IMPAQT

Intelligent Management System for Integrated Multi-trophic Aquaculture

HANDBOOK

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 774109

The IMPAQT Handbook is part of the activities included in WP6 Dissemination, communication, exploitation and training activities of the IMPAQT Project — Intelligent management system for Integrated Multi-Trophic Aquaculture. The publication presents the results of the project, developed between May 2018 and August 2021. IMPAQT has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 774109.

AUGUST 2021 - 1 st Edition

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WELCOME TO IMPAQT

The IMPAQT project is a Horizon 2020 research and innovation action to promote and support the eco-intensification of aquaculture production systems. It started in 2018 bringing together 21 partners from 12 countries, with the aim to develop and validate in various operational environments, a multi-sensing and multi-functional management platform for sustainable IMTA production, with a view to validate the concept of IMTA as a viable aquaculture approach for future European aquaculture. In this handbook, we report the results of all this work in a detailed, organised and accessible way for all people —from researchers to policymakers and industry stakeholders— engaged in the development of sustainable aquaculture.

Looking back, it has been an intense period of collaborative work for the diversity of partners. We have built a team who displayed motivation and dedication throughout to achieve the project goals and overcome the challenges presented — and the additional constraints that covid-19 added to IMPAQT. Despite the mountain of emails and the hours-and-hours of online meetings, it has all been worth it to see the ambitious plans from the IMPAQT proposal come to fruition.

It was interesting watching the biology people had to learn to converse with the technology people to communicate their needs and requirements to each other in order to help design the framework for the IMPAQT platform, the communications, the model, and the management system. The six pilot sites were pivotal in the development, deployment, testing and validation of the systems, as well as conducting the IMTA trails, producing the product, and gathering the required information to support the assessments and validations. The innovative prototypes developed in the project will be useful tools for future precision aquaculture. The project successfully demonstrating the sustainability and circularity of IMTA practises, with the results and findings communicated to the stakeholder eco-system through the various communication channels, dissemination and training activities. It has been a

pleasure to see the support for young researchers, working with experienced individuals, within the project, as well as the good balance of women and men working in the project. I look forward to see the work continue, and the outputs of the project progress the eco-intensification of aquaculture with more environmentally friendly and efficient production systems.

Concluding, I would like to thank you for your interest in our project, and your support and engagement throughout the period. I would also like to thank all those who worked on the project for their efforts and dedication over the 40 months – it is much appreciated.

Keep an eye on the IMPAQT website and social media as more results and publications from the project become available.

Frank Kane
IMPAQT Project Coordinator

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1 NO GREEN WITHOUT THE BLUE

Aquaculture is an attractive and essential component of rural and coastal livelihoods providing employment and facilitating a sustainable economy through business development and diversification.

The opportunities for growth of the aquaculture industry in the EU remain substantial given the potential for innovation in culture techniques, technological advances, species and product diversification. The aquaculture sector has a particular role in contributing to the transition to sustainable food systems and the development of the bioeconomy and circular economy. It creates jobs and economic development opportunities. It can contribute positively to urgent current issues such as decarbonising the economy, fighting climate change and mitigating its impact, reducing pollution, preserving ecosystems and reaching more circular management of resources.

The importance and impact of aquaculture are also well described in the recent strategic guidelines for a more sustainable and competitive EU aquaculture [1], with sustainable aquaculture in the EU as an important sector for delivering public goods. The objective is to create the path for EU aquaculture to become a resilient, competitive, sustainable, and high-quality sector. To achieve this objective, the support of all relevant actors is vital.

A strategic and long-term approach for the sustainable growth of EU aquaculture is therefore more relevant today than ever. Since its inception, the actions of the IMPAQT project have been directed towards this, with a focus on transforming traditional monoculture practices into a more circular and sustainable aquaculture model: The Integrated Multi-Trophic Aquaculture or IMTA. However, promoting a more sustainable sector cannot be separated from efficiency and productivity. For this reason, at the IMPAQT project, sustainability and circularity are framed in developing precision aquaculture tools to improve the future of this essential sector.

2 TOWARDS A SUSTAINABLE, RESILIENT AND COMPETITIVE SECTOR

2.1. State of the art

Aquaculture is the fastest growing animal food producing sector in the world and increasingly is an important contributor to economic growth and global food supply. The sector has previously increased by 76% since 2004, 4 times more since 1990 [2] reaching an all-time production high of 90.4 million tonnes (live weight equivalent) in 2012 (US$144.4 billion) [3]. Furthermore, global aquaculture operations in 2014 supplied over one half of the fish and shellfish that was directly consumed by humans [4].

In contrast, the EU aquaculture has seen little or no volume growth (estimated at 0.5%) over the last decade, this compares poorly with the estimated global aquaculture growth of approximately 7% over the same period [5]. EU contribution to world aquaculture production represented only 1.7% in volume and 3.2% in value of global production in 2014. Although Europe represents the largest market for fish in the world with steadily increased seafood consumption, the EU's self-sufficiency is currently estimated to around 47.5% and is highly dependent on imported seafood [2]. The fact that the production value increased between 2008 and 2014 can be interpreted as an indication that the industry has increased the unit value and quality of its product.

EU legislation includes environmental respect and management [6], health and welfare of livestock, feed composition, food safety and consumer interests, which the EU aquaculture industry has to comply with. In addition, there are several policies that influence EU aquaculture, more broadly under the EU 2020 Strategy for smart, sustainable and inclusive growth (e.g., sustainable and best use of resources, Blue Growth, Circular Economy, Bioeconomy strategy and action plan). Although these policies pose cost implications for producers, with consumers becoming more interested in quality and sustainability there is the potential to turn the application of these policies into a competitive advantage.

> High quality, sustainability and consumer protection standards can be a competitive advantage for the EU aquaculture sector and accelerate its growth

The significant challenges to EU aquaculture growth can be summarised as the capability to adapt to market changes and competition and the need for technical improvements (maintaining health/welfare of livestock, integration of activity with the environment, optimising use of resources and spatial planning) [5]. To that respect, the problem statement for the IMPAQT project is formulated as: maximise the growth rate whilst minimising the production costs through the optimisation of production systems, while ensuring seafood product quality, optimal resource use and minimising environmental impact.

Current practices in aquaculture production, mainly aquatic monoculture or cultivation of species from the same trophic level, do not meet the market pressure and the EU requirements for cost-effectiveness, optimal resource use and environmental management. The heart of IMPAQT, the Integrated Multi-Trophic Aquaculture (IMTA) concept, offers the most attractive approach [6]. IMTA involves cultivating various species in a way that allows the uneaten food and wastes (e.g., nitrogen, phosphorus, etc.) associated with some species to be recaptured and converted into inputs (fertilisers, food and energy) for the growth of other species. "Multi-trophic" refers to incorporating species from different trophic or nutritional levels into the same system. "Integrated" refers to the more efficient cultivation of the various species in the proximity of each other, connected by nutrient and energy transfer through water.

IMTA shows multiple benefits aligned with the challenges to address in the aquaculture sector identified by the European Commission in the 2021 Strategic guidelines for a more sustainable and competitive EU aquaculture for 2021 to 2030 [1]. Nonetheless, IMTA systems also face some challenges even in countries where it has been practised for decades, such as Asian countries. Moreover, as yet, IMTA is not widely adopted at a commercial level in Europe and understanding the validity of this approach, the interaction of the trophic levels and, the management of IMTA systems is essential for the sector. IMPAQT, as well as other H2020 projects working in eco-intensification of aquaculture, and with the support of the European Commission and stakeholders, can be considered as necessary steps to progress IMTA.

LEARN MORE!

o A short article about IMTA's benefits and challenges can be read here.

2.2. Integrated Multi-Trophic Aquaculture (IMTA) concept

> IMTA is a concept, not a formula.
> (Thierry Chopin, 2021)

IMTA is a fresh concept in aquaculture where multiple species, from different levels on the food chain, are farmed on the same site, or within the vicinity of each other, in an integrated and complementary way.

IMTA farming combines species that need supplemental feed, such as fish, with "extractive" species. Extractive species use organic and inorganic materials and by-products from the other species for their own growth. Extractive species can be primary producers (algae and plant species that transform inorganic nutrients into organic biomass) or secondary producers (using organic material from the water column or the seabed as food). The secondary producers can be filter feeders (generally shellfish that sieve organic particles such as algae from the water column) or deposit feeders (organisms such as worms, sea urchins, sea cucumbers, etc. feed on organic material on or within the sediment). Extractive species act as living filters. Their natural ability to recycle the nutrients (or waste) present in and around fish farms can help producers improve the environmental performance of their sites. In addition, the extractive species have commercial value as marketable products, providing extra economic benefits.

The IMTA concept is sometimes used strictly: having the different trophic levels integrated into one farm or business at the same site. However, as identified in other projects (notably the EU project IDREEM), co-locating different trophic levels in very close proximity may not always result in optimal use of resources and increased productivity. Trophic links in aquatic ecosystems can extend over a large spatial scale. Depending on the local hydrodynamics and the biogeochemical processes involved, spatial separation may even be beneficial. For example, as the transformation from fish waste into nutrients takes time and if there is a residual current, the best location for a seaweed farm to optimally utilise these nutrients may not be very close to the fish farm but further downstream.

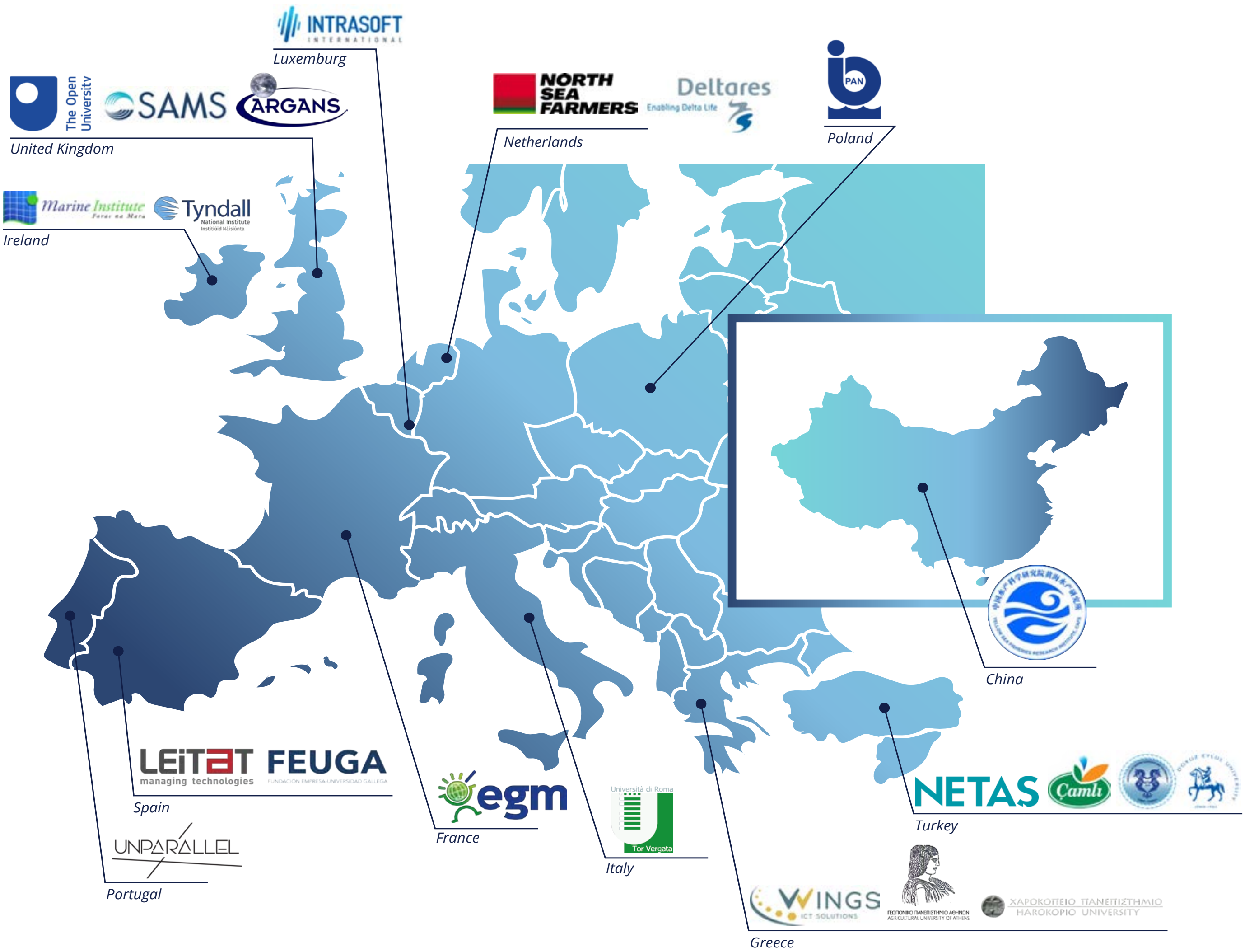
Conversely, cultivation of different species at the same site may occur without a direct trophic link between the crops, due to the economic benefit of co-location and being able to use a production site in all seasons and for multiple products at the same site. This type of co-location is perhaps a bit beyond the strict definition of IMTA but still highly relevant for developing business cases for new forms of aquaculture. As aquaculture heads towards more organised spatial planning, IMTA will become a reality to optimise limited space.

