps of cellular growth (genome sequencing, characterisation of cell morphology, etc). This has created a vacuum for private investors, eager to establish an initial foothold in this emerging industry. The US is currently dominating the industry, propelled by its strong private investment attractiveness. Other countries however, have come to realise the importance of this industry for their food security objectives. India, Australia, Israel, China, Singapore, and Japan have recently invested in the development of cell-based meat and seafood in their respective countries[117].

The EU possesses a variety of funding tools, programmes, and platforms designed to foster innovation in the field of blue biotechnologies, notably under the 2nd pillar of the Horizon Europe programme and the "Farm to fork" strategy[118]. Likewise, an interim report conducted by the Mission Board on Health Oceans, Seas, Coastal and Inland Waters also identified "decreasing the environmental footprint of fisheries and aquaculture" as one of the key objectives of the EU[119]. These tools however are not oriented towards the cell-based seafood industry. Indeed, the industry fails to appear in the various EU strategic documents and reports. A 2017 report conducted by DG Research and Innovation on future food systems did not mention anything about cell-grown products (vegetal or animal)[120]. The potential of cell-based seafood was equally absent from a 2017 report entitled "Food from the oceans" written by a high-level group of scientific advisors to EU[121]. Finally, none of the Horizon 2020 FET biotechnology projects are related to cell-grown products[122]. The issue of food security and new sources of proteins has nonetheless appeared in various EU projects. The EU recently funded the "Smart Protein" project, which seeks to develop a range of nutritious alternative protein products. The project, which intends to only produce plant-based products, fails to include cell-based meat or seafood products[123]. The EU could therefore more explicitly address the potential of cellular agriculture and ensure that future funding be directly attributed to cell-based meat or seafood projects.

3.3.7.3 Institutional support and regulatory guidance

Financial support notwithstanding, the EU could develop a regulatory framework which might act as a catalyst for this new industry. In the case of aquaculture, Kaiser and Stead underlined the importance of combining the Integrated Coastal Zone Management strategy, the Strategic Guidelines for the Sustainable Development of EU Aquaculture, and the EU Directive on Maritime Spatial Planning, and stressed that "given that uncertainty can arise from poor and fragmented information, it is important that a holistic approach to management is adopted, with a multidisciplinary framework encompassing issues on the environment, technology, scientific and non-scientific research, sociology, culture, economics, law, politics"[124]. As explained above, no country has yet developed a sufficient regulatory framework to address this new industry. Food safety regulators in Singapore are currently developing a comprehensive framework to regulate cell-based meat for human consumption[125]. The AMPS Innovation is effectively urging for rapid regulatory oversight in the US. EU regulators have not yet taken this field into account but the EFSA and FIC will undoubtedly play a key role in establishing industry ESG standards. These processes will ensure that the European industry grow in the most sustainable manner and reassure consumers with regards to the safety of the products being sold.

3.3.7.4 Trans-sectoral coordination

Like all other industries, the stability and growth of cellular mariculture will ultimately depend on its ability to work and learn from other sectors. Indeed, the development of these technologies, which will inevitably be produced and supplied by the private sector, requires the coordination of activities between different stakeholders: companies, investors, governments, trade associations, and research institutions. The technology used in cellular agriculture was already pioneered in other industries working on the cultivation of cells (pharmaceutics, regenerative industry, etc). Hence, the maturation of the cell-based seafood industry would increase if trans-industry mechanisms were put in place to share critical technological knowledge and experiences. The EU might want to position itself as a trans-sectoral coordinator, encouraging different actors to share knowledge between each other. The global nature of the seafood industry requires such a de-centralised but coordinated governance approach. Moreover, the fragile economic ecosystem has pushed many biotechnology companies to solve issues independently, as opposed to confronting issues in a more collective manner. Enhancing coordination efforts would not only increase the effectiveness of resource allocation (by avoiding duplication of research and investments) but would also accelerate the development of the technology and thus reduce the cost of the product for consumers.

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