The overall IMTA benefits are environmental sustainability through bioremediation, economic stability through product diversification and risk reduction, spatial optimisation by increasing productivity of a site, and social acceptability through better management practices. IMTA also shows some challenges since it has been only tested on a small scale in Europe. Even in countries where IMTA is a well-known practice (mainly in Asia), the management of large-scale IMTA areas remains challenging [7]. The main cause is the limited knowledge of how the separate components of an IMTA ecosystem interact and function as a whole and their impact on the environment and the broader community where it is practised. Nevertheless, implementing and applying new/emerging technologies and innovations in monitoring and management systems can provide guidance to adaptively manage IMTA systems to ensure ongoing sustainability.

> IMTA enhanced by new/emerging management technologies can enable economically, environmentally and socially sustainable aquaculture development and generate enhanced public and investor confidence in EU aquaculture

2.3. IMPAQT project: Intelligent Management System for Integrated Multi-Trophic Aquaculture

In light of the aspects detailed above, IMPAQT — Intelligent management system for Integrated Multi-Trophic Aquaculture brings together 21 partners including 14 academic/research organisation, 4 SMEs, and 3 large industries, all leaders in their respective fields/business and with access to 6 pilot sites, to achieve the overall objective below.



LEARN MORE!

Take a look to the project video and brochure to find out about IMPAQT work.

o Project video
o Brochure

The overall objective of IMPAQT is to develop and validate in-situ a multi-purpose (inland, coastal and offshore), multi-sensing (heterogeneous sensors and new/emerging technologies) and multi-functional (advanced monitoring, modelling, data analytics and decision making) management platform for sustainable IMTA production. The high-level ambition is to drive a paradigm shift in the European industry and its acceptance of IMTA as a viable approach, by paving the way to both a more environmentally friendly and more efficient/higher yielding sector.

IMPAQT adopts a holistic approach addressing the complete system view. This comprises three main interacting subsystems: the autonomous data acquisition and communication system, the advanced IMTA model and the integrated management system (Figure 01).

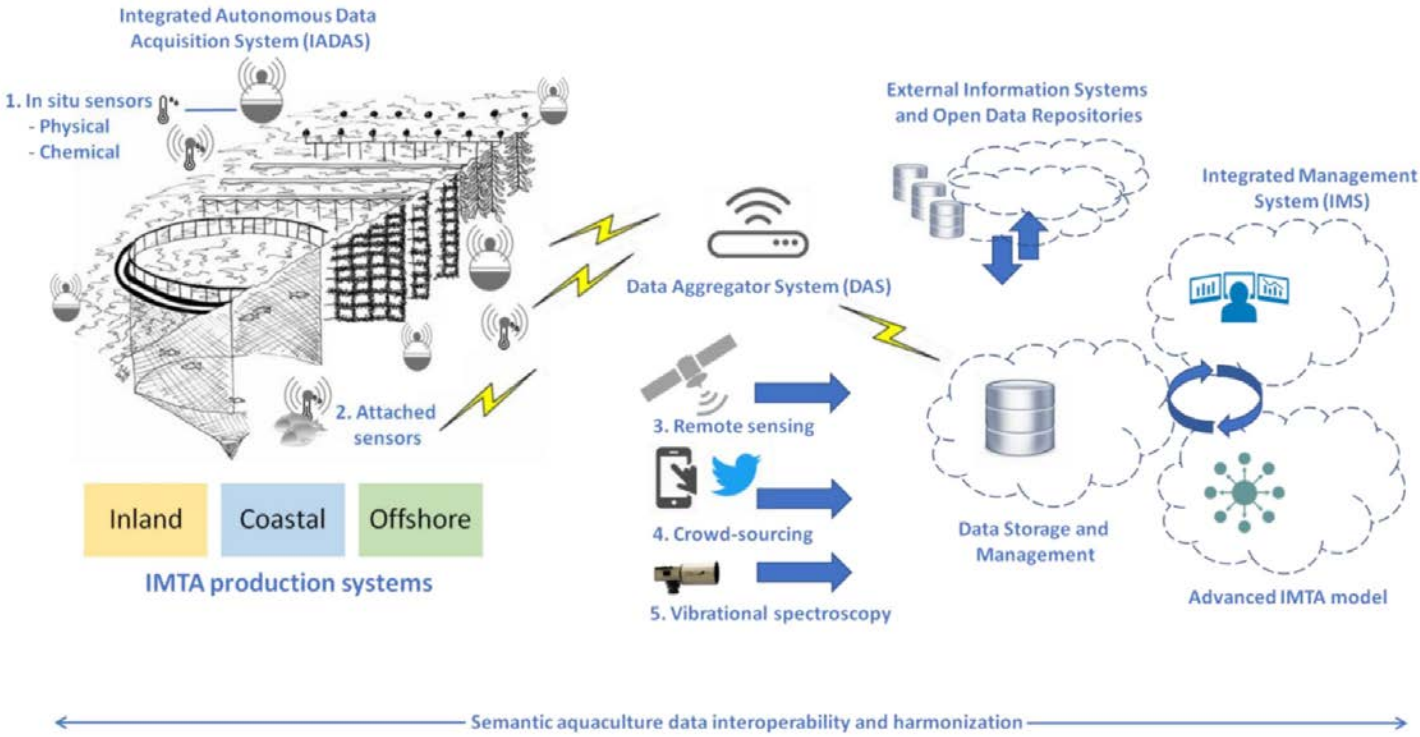


Figure 01. High level overview of IMPAQT platform

The autonomous data acquisition and communication system comprises five categories of data sources, namely:

- *chemical and physical sensors for in situ determination of water quality,*
- *attached in species sensors for measuring vital parameters of animals,*
- *remote sensing algorithms and products derived from satellite observation for monitoring water quality, growing conditions and environmental impact,*
- *crowd-sourcing via a smart application for in-situ observations linked to water quality and farming environmental conditions and threats,*
- *vibrational spectroscopy (FTIR) for in vitro species characterisation (e.g. cortisol, etc.).*

In situ chemical and physical sensors are integrated in a modular autonomous smart sensing unit, entitled as Integrated Autonomous Data Acquisition System (IADAS), incorporating the necessary technologies for long term, autonomous deployment of sensors in operational environment.

The Data Aggregator System (DAS) is an edge Gateway in charge of interfacing the sensors nodes (IADAS and attached in species sensors) deployed over the IMTA fishery sites with the cloud, aggregating these datasets and providing validated datasets (information) to the Data Storage and Management infrastructure, using short/ long-range low power communication capabilities.

The Data Storage and Management receives real time data and/or information from the DAS module, but also crowd sourced data via the smart application, remote sensing and satellite data, as well as spectroscopy data, through appropriate Application Programming Interfaces (APIs) in an automated fashion. It can also connect to external Information Systems and Open Data sources if corresponding APIs exist.

IMPAQT develops two sets of tools that work on different scales and are used by stakeholders for different purposes. First, the advanced IMTA model essentially yields spatially explicit information on how the different farm components interact with the environment on the scale of an ecosystem. Model scenarios can be used for planning decisions by both farmers and regulators. Second, a powerful Integrated Management System (IMS) operating at the scale of an IMTA farm, online integrated with sensors and comprising novel technologies to enable improved operational decisions for animal welfare, production optimization, environmental protection, food quality and consequently sustainable productivity.

The Data storage and management infrastructure takes care of handling data for both IMTA model and operational IMS. Furthermore, the scenario studies performed with the IMTA model can serve as input to set up the IMS for specific sites. Finally, IMPAQT relies on an Open Systems approach and an "everything-as-a-service" thinking, while Semantic Aquaculture Data Interoperability and Harmonization enables data federation and knowledge exchange between different systems.

IMPAQT tools benefits aquaculture stakeholders in different ways. The two sets of tools developed in IMPAQT enable a more efficient IMTA practice. Firstly, the advanced IMTA model allows selecting the optimal site and spatial configuration for various aquaculture components at the planning phase. Both benefits to be gained from combining trophic levels and marginal benefits will be identified if present. If risks emanate from co-location (e.g., contamination of shellfish or seaweed crops with pollutants from fish farms, such as remnants of medication), it can be quantified. Moreover, impacts and interactions are assessed at an ecosystem scale rather than just at the scale of individual farms. Secondly, at the operational phase, the IMS enables assessing the current status and responding timely to production and environmental challenges at the scale of an IMTA farm.

<table>
<tr><th>STAKEHOLDERS</th><th>ADVANCED IMTA MODEL</th><th>INTEGRATED MANAGEMENT SYSTEM</th></tr>
<tr><td>AQUACULTURE PRODUCERS (e.g. marine fish, freshwater fish, shellfish, algae and other species)</td><td>~ To select optimal sites and optimal site configurations, both in terms of maximizing yields and in terms of minimizing environmental impacts.
~ To assess effects of autonomous changes in the environment and the effects of policy measures on future yields.
~ To support obtaining permits.</td><td>~ To assess the actual status and behaviour of the farm in relation to a pre-determined development/production scenario.
~ To trigger alerts (e.g. disease occurrence, water quality deterioration, etc.) and propose management actions (e.g. when to harvest, levels of feeding, etc.) to maintain or enhance the farm's performance.</td></tr>
<tr><td>REGULATORS (authorities)</td><td colspan="2">~ To assess the environmental impact of IMTA set-ups and aid marine spatial planning decisions.
~ To assist decisions on permits.</td></tr>
<tr><td>AQUACULTURE TECHNOLOGY AND EQUIPMENT PROVIDERS</td><td colspan="2">~ To enable novel applications derived by bundling together IMPAQT tools with services from different technology providers and stakeholders due to Open Systems approach and "everything-as-a-service" thinking of IMPAQT platform</td></tr>
<tr><td>CONSUMERS AND CITIZENS</td><td colspan="2">~ To provide sustainably-produced (and eco-friendly), high quality and healthy aquatic food.</td></tr>
</table>

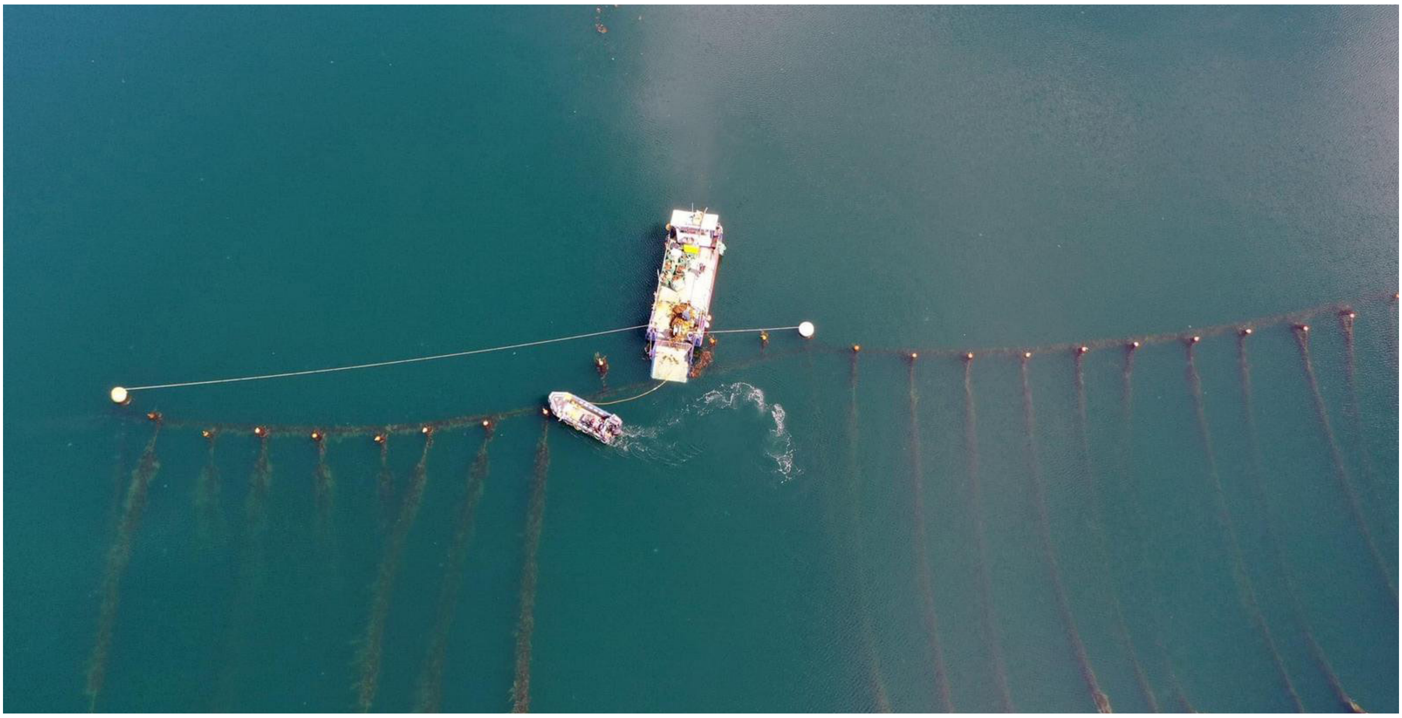
Figure 02. IMPAQT tools and benefits to aquaculture stakeholders

Each conceptual piece of the IMPAQT system initially proposed could not have been developed and tested without the 6 pilot sites. To understand this development process and contextualize the multiple results of IMPAQT, the following section details the characteristics of each pilot site.

3. IMPAQT PILOT SITES

3.1. Pilot in UK (by SAMS)

The Scottish pilot 'Port-a-Bhuiltin' (PaB) is a coastal aquaculture site located 0.25 km off the shore on the West coast of Scotland. The site has been operated by the Scottish Association for Marine Science (SAMS) as experimental seaweed cultivation site since 2014.



During the IMPAQT lifetime, the UK site was expecting to show the benefits of co-locating both seaweeds and shellfish and validate such a model. This would provide confidence to both the regulator, in terms of potential environmental impacts, both negative and positive, and more consumer confidence in this form of IMTA.

The use of the IMPAQT system would show the improved monitoring with real-time data for this type of IMTA setting, and maximizing the use of the site would demonstrate the economic benefits of co-location, both having a relevant impact on aquaculture producers and site managers.

Throughout the project, the site has transitioned from seaweed monoculture to co-cultivation with shellfish following the required amendment to the existing algae farm license. Different species of seaweed (sugar kelp *Saccharina latissima*, winged kelp *Alaria esculenta*, and oarweed *Laminaria digitata*) have been cultured in combination with native oysters (*Ostrea edulis*) since November 2020 to further exploit the logistical and ecological synergies between seaweed and shellfish aquaculture while providing the infrastructure to develop and validate cultivation approaches for low-trophic extractive aquaculture (LTA). A description of this pilot site and its IMTA system design, or LTA system to be precise, can be found below.

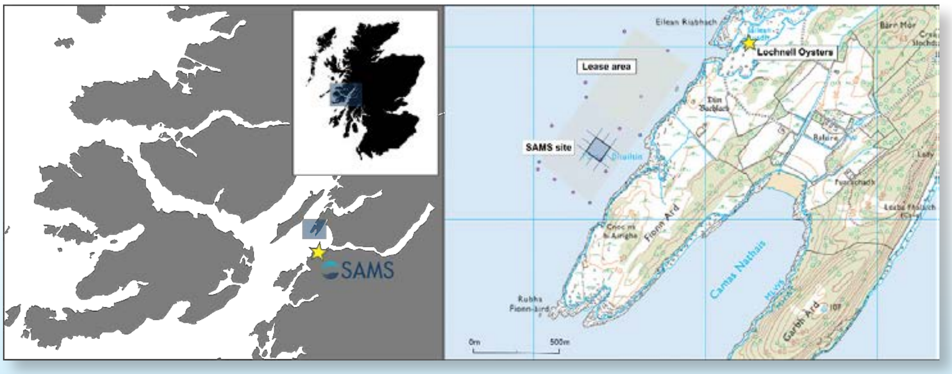


Figure 3. Location of the Scottish Association for Marine Science SAMS (left) and its main experimental cultivation site, Port-a-Bhuiltin (right; 56° 29.176 N, 5° 28.315 W) on the West coast of Scotland, UK.

SIZE/SCALE	**30 hectares with on submerged tensioned grid system of 100m x 100m (=1 hectare) with a maximum capacity for 2.4km of seaweed growing line.**	
TYPE	Coastal site with distance from shore of 0.25 km. It is accessible only by boat.	
PHYSICAL BOUNDARIES CONDITIONS AND HYDRODYNAMICS	30 hectares with on submerged tensioned grid system of 100m x 100m (=1 hectare) with a maximum capacity for 2.4 km of seaweed growing line.	
	PRIOR TO IMPAQT	**DURING IMPAQT**
SPECIES AND PRODUCT	Winged kelp *Alaria esculenta* and sugar kelp *Saccharina latissima*.	Oarweed *Laminaria digitata* and native oysters *Ostrea edulis* was added.
PRACTICES RELATED WITH IMTA	Seaweed cultivation along with salmon (IDREEM project).	Cultivation of seaweeds Winged kelp *Alaria esculenta*, sugar kelp *Saccharina latissima*, and oarweed *Laminaria digitata*, and native oysters *Ostrea edulis*
MONITORING/ COMMUNICATION/ MANAGEMENT SYSTEM	Prior to IMPAQT, site monitoring was performed using a combined approach of water sampling for nutrient concentrations together with continuously deployed temperature and light loggers as well as a temporarily deployed multi-parameter probe recording main physical (temperature, salinity) and biological (dissolved oxygen, chlorophyll-a, etc.) seawater parameters. Data was not available in real-time, with recording instruments deployed individually and no power supply or remote communication facilities set-up on site. Data and information were recorded manually. In addition, information on other parameters crucial for seaweed cultivation, such as water current regime and availability of photosynthetically active radiation PAR, was missing entirely.	Data buoy for real-time monitoring incorporating: ~ 2x PAR sensors ~ 1x multi-parameter probe ~ 1x single-point doppler current meter ~ several Bluetooth-enabled pendant temperature and light loggers ~ three 20W solar panels and two 66Ahr rechargeable battery packs ~ data logger encased in an IP66 enclosure ~ energy management system with solar regulator ~ service hatch All instruments were incorporated in a single monitoring platform (i.e. data buoy) allowing for autonomous real-time monitoring of the cultivation conditions on site. Remote server connection with the IMPAQT IMS was established, allowing data transmission and visualization in real-time. Additional monitoring data (i.e. seawater sampling, species monitoring) are entered manually to the IMS. In general, the IMS provides data visualization and predictive analytics to follow environmental and species performance.

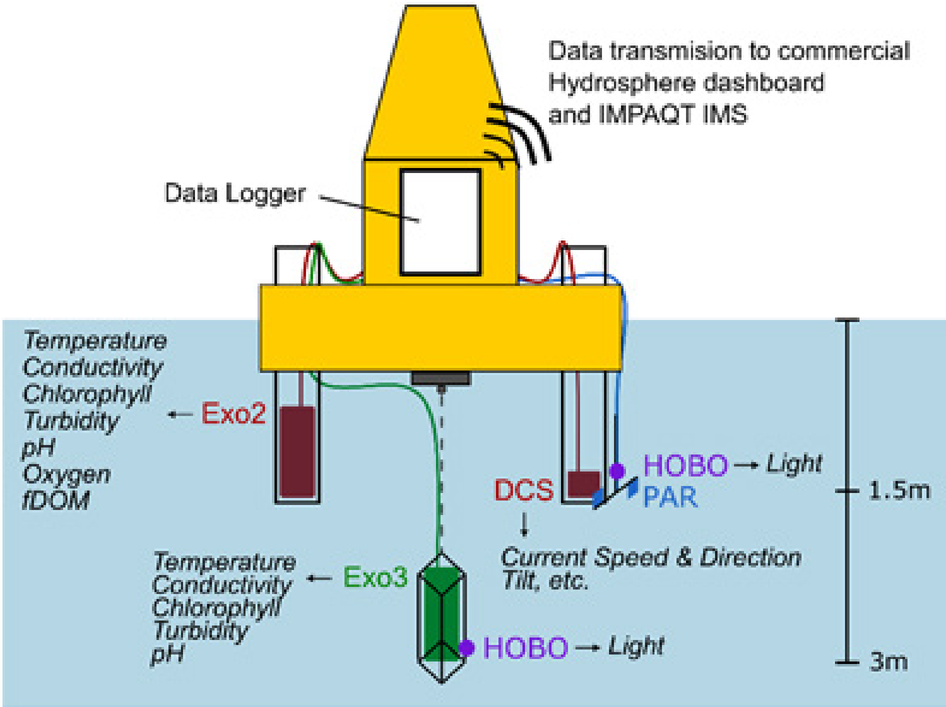


Figure 4. Left: SAMS data buoy launch (Oct 2020). Right: In-situ real-time monitoring set-up, covering two water depths of interest (1.5m: main seaweed cultivation depth; 3m: potential cultivation depth) for the recording of environmental cultivation conditions. Shown are all sensor including their recorded parameters.

3.2. Pilot in The Netherlands (by Noordzeeboerderij)

The NSF Pilot is located at the North Sea Farmers Offshore Test Site (previous name North Sea Innovation). The Offshore Test Site (OTS) is an 6 km^2 pilot site located 12 km off the coast of Scheveningen, The Hague (The Netherlands) and is a multi-disciplinary test site for sustainable innovations, with seaweed cultivation since 2016. Here, the water depth is 18-20 m. The location faces the harsh conditions of the North Sea: wind, waves/swell and water currents.

The expected benefits from IMPAQT focus on the system and methodology to improve on the design of IMTA system as well as its management. More predictable results for all of the food products at the IMTA site should be obtained, as well as transparency towards regulators on the environmental impacts of these type of system when scaled-up.

IMTA system is of interest on this pilot site because multi-use is one of the main objectives of the Dutch section of the North Sea. Seaweed farming is a viable option but only requires the upper part of the water column. The lower parts can be used for other forms of food production without any significant additional investments in aquaculture. In addition, the cultivation of different species in proximity to each another can enhance nutrients, water quality, symbiosis, among other, leading to higher yields and benefits for the surrounding ecosystem.

Figure 5. Location Offshore Test Site in The Netherlands

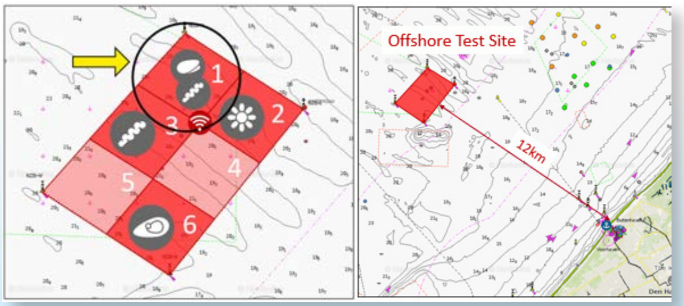


Figure 6. Location IMPAQT pilot at Offshore Test Site and plots

SIZE/SCALE	**6 km², with 6 research plots, 1 plot for the IMTA pilot within IMPAQT with a size of 25 ha, and possibility of being extended to 600 ha. The other plots, next to the IMPAQT pilot, tests with floating solar, seaweed and artificial reefs are running at this site.**	
TYPE	Offshore, 12 km of the coast of Scheveningen, The Netherlands	
PHYSICAL BOUNDARIES CONDITIONS AND HYDRODYNAMICS	General offshore North Sea conditions, fully exposed with significant wave height (Hs) up to 5 m, salinity of 34 -35 ppt, temperature range between 3 °C - 18 °C, and current NE-SW direction.	
	PRIOR TO IMPAQT	**DURING IMPAQT**
SPECIES AND PRODUCT	Seaweed *Saccharina latissima* & mussel seed collection (*Mytilus edulis*)	Seaweed *Saccharina latissima* & mussel seed collection (*Mytilus edulis*)
PRACTICES RELATED WITH IMTA	*Saccharina latissima* is being cultivated in combination with mussel seed collection. At the seabed, new geopolymer substrate is being tested for nature restoration and ecosystem services.	*Saccharina latissima* is being cultivated in vertical lines, in one line system with sawtooth pattern as well as one vertical cultivation net. This seaweed cultivation ocurrs in combination with mussel seed collection.
MONITORING/ COMMUNICATION/ MANAGEMENT SYSTEM	Prior to the IMPAQT project only GPS monitoring and manual sampling took place. Also, there is GPS monitoring telephone/internet network connection at the test site.	At the IMPAQT pilot a sensor setup is installed to gather (partly real-time) data as input for the IMS. To gather this data, several methods are used: ~ Installation of a big data buoy to gather reference data for comparison with the IMTA system as well as getting a vertical current profile ~ Installation of a small data buoy in one of the seaweed cultivation systems (SMAC2.A) to gather data within the IMTA system that can be compared with the reference data of the big data buoy ~ Manual seawater sampling during inspection trips for nutrients and chlorophyll-a ~ Single sensors at the installations for GPS and light and temperature measurements The real-time data is visible in one dashboard and later on in the IMS dashboard. This way it is possible to both check if the sensor set-up is still working or maintenance is needed. The monitoring data is ultimately collected in the IMS platform. For the vertical water current profile as well as the light and temperature measurements it is done manually. Sensor data retrieved by IADAS is send to the DAS located at the big data buoy, which sends it to the cloud and then to the IMS.

Figure 7. Set-up big data buoy

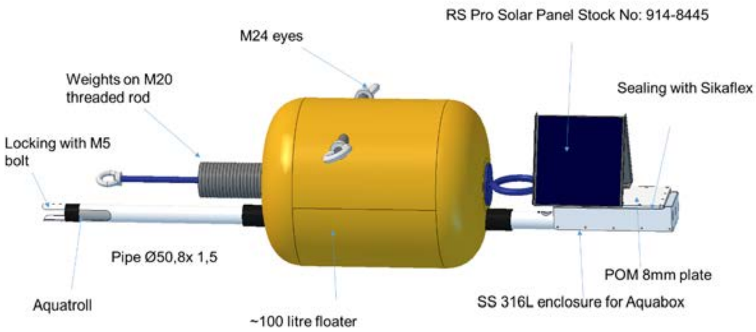


Figure 8. Set-up small data buoy

3.3. Pilot in Ireland (by Marine Institute)

Lehanagh Pool Research site is a coastal aquaculture installation located 0.25 km from the shore in Bertraghboy Bay, on the West Coast of Ireland. This Ireland's only licensed multi-species marine research site has 23 hectares and is a fully experimental non-commercial cultivation site. It seeks to progress the sustainable development of aquaculture by researching into integrated Integrated Multi-Trophic Aquaculture (IMTA) production. It has been developed specifically for multi-species production, including macroalgae, molluscs and finfish with intensive environmental monitoring and site modelling capabilities.
The motivation to use IMTA is to demonstrate the potential of this system and validate the concept, with the intention to encourage the adaption of the system on commercial sites and within the broader aquaculture industry. Demonstrating the benefits of the bioremediation aspect of IMTA is a key priority, but also is the demonstration of the advantages of IMTA in maximising the production and optimising the marine space by including multiple species.

The use of IMPAQT IMS should provide better insights into the fish growth, health and behaviour, as well as reliable and better-quality environmental information allowing smart use of feeds and feed waste management functions, and the development of a more efficient IMTA methodology.

Figure 9. Lehanagh Pool, in Bertraghboy Bay, Connemara, Co. Galway, Ireland Lat/Long: 53.40078, -9.81881

SIZE/SCALE	**23 hectares. Currently, it has 6 x 50m diameter circular fish pens, 5 suspended culture lines and 3 moored longlines of varying lengths.**	
TYPE	Coastal Distance from shore is 0.25 km. The site is easily accessible from a local pier (except for 1 hour either side of low water).	
PHYSICAL BOUNDARIES CONDITIONS AND HYDRODYNAMICS	The location is relatively sheltered with no significant fetch or swell; waves are produced by local wind conditions. The tidal range is approximately 5m, salinity is usually >32 ppt but can range from 24 to 35 ppt. Water temperatures range from 5ºCC – 18ºC, and current velocities are moderate with a predominantly NW-SE flow of approximately 1.5 m/s.	
	PRIOR TO IMPAQT	**DURING IMPAQT**
SPECIES AND PRODUCT	Atlantic salmon (*Salmo salar*), lumpfish, lobsters, seaweeds.	Atlantic salmon (*Salmo salar*), winged kelp (*Alaria esculenta*), several species of *Ulva* and other seaweed species, scallops (*Pecten maximus*), juvenile lobsters.
PRACTICES RELATED WITH IMTA	The site is a fully licensed as a multi-species IMTA research site. At the moment, there was work looking into the potential for polyculture from multiple trophic levels, particularly the potential for lobster and seaweed cultivation alongside salmon cultivation, but the pre IMPAQT site was mainly monoculture.	The species farmed are associated with 'typical' IMTA scenarios i.e. fish, shellfish and seaweeds.
MONITORING/ COMMUNICATION/ MANAGEMENT SYSTEM	Monitoring was primarily low resolution, with no real-time data and all individual logging equipment. Temperature, salinity and dissolved oxygen levels are monitored using a handheld meter. There was no remote communication set-up on the site. Farm management operations (e.g. feeding) are performed manually. Data and information were recorded manually.	Overall, 11 sensors, 3 x Power supply units, installation of 2 data logging capabilities (DAS and IADAS) and creation of on-site communications: ~ Main monitoring system includes data buoy housing 5 sensors and data logger storing housekeeping data; weather station and several sensors connecting with IADAS and DAS; EMS. ~ Secondary monitoring point: a high-density composite backboard supports the EMS, IADAS and EMS battery in a single neat location; solar panels; black box units inside an IP67 enclosure. ~ Sensors for wireless communication and for communication between the IADAS and DAS. ~ Communication off the site is through 4G. All other communication is wired, FTDI, serial and ethernet. 25 abiotic parameters are being recorded thanks to these technologies, at 28 sampling points at multiple depths and locations. Overall there is a move to high resolution monitoring. Site observations, records and biotic monitoring is being digitised and centralised.

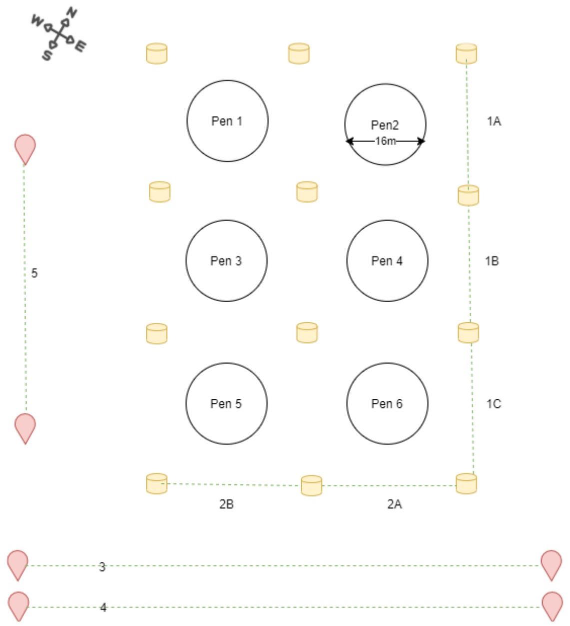


Figure 10. Plan view of structure orientation at Lehanagh Pool Research site including 6 pens and numbered longlines

3.4. Keywater Fisheries pilot site in Ireland (collaborating with Marine Institute)

Keywater Fisheries is a family run freshwater fish farm in Ireland. This IMTA site is operated by Keywater Ltd, who are a private company, and are supporting the IMPAQT project, in conjunction with Bord Iascaigh Mhara (BIM). It is an inland, freshwater location. It is a fully licenced site producing for market.

At IMPAQT, Keywater promote and support the eco-intensification of aquaculture. The farm is on a 1.5hectare site and comprises of a hatchery, nursery, broodstock unit and 3 outdoor spiltponds. They produce Perch for the table in environmentally friendly and sustainable pond rearing systems, where good water quality is maintained by plants and algae that naturally grow on their farm. They believe that healthy fish grown in a natural environment results in the finest quality product, and their innovative split pond design allows them to do just that.

The split-pond technology is a novel approach to freshwater aquaculture and has potential to improve water treatment (sediment and nutrient removal) within a recirculation system. Demonstrating the benefits of this bioremediation aspect of IMTA is a key priority, but also is the demonstration of the advantages of IMTA in maximising the production from a pond and optimising the use of areas by utilising multiple species.

The involvement of this pilot site in the IMPAQT project aimed to help to progress the Perch sector into a modern, high-tech freshwater aquaculture industry. The novel split-pond culture technique has the potential to open up large areas of marginalised land to freshwater pond culture. The IMPAQT management platform can be a key tool is demonstrating the suitability and adaptability of the approach.

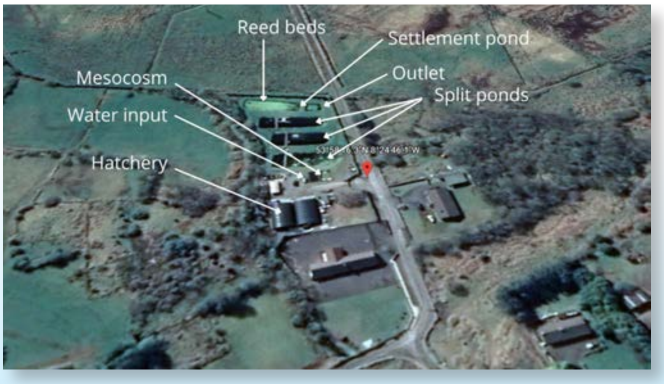


Figure 11. Keywater Fisheries Ltd, Cloonloo, Co. Sligo, Ireland Lat/Long: 53°58'16.3"N -8°24'46.1"W. Key locations indicated (Input point, mesocosm, split ponds, reed beds, outlet point).

SIZE/SCALE	**This is an inland 1.5 hectare site.**	
TYPE	Inland Freshwater situated in rural farmland on the One river a tributary of the River Shannon.	
PHYSICAL BOUNDARIES CONDITIONS AND HYDRODYNAMICS	Water temperature ranges from 2 °C to 25 °C. Water flow through the site is intermittent and dependent on water usage needs. Water is provided by a dammed river and a groundwater well. The site is accessible by road and on foot.	
	PRIOR TO IMPAQT	**DURING IMPAQT**
SPECIES AND PRODUCT	The European Perch (*Perca fluviatilis*), Common Duckweed (*Lemna minor*), Tench (*Tinca tinca*), *Algae* – various species	The European Perch (*Perca fluviatilis*), Common Duckweed (*Lemna minor*), Tench (*Tinca tinca*).
PRACTICES RELATED WITH IMTA	The farm site practices freshwater IMTA, utilising a novel split-pond technology and duckweed bioremediation to close the production cycle in a controlled yet extensive manner. The duckweed grows naturally in the ponds.	
MONITORING/ COMMUNICATION/ MANAGEMENT SYSTEM	Pre IMPAQT site was monitored primarily in low resolution, with no real-time data and all individual logging equipment. Farm management operations (e.g. feeding) were performed manually. Data and information were recorded manually.	Three in-situ monitoring points, with a total of 9 sensors. ~ At each point an IP67 weather box enclosure is pole-mounted above the ground. Each point contains an IADAS and AP5000 multiparameter probe. ~ Three loggers are measuring light intensity and temperature. ~ Weather station ~ The main DAS is connected to the existing monitoring solutions enabled at the site. ~ A Biomark pitt tag reader with Bluetooth connectivity expedites broodstock management at the site. ~ Communication from existing technology on site is using a network of ZEMs in 3 Tough-boxes which link to an alarm system; communication using Wi-Fi and cable connections. There is limited 4G/GSM signal strength. ~ IADAS units connected to the primary DAS In this pilot, access to real-time data and smart analytics enable the operators to react quicker to potential stressors occurring in the system. Site observations, records and biotic monitoring is digitised and centralised.

3.5. Pilot in Turkey (by Çamli)

Çamli pilot is a marine offshore facility located at 1.5 km from Ildırı Bay, Izmir, West coast of Turkey. The IMTA set-up is a 21 km^2 site located next to the company's production system.

Çamli originally tested an IMTA system in 2013 as part of a research project examining the integration of sea cucumber, seaweed (Gracilaria sp.), mussels and oysters. The results illustrated the benefits of employing an IMTA system for future operations and environmental impact management. IMTA has been shown to be an extremely effective method for obtaining maximum efficiency of production yields while monitoring/protecting the environment. At the same time, the increasing demand requires aquaculture to find solutions both for maximum yield from a site and secure environment.

IMPAQT is adding value to IMTA systems with the inclusion of intelligent monitoring sensors and systems for environmental observation and production management. This type of system will allow for quick intervention to protect the environment and species welfare at the same time. It should also allow for improvements in operational procedures like feeding and waste reduction efficiency. This knowledge could be useful to both farmers and regulatory authorities and should lead to the production of high-quality seafood for human consumption.

Figure 12. Location of the Çamli pilot site and base facility

SIZE/SCALE	**21 km² site located next to the company's production system**	
TYPE	Marine offshore facility located 1.5 km from Ildırı Bay, Izmir, West coast of Turkey, accessible by boat.	
PHYSICAL BOUNDARIES CONDITIONS AND HYDRODYNAMICS	Strong current (Surface 10-20 cm/s to 30-40 cm/s and 3-5 cm/s below surface) with predominantly southerly direction. Salinity range from 38-40 ppt. Average wind speed: 4.71 m/s. Water temperature range from 13 °C to 29 °C.	
	PRIOR TO IMPAQT	**DURING IMPAQT**
SPECIES AND PRODUCT	Çamli was producing mainly sea bass and seabream in the site as monoculture principle. In the vicinity there were also bass and breams in the cages.	European seabass (*Dicentarchus labrax*), black mussel (*Mytilus galloprovincialis*), and sea lettuce (*Ulva rigida*).
PRACTICES RELATED WITH IMTA	Conducted offshore R&D IMTA project for sea bass, bivalves and seaweed.	Offshore IMTA system with fish, mussels and seaweed.
MONITORING/ COMMUNICATION/ MANAGEMENT SYSTEM	Data transfer system from the computer-controlled feeding system to the stock management office via internet. Monitoring was performed by the operators only visually and not real time. System was covering underwater and surface camera system only that has been used for monitoring of feeding activity. Measurements were only performed by the handy probe measurement devices and just for dissolved oxygen level.	~ Data buoys with sensors and EMS. Measurements at three sampling locations. ~ IADAS and DAS ~ A meteorology station was also deployed. ~ Underwater and surface cameras are mounted in the fish pens recording live-stream footage to assess fish behaviour and run disease diagnosis algorithms. All measurements and data are sent to the IMS via network-streaming, allowing real-time monitoring.

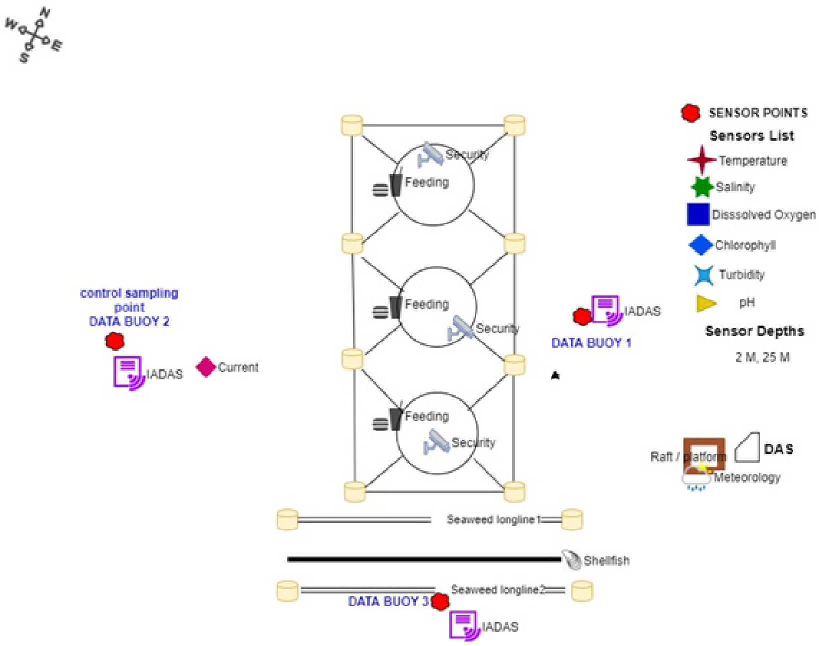


Figure 13. Final Setup of Çamli pilot

3.6. Pilot in China (by YSFRI)

[The IMTA site, operated by the Yellow Sea Fisheries Research Institute]() (YSFRI), is a commercial IMTA site in the Sanggou Bay with multiple aquaculture industries, located at the east end of Shandong Peninsula in China. Commercial IMTA covers more than 60% of the bay area and produces considerable amounts of seaweed, shellfish, sea cucumber and other species. Besides the commercial aquaculture activities, Sanggou Bay is also a main site of research in the fields of aquaculture ecology, culture animal physiology, ecosystem dynamics, carrying capacity estimation, and many more.

This pilot run by YSFRI is a small semi-enclosed bay (about 144 km^2) with a mean depth of 7.5 m. The main species grown are seaweed and shellfish, but on the bottom of the IMTA area, there are many other species such as sea cucumber, sea urchin, finfish, abalone, clam, sea snail, etc., which could be integrated into the IMTA systems. The artificial reef and seagrass bed are parts of the IMTA systems. All the associated species benefit and support each other to reduce the environmental impact.

The site has operated as commercial IMTA for a number of decades and as such has shown the benefits of the system to maintain a relatively stable environment and a high yield of seaweed and shellfish. The IMPAQT project allow to demonstrate how largescale IMTA maintains sustainability based on long-term and high spatial coverage data. Such improvement in IMTA help to quantify its benefits based on scientific data alongside the good production practice.

The IMPAQT project innovations would improve the quality and reliability of the data by increasing the monitoring (temporal/spatial) scale, frequency and availability. The system would allow researchers and practitioners to have quicker response times to changes in environmental conditions and would assist in quantifying environmental impact allowing opportunity to minimise the effect on sensitive species to avoid product loss. It will assist with monitoring of water quality as well as growth conditions of cultured animals.

LEARN MORE!

Complete information about each pilot site, such as spatial configuration, technical aspects or IMTA system design can be found in the project deliverables D1.1, D1.2, and D1.4.

o D1.1. Pilots description and reference case studies for IMTA
o D1.2. Analysis of Use Cases and Requirements
o D1.4. Final IMTA system design specifications

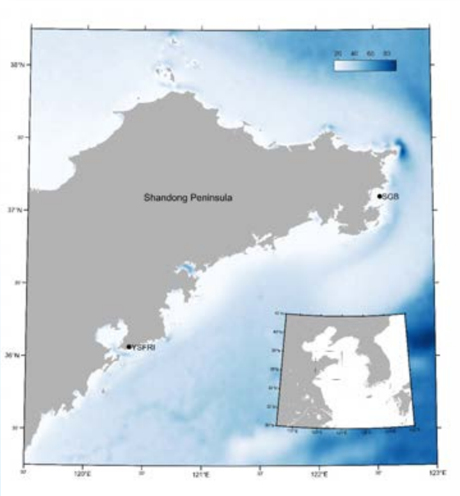


Figure 14. Location of the Yellow Sea Fisheries Research Institute (YSFRI) and the pilot at Sanggou bay (SGB, 37°01′–37°09′N, 122°24′–122°35′E) at the east end of Shandong peninsula.

SIZE/SCALE

The area of the bay is of 140 km^2.

TYPE

Coastal bay distance from shore about 0.5-2 km. The site is easily accessible from local piers.

PHYSICAL BOUNDARIES CONDITIONS AND HYDRODYNAMICS

Sanggou Bay is a small semi-enclosed bay (about 144 km^2) with a mean depth of 7.5 m which lies off the coast of Shandong Province, China. Water exchange between the bay and Yellow Sea is through an 11.5 km opening of the bay and is driven by semi-diurnal tides (tidal range 2 m). The Sanggan and the Shili rivers flow into Sanggou Bay with the annual water discharge 1.7–2.3 × 108 m^3. Typical current near the surface inside the bay can reach 70 cm/s at the entrance, water temperatures are from 2 °C - 25 °C in an annual cycle and the salinity ranges from 30 to 32 psu.

	PRIOR TO IMPAQT	DURING IMPAQT
SPECIES AND PRODUCT	Pacific Oyster (*Crassostrea gigas*), Kelp (*Saccharina japonica*), seaweed (*Gracilaria lemaneiformis*), Scallop (*Chlamys farreri*).	Kelp (*Saccharina japonica*), Pacific Oysters (*Crassostrea gigas*),
PRACTICES RELATED WITH IMTA	Year-round seaweed aquaculture: ~ Nov.-May *Saccharina japonica* and Jun.-Oct. *Gracilaria lemaneiformis* ~ Bivalves + Seaweed IMTA system ~ Abalone + Sea cucumber + Seaweed IMTA system	IMTA with kelp and oysters. Horizontal kelp rope cultivation and lantern net with scallops or oysters inside hanged from the longlines.
MONITORING/ COMMUNICATION/ MANAGEMENT SYSTEM	Prior to IMPAQT, there has not been systematic site monitoring as for the busy daily management and aquaculture production. There were several running environmental monitoring related projects for hydrodynamics which is usually operated by IOCAS with a single data buoy. The common method to get environmental data is the project related field observations covering an area in the bay, which is usually seasonally cruises, data was not available in real-time, and with huge gaps in time and space. Observations and measurements were mostly manually.	Monitoring platform includes: ~ 1x multi-parameter probe, ~ 1x automatic nutrient analyser, ~ 2x acoustic doppler current profiler (ADCP). Instruments other than the ADCPs were incorporated into the monitoring platform allowing for autonomous real-time monitoring of the environmental conditions and species growth performance on site. ~ buoy platform with solar panels ~ 4 high-definition cameras (2 underwater, 2 surface), ~ automatic weather station ~ automatic nutrient analyser ~ IoT system making accessible all component data.

Figure 15. The platform which have been deployed to the pilot since October 2020. With solar panel power supply and its own management system. Most devices are attached to the platform and integrated to the IoT system for real-time data transmission to the local IMS system. Two ADCPs are moored at different locations of the region, and will be manually reclaimed to obtain data and upload to the IMS.

4 DECISION MAKING WITH IMTA MODELLING

4.1. What is an IMTA model

The potential benefits of IMTA are very much scale dependent as well as dependent on the trophic status of the local ecosystem. In eutrophicated systems the relative benefit of e.g., fish farms to seaweed is limited, however, the reverse is probably more important. In oligotrophic systems, overstocking and exceeding the system's carrying capacity is high [8] and augmenting the available nutrient pool can increase maximum yields. In systems with a very high exchange rate with larger bodies of water, the benefit of co-location may be limited to simply more efficient use of marine space. While in a relatively open system, seaweed cultivation in the proximity of a mussel farm may be beneficial for the seaweed yield, at the scale of an ecosystem they are ultimately both competing for nutrient resources. Therefore, the scale of the farming locations relative to the system's carrying capacity matters [9].

Optimal spatial configuration is key to an effective IMTA-concept in open water [10]. This requires insight in the local hydrodynamics, primary productivity, retention times of water, and remineralisation times for nutrients from faeces. In certain systems, it may be most effective to position various trophic levels very close to each other, while in other systems, it may be more effective to position extractive aquaculture at some distance downstream of sources of waste material. This depends on local flow conditions and the flux of materials.

Numerical models taking all these factors into account can be very useful tools to:

- Investigate the effectiveness of IMTA lay-outs
- Investigate system limits for aquaculture in general and IMTA setups specifically
- Assess and quantify the ecosystem services of IMTA

This requires modelling hydrodynamics, nutrient dynamics, light availability, and the production of relevant ecosystem and farm components [10; 11].

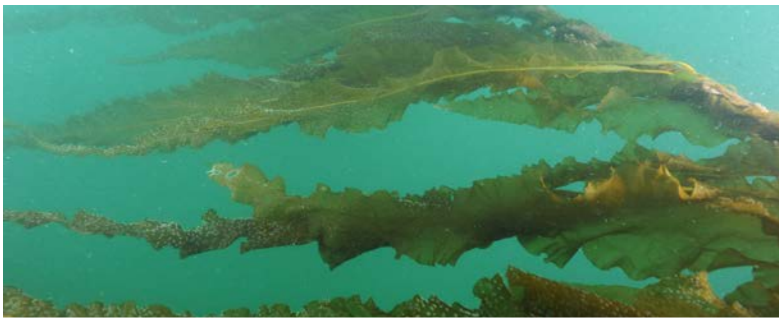
Thus, in the planning stages of IMTA farms it is essential to get some information on a lot of aspects such as:

- potential yields for extractive aquaculture
- potential impacts that may be detrimental to the environment
- the best spatial lay-out to get optimal benefits from nutrient and oxygen footprints
- the "IMTA-effect" relative to single species farming.

One way of obtaining this is through the before mentioned numerical models that can simulate the environmental conditions as well as the growth, uptake and excretion rates of farmed organisms. Within IMPAQT such models have been developed and tested on two of the project sites, i.e., the Netherlands and Turkish pilot sites.

Such models are fairly complicated. They require significant calculation power and data storage facilities, and setting up and running requires a good understanding of the physical and ecological environment and of many essential ecological processes.

An IMTA model describes the essential IMTA processes in the form of differential equations solved on a 3-dimensional computational grid. The modelled processes can be categorized in two groups: **hydrodynamic processes and biogeochemical processes**. The IMTA model is formed from a combination of two modelling tools or software packages that each describe one of the two groups of processes.



Hydrodynamic processes

The foundation part of such models is hydrodynamics, i.e. water currents and movement. Water carries nutrients, oxygen and waste material towards and away from aquaculture installations. In most cases this requires a 3D model. Many marine areas are stratified. This means that the water column has layers of different densities that don not easily mix. Nutrients available in the bottom layers that do not receive enough light are of little use to seaweed growing in the top layers. Furthermore, the model needs to give information about light penetration in the water column.

The growth of seaweed and phytoplankton depends on light. Both the presence of fine suspended sediment in the water and the presence of phytoplankton itself can increase turbidity and reduce the amount of light available for photosynthesis. Another vital aspect for the growth of phytoplankton and seaweed is the availability of nutrients. The most important are nitrogen compounds (nitrate, ammonium), phosphate and for certain groups of phytoplankton also silicate.

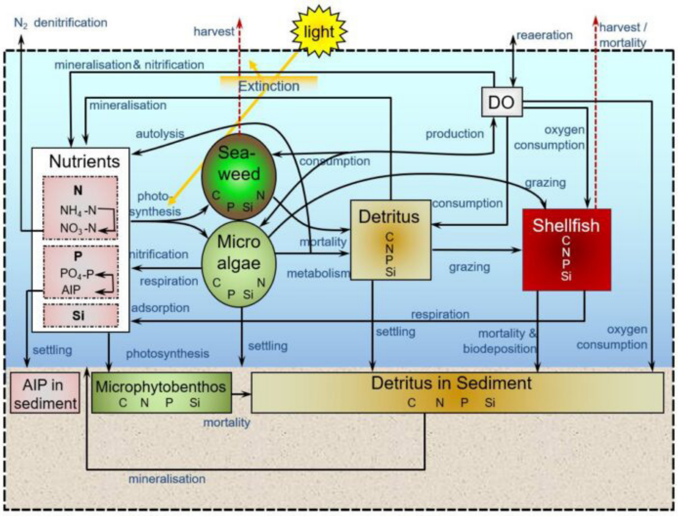


Fig. 16. Schematic representation of the environmental and ecological processes in the model. Note: "seaweed" represents a separate sub-model to represent the growth of seaweed. This also goes for "shellfish", this is a so-called dynamic energy budget model to simulate the growth of shellfish.

Nutrients can get into the water in many ways. In coastal areas this is mostly through the discharge of rivers, streams and sometimes waste water from urban areas. For more offshore areas and also for enclosed bays with little run-off from land, the exchange with the open ocean is essential. Nutrient concentrations are important but are only half the story. Even high nutrient concentrations can be depleted quickly if they are not replenished. So, the nutrient concentrations, together with the flow determine the carrying capacity for seaweed and phytoplankton.

The hydrodynamic processes are captured by a D-Flow Flexible Mesh model (D-Flow FM, see https://www.deltares.nl/en/software/delft3d-flexible-mesh-suite/). D-Flow Flexible Mesh is a hydrodynamic simulation program developed by Deltares. It is part of Deltares' unique, fully integrated computer software suite for a multi-disciplinary approach and 1D, 2D and 3D computations for coastal, river and estuarine areas, named Delft3D Flexible Mesh Suite or D-HYDRO Suite. It can carry out simulations of hydrodynamic flow, waves, water quality and ecology. It has been designed for experts and non-experts alike. The Delft3D Flexible Mesh Suite is composed of several modules, grouped around a mutual interface, while being capable to interact with one another. D-Flow FM is one of these modules. D-Flow FM is a multi-dimensional (1D, 2D and 3D) hydrodynamic (and transport) simulation program which calculates non-steady flow and transport phenomena that result from tidal and meteorological forcing on structured and unstructured, boundary fitted grids. The term Flexible Mesh in the name refers to the flexible combination of unstructured grids consisting of triangles, quadrangles, pentagons and hexagons. Figure 17 is an examples of D-Flow FM hydrodynamic model grids.

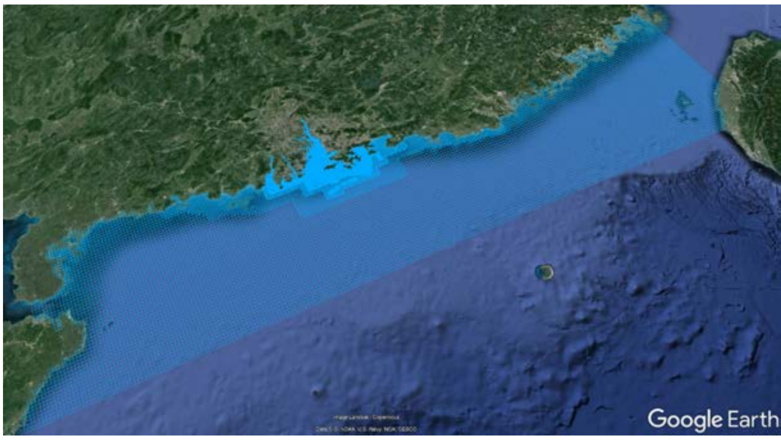


Figure 17. A Delft3D FM model grid for Hong Kong and the surrounding coastal waters

In the context of an IMTA model, the D-Flow FM model calculates flow velocities, salinity, temperature, turbulence, and the resultant stratification. It provides the geometrical framework for the subsequent biogeochemical model and defines water exchange, volumes, and surface areas required for such computations.

Biogeochemical processes

The models also need basic information on the biological processes of the cultivated species. For fed aquaculture (e.g. fish) you need information on the rates at which food and excrement from fish are released into the water and how quickly they are converted by bacteria into inorganic nutrients and organic compounds that can be taken up by either extractive cultivated species or by naturally occurring species in the environment. How far nutrients are dispersed and how quickly they get diluted to background concentrations depends on local currents.

For cultivated seaweed species, you need information on the uptake rates for nutrients and how much light they need to grow. These uptake rates are different for e.g. *Saccharina latissima*, cultivated in the North Sea and *Ulva rigida* cultivated at the Çamli site. For example, for shellfish, there is an intermediate step: phytoplankton. We need to be able to model the growth of phytoplankton, the filtration rate of the shellfish and the growth of the shellfish in relation to the environmental conditions (food availability but also temperature).

Figure 18. Seaweed from IMPAQT pilot sites. Ulva rigida, from the Çamli pilot site, and Saccharina latissima from the NSF pilot site

The biogeochemical processes are described by a DELWAQ (or D-Water Quality, abbreviated to D-WAQ) model, which is the biogeochemical module of the Delft3D Flexible Mesh Suite. D-WAQ is a multi-dimensional water quality model framework. It solves the advection-diffusion-reaction equations on a predefined computational grid and for a wide range of model substances. D-WAQ allows great flexibility in the substances to be modelled, as well as in the processes to be considered. D-WAQ is not a hydrodynamic model, so information on flow fields and geometric properties are derived from D-Flow FM. This derivation is completed in an offline way, meaning that first the hydrodynamic model is run, and then the water quality can be run using the hydrodynamic information output from the hydrodynamic model.

In the context of an IMTA model, D-WAQ calculates the fate and transport of geochemical substances such as dissolved and particulate carbon and nutrients, dissolved oxygen, and suspended sediment. It also computes the dynamics of primary and secondary producers via the ecological modules BLOOM (microalgae), DEB (shellfish) or MALG (macroalgae/seaweed). As the biogeochemical constituents reside in the same domain as the biological ones, D-WAQ is built to calculate the cycling of nutrients in the aquatic environment and to determine the effect of various conditions on the viability of certain ecological units. A D-WAQ IMTA model is directly coupled in an offline way to a D-Flow FM hydrodynamic model, and, through this coupling, the transport of nutrients into and out of an IMTA farm can be dynamically calculated, and the subsequent effect on biomass dynamics determined. The flow within the farm, however, is too small scale to be resolved by a model on the scale of an ecosystem IMTA model, and thus flow and concentrations are essentially assumed to be homogeneous through each model grid cell within which a part of the IMTA farm resides. A schematic that provides an overview of many of the processes and substances available in D-WAQ is shown in Figure 19.

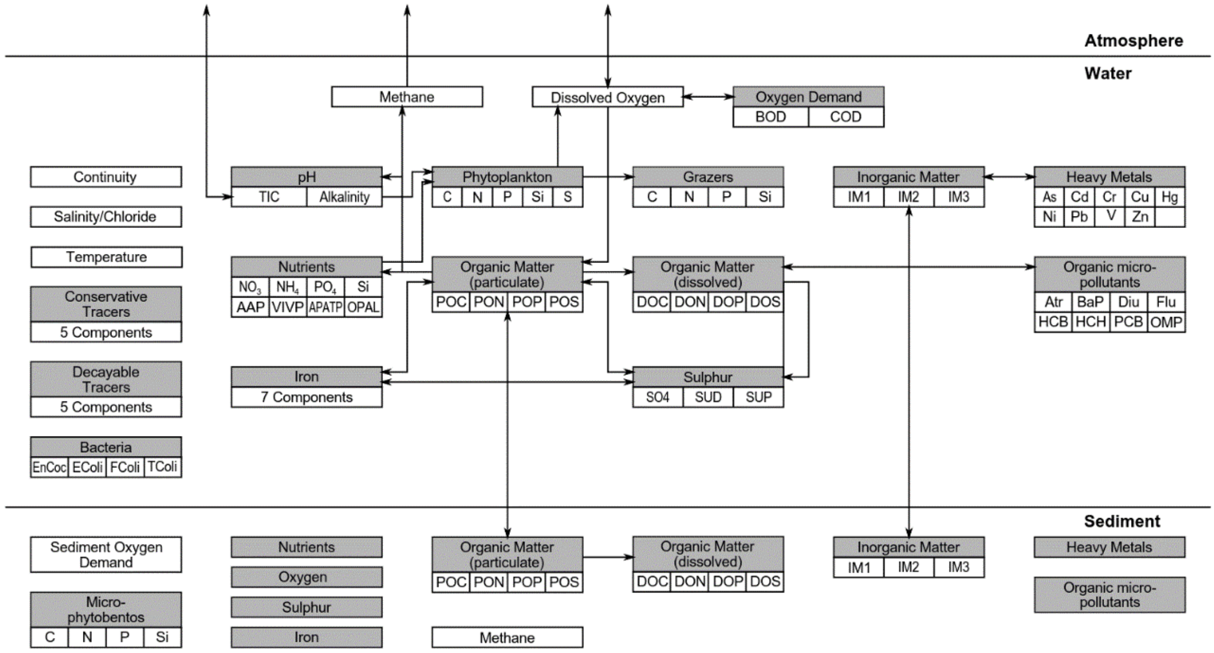


Figure 19. A flow chart providing an overview of the processes available in the standard D-WAQ library. The DEB (shellfish) and MALG (seaweed) models are not present in this schematic

Going back to figure 16 (**Schematic representation**), a quick overview can give an idea about the importance of feedback effects in IMTA. There are many ecosystem models available (simple, complex, 1D, 2D, 3D), but even many of the relatively complex models are often one-way traffic. Nutrients are available for phytoplankton, which is available for shellfish and that determines how much shellfish can grow. However, for IMTA it is quite important that also the feedback effects can be resolved. Following the before-mentioned example, the effect of shellfish on phytoplankton should also be taken into account.

Shellfish feed on phytoplankton, but through their faeces they also ensure that nutrients become available again. It sounds paradoxical, but in areas with dense shellfish cultivation the growth of phytoplankton is larger than it would be in a similar system without shellfish. This is clearly relevant when shellfish and seaweed are cultivated in close proximity.

It is less important in areas that are very open and have a large exchange rate with the larger ecosystem. However, in enclosed bays with a large residence time, this can make a big difference. The IMTA models developed within IMPAQT can take these feed-back loops into account. This is not entirely unique for ecosystem models but not common.

4.2. Applying IMTA modelling

In the scope of the EU H2020 IMPAQT project, partners from Deltares developed two far-field models (called herein North Sea model and Aegean Sea model) to run a set of scenarios estimating the benefits of IMTA in the setup of two pilot sites that contrast in their farm settings and natural environment to investigate the effects and benefits of IMTA faming.

The first IMTA model was set up to investigate the effects of combined seaweed (*Saccharina latissima*) and mussel (*Mytilus edulis*) production in the Dutch North Sea, in the Rhine region of freshwater influence, characterized by a nutrient-rich environment with high current velocities and hence short residence times. The second IMTA model was set up to investigate the effects and benefits of fish farming European seabass (*Dicentarchus labrax*) in combination with seaweed (*Ulva rigida*) and mussel (*Mytilus galloprovincialis*) production off the Turkish coast. The domain of this second model covers most of the Aegean Sea, which is an extremely oligotrophic environment with very little freshwater inputs.

Even these models still require further validation before they can be fully relied upon to take decisions either regarding the management of a farm or the management of an ecosystem by regulators, they provide valuable information on far-field interaction between the environment and IMTA farm components. Through these experiences, we gained insight in the requirements of IMTA model setups, their limitations, and choices that the modeller has to face depending on the simulated environment.

The two IMTA models are set up using coupled hydrodynamic and water quality modules from the before-mentioned Delft3D Flexible Mesh Suite. The horizontal and vertical grid resolutions are adapted to correctly resolve local flow patterns and stratification and capture the effects of the farms on water quality. The hydrodynamic module simulates currents, water levels, salinity and temperature. The water quality module incorporates biogeochemical processes affecting the growth of seaweed and mussels, and that can be affected by the dynamics of these living species (i.e., nutrient cycling, primary production and air-water exchanges). Special attention was paid to representation of phytoplankton dynamics to account for competition with seaweed species in nutrient-poor environments. The effects of fish cages are represented as additional nutrient and organic carbon loads. Seaweed and mussel metabolism dynamics are explicitly modelled, allowing for the simulation of feedback processes in the food chain, which is pivotal to IMTA. [12]

With the current model implementation, the North Sea results show that seaweed and mussel production can be increased up to 10 tons/ha of seaweed and 5 tons/ha of mussels within a 6 km^2 farm, with very little environmental impact (in terms of nutrient depletion and oxygen concentrations and phytoplankton biomass). Upscaling of IMTA farming to potential future designated areas, further offshore and outside of the influence area of the Rhine plume would be more fruitful in terms of seaweed production, and less in terms of mussel production. This is due to higher nutrient turnover due to higher mixing, and lower phytoplankton biomasses (hence lower food availability for mussel cultivation). [14]

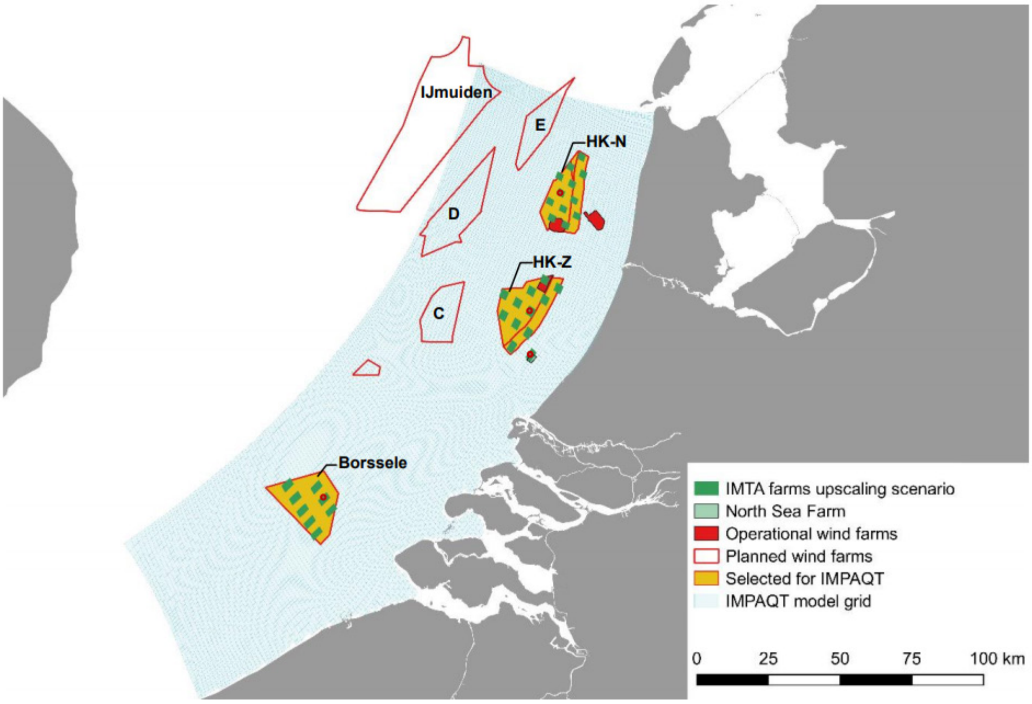


Fig. 20: Map of the model grid and locations of the selected areas for IMTA in the IMPAQT North Sea upscaling scenario

The environmental impacts of IMTA development in these areas, such as decrease of nutrient concentrations and of chlorophyll-a, is more visible, especially where water velocities are the lowest and hence retention times highest. Results also show advantages of IMTA farming, since, in the tested scenarios, mussel oxygen consumption is overcompensated by production by seaweed photosynthesis.

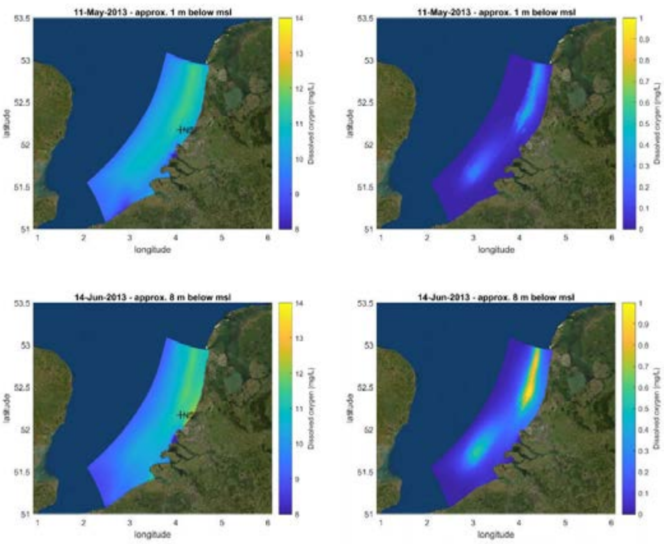


Figure 21. Oxygen concentrations in upscaling scenario (left panels), and difference with 'base case' concentrations (right panels)

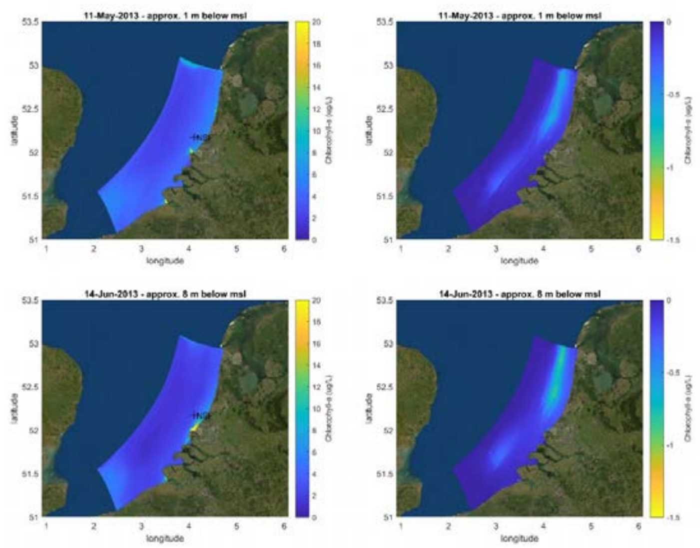


Figure 22. Chlorophyll-a concentrations in upscaling scenario (left panels), and difference with 'base case' concentrations (right panels)

Results from the Aegean Sea model show that in such an oligotrophic environment, the additional nutrient input provided by fish production (and subsequent increase in phytoplankton biomass) is indispensable to be able to produce mussels. According to the model, the current IMTA model scenario does not show a clear reduction in nutrient emissions (and associated environmental impact) compared to fish monoculture. The level of nutrient concentrations remains too low for the survival of *Ulva rigida*, which is unable to extract the extra nutrient loads from the system.

Figure 23. Çamli pilot site with IMTA setup

At the Aegean Sea the IMTA model show a much more pronounced footprint of aquaculture on the ambient environment than that simulated in the NSF scenarios, due to the oligotrophic conditions. These nutrient-scarce conditions require adapted modelling tools. This notably includes the choice of the right modules to represent competition between phytoplankton and macroalgae. In the future, the Aegean Sea model could be used to test the potential cultivation of seaweed species better adapted to oligotrophic environments (provided nutrient uptake and growth parameters are available for these species), and its benefits for nutrient reduction.

This work shows the different responses of (and interactions between) IMTA farm components and their footprint on the environment in both nutrient-rich and nutrient-poor environments. It also helps identifying controlling processes, which should be incorporated in future models, to improve their **predictive value**.

The IMTA model results are integrated into the Integrated Management System (IMS) developed in the project and presented in section xx. Outputs from the IMTA model, such as those presented before, will be available for users. The integration with the IMS is divided into “offline” and “online” components. The offline interaction with the IMS refers to the model development, setup, run and postprocessing. All steps, excepting postprocessing, are carried out independently from the IMS. After the model is run, the results are saved to a 4D maps (3D + time) and time series files. These maps are then transferred to the IMS and can be visualized at any time by the operator.

The outputs from the **offline interaction** constitute the online integration of the IMTA model with the IMS. All the pre-calculated scenario outputs will be stored in the IMS in NetCDF files, and available to be visualized by the user as time series of the variables of interest at different observation points or as 2D maps over the entire model domain of the variables of interest.

LEARN MORE!

The detailed analysis and results applying the IMTA model at the North Sea and the Aegean Sea can be found in several project deliverables, i.e., D3.2, D3.4, and D3.6.

o D.3.2 First version of IMTA Model focused on North Sea
o D3.4. Updated version of North Sea IMTA model and first scenario studies
o D3.6. Model application to second pilot site

4.3. Application for users

Since IMTA models were used in IMPAQT to distil a generically applicable blueprint that others can use as a template, a blueprint to guide future design and use of such far-field IMTA models was developed and made available in deliverable *D3.7. IMTA-modelling blueprint*. This blueprint addresses the requirements in terms of simulation tools, software capabilities, modelling skills and observation data to set up the model, and how IMTA farm components can be represented. Model applications and limitations are also discussed and several examples are illustrated regarding the Dutch coast and Aegean Sea IMTA models.

The models are currently valuable as research tools to get more general insight in how ecosystems react to aquaculture and to assess the response of individual species to an increase in competition or an increase in food availability. It is clear that the current IMTA models still need some further development before they can be fully relied upon to take decisions. However, the first developments are encouraging and open up various application potentials, both for farmers and for regulators.

Applications will generally strongly depend on the users. Investigating the effect of potential changes in the environment (e.g., expected changes in nutrient run-off, climate changes or the effect of other farms in the same system) on yields, are typical applications. Other scenarios that are geared to increasing revenue can relate to the optimal spatial lay-out of different trophic levels with respect to each other, ensuring that extractive species can make optimal use of waste streams of fed species. Other types of scenarios are linked to upscaling. This could be upscaling of production or upscaling of space covered by aquaculture. Such scenarios can be of use to farmers, but particularly to regulators interested in the carrying capacity of areas for certain types of cultivation. More user-specific examples are given below.

Applications for farmers

IMTA models can become important tools for farmers at different stages in farm development. Firstly, in the planning stage, prior to the presence of any farms or while single species farms are present in the system, models can give a good indication of expected yields as well as other ecosystem services that can help a farmer with obtaining the required permits.

In addition, IMTA models can be instrumental in finding the optimal seeding and stocking densities for different species, ensuring that the maximum stocking potential can be used and avoid overstocking, which can lead to either environmental damage and / or reduced revenue. When properly validated and calibrated to the local environment and appropriate species, this type of models can also help farmers in finding an optimal spatial configuration of different IMTA components by running dedicated scenarios. Also, they can be valuable to farmers in the case of expected changes in the environment.

For example, in North Western Europe the consequences of the European Water Framework Directive are becoming visible, even in coastal waters [13] with gradually reducing nutrient levels. For eutrophic coastal waters it will be some time before serious carrying capacity issues arise, but in already oligotrophic waters, (such as the Çamli site at the Aegean Sea), a further reduction in nutrients may impact the production potential for fed aquaculture and possibly even enhance the value of the IMTA concept. Also, development of other aquaculture in the same system can impact the productivity of a particular farm. Having advance indication of the effect of such changes over time can help planning and budgeting for further developments.

LEARN MORE!

Find out more:

o D3.7. IMTA modelling Blueprint

Application for regulators

IMTA is a concept that seems to be valuable not just at the level of a single multitrophic farm, but particularly at the level of an ecosystem, or a subsystem. IMTA models can therefore be particularly valuable for regulators to gain insight in the responsible levels of fed and extractive aquaculture in an ecosystem, without compromising targets for Good Ecological/Environmental Status, under the Water Framework Directive (WFD) or the Marine Strategy Framework Directive (MSFD).

For authorities responsible for licensing and for conservation targets, IMTA models allow for running scenarios not only with different stocking densities and farm lay-outs, but also taking other local measures into account (e.g., reduction of nutrient inputs from other sources). If regulators can ascertain that indeed IMTA set-ups are effective in reducing environmental impacts and may even be cost effective in terms of meeting water quality targets [14], they can boost the local economy as well as safeguard the environment.

The models can in many areas help to quantify how environmental indicators would change under certain scenarios. Currently, licensing procedures in most countries appear to be geared towards single species farms. Mostly pilot scale IMTA setups tend to be treated as experimental add-ons by licensing bodies and are operating on additional licenses or research licenses. This situation seriously hampers the further upscaling to commercial levels of the IMTA concept [15]. Changing licensing procedures is generally a slow and complicated process and the licensing authorities need to be convinced of broader benefits to change a legislative framework, rather than benefits to individual farmers. Further development of IMTA models such as presented here and linking them to economic models may be instrumental in overcoming this hurdle [16].

Last but not least, improving social acceptance of aquaculture is also an issue where the IMTA concept as well as the models can contribute. The models in conjunction with measurements can ultimately be used in procedures such as certification of environmentally friendly food production. These certificates (e.g., Aquaculture Stewardship Council certifications) are important instruments in reducing the negative image that certain types of aquaculture (particularly fed aquaculture) still have.

Application for the general public

Advanced models such as the IMTA model developed here require both skills to set up and run them, as well as a significant amount of understanding both of the ecosystem and the model in order to interpret the results accurately. The present state of model development makes the models useful as a research tool rather than immediate decision support.

However, in future model results and outputs can also be used in stakeholder engagement to discuss the ramifications of decisions in marine spatial planning for other groups besides farmers. Such stakeholders can include conservation NGOs, fishermen, representatives from the tourist industry, etc.

Mapping tools are ever increasingly used in stakeholder meetings. However, as using model results at face value can lead to the wrong conclusions, it is imperative that discussions addressing model results with stakeholders are moderated by someone with sufficient background knowledge.

Wider application of the IMTA modelling system

The modelling concept used in the IMPAQT project is based on a very generic ecosystem modelling approach. The essential characteristics, i.e., being able to integrate effects of fed and extractive aquaculture on the environment, including the feedback mechanisms within the food web between cultivated species and natural components of the ecosystem, make this framework suitable for other questions as well as relating to improving yields and minimising impacts of aquaculture.

This type of model and schematisation has already been used to assess the impacts of dredging and sand mining on the North Sea ecosystem, and currently Deltares is applying the same modelling tool to gain insight into the very large upscaling of offshore wind on the North Sea. Under the European Green Deal, there are calls to build "digital twins" of systems such as the North Sea. Such concepts are already widely used e.g., in the oil and gas industry and are finding now much wider applications. By combining deterministic process models such as IMTA models with data driven models, their accuracy and applicability can be enhanced.

5 THE IMPAQT INTELLIGENT MANAGEMENT SYSTEM

To understand the farming environment and be informed on the interaction between the various species it is critical to have effective and real-time monitoring, supplying reliable information. To achieve this, the project worked to validate the concept of IMTA by developing an intelligent management platform that supports the operator and improves the understanding of the processes.

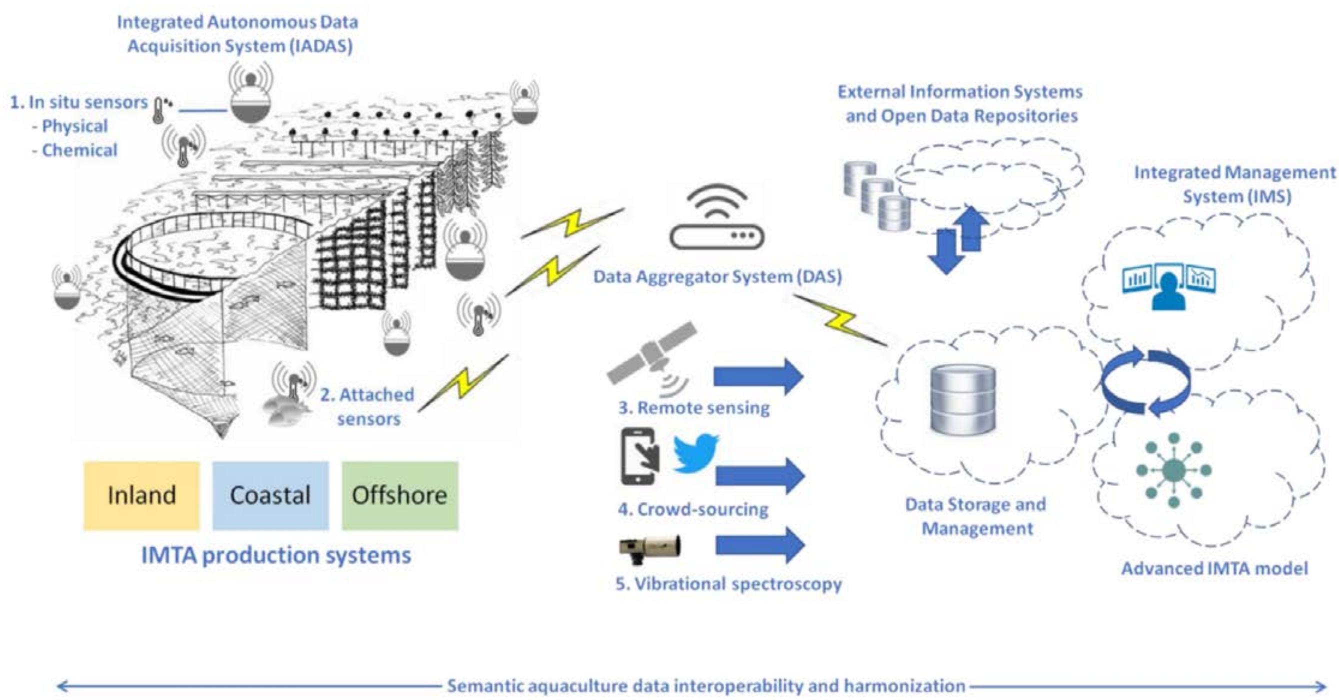


Figure 24. High level overview of IMPAQT platform

A comprehensive scheme of the IMPAQT platform is showed in Figure 24. This comprises several technological innovations covering three main functions: real-time measurements, monitorisation and communication based on two main interacting systems:

- Autonomous Data Acquisition and Communication System
- IMTA Model and Integrated Management System (IMS).

LEARN MORE!

o [Take a look to the IMPAQT results video here.]

5.1. Autonomous Data Acquisition and Communication System

The Autonomous Data Acquisition (IADAS) and Communication System includes the pilot site sensors that are connected to the IADAS (e.g., chemical and physical sensors that obtain data required for the IMS), together with cameras, all which connected to Data Aggregator System (DAS). The system also make use of remote satellite imagery and crowd-sourcing applications connected directly to the cloud, as complementary data feeder to the IMS.

IADAS - Integrated Autonomous Data Acquisition System

The IADAS is a self-contained Integrated Autonomous Data Acquisition System situated locally on the side of the fish pen or structure. It is a versatile data acquisition tool, configurable according to the various sensors it needs to manage and to where it is deployed. It is composed of multiple sensor interfaces, data acquisition system interfaces, a core management module, and an Energy Management System (EMS).

The IADAS has two main purposes. The first is to provide autonomy in terms of power and connectivity. It connects to a wide variety of sensors, manages the transmission protocols, the sensor readings and configuration strategies and the autonomous powering of the overall sensors set as required by the individual pilot sites.

The second purpose is to control the operation of sensor components and to offer connectivity to the sensors with the DAS. It sends the collected data to the DAS and receives (through a downlink) the configuration parameters for each of the individual sensors.

Figure 25. IADAS deployed at the Keywater Fisheries pilot site

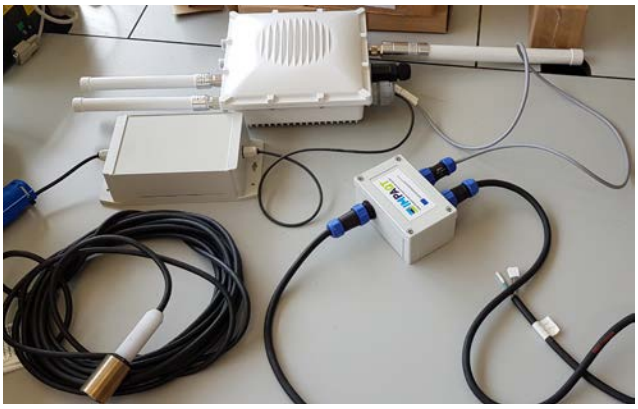


Figure 26. Combined DAS & IADAS, EMS and a Licor sensor in the lab

LEARN MORE!

o IADAS factsheet
o IADAS video

Sensors

The adequate performance of sensors relies on some quantitative properties:

- the sensor's response curve (the plot of the sensor signal versus the concentration of the analyte),
- sensitivity (the variation of the sensor signal with respect to a variation of the analyte concentration),
- resolution (the smallest change of analyte concentration that can be measured),
- reproducibility and reversibility, and the drift that strongly impairs many sensor technologies.

Besides the quantitative properties, the most crucial aspect of sensors is selectivity. This describes the capability of the sensor to detect the target analyte when it is presented in a mixture with other compounds.

Remember that one of the main characteristics of the IMPAQT platform aimed is multi-sensing (i.e., heterogeneous sensors and new/emerging technologies). This requires the definition of several parameters to measure in the IMTA environment. Therefore, IMPAQT consortium analysed the specific requirements and conditions of each of the six pilot plants involved in the project. Each of them provided a list of sensors, as well as a list of parameters of importance to be determined, that according to their experience are of primary importance for the description of the status of their IMTA system.

Eight targets were identified as the core for the management and control of IMTA systems: temperature, salinity, turbidity, current, light, pH, dissolved oxygen, and chlorophyll. Other parameters with a general consensus regarding their importance are related to chemicals such as nitrate, ammonia, phosphorous, and particulate organic matter.

In IMPAQT two type of sensors where integrated in the platform: commercially of-the shelf (COTS) solutions (purchased) and "novel sensors", as the ones developed by the IMPAQT team, since the complete control of IMTA would require more sensors than those commercially available.

Current COTS sensors for nitrites and phosphates are either too costly or not reliable for the scope. In order to ensure a long lifetime and a limited maintenance, it was decided to develop these sensors according to the principle of lab-on-chips. The contribution of these sensors to IMTA is based on the model about the correlation between nitrites and phosphates with aquaculture plant condition.

LEARN MORE!

More about sensors development can be found here:

o D2.1. Report on compatible off-the-shelf sensors and specifications for novel sensors

o D2.4 Final version of Autonomous Data Acquisition and Communication Systems

In the context of in-situ chemical measurements, **Low power consumption platforms for the automatic, repeatable and reliable measurement of nitrites and phosphates, using microfluidic chips were developed.**

The optical detection of nitrites is a lab-on-a-chip where micro-volumes of Griess reaction indicators and water samples are mixed together in a microfluidic chip.

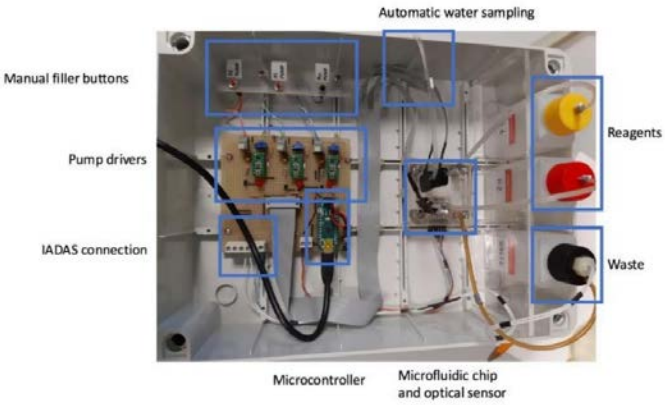


Figure 27. Top view of the nitrites sensor system.

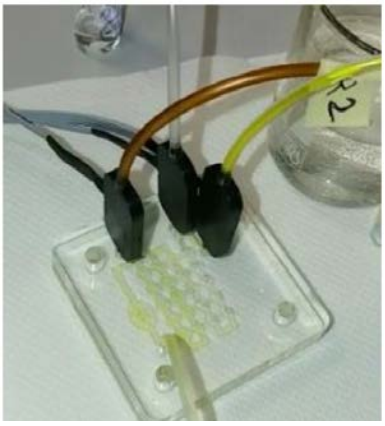


Figure 28. Micro-fluidic chip and trandsducers

For the phosphate sensor, the two possible detection approaches (electrochemical and optical) have been developed in parallel. The phosphate sensor system contains most of the features of nitrites sensor. Thus, for these sensors a microfluidic chip incorporating an electrochemical transducer has been designed and developed.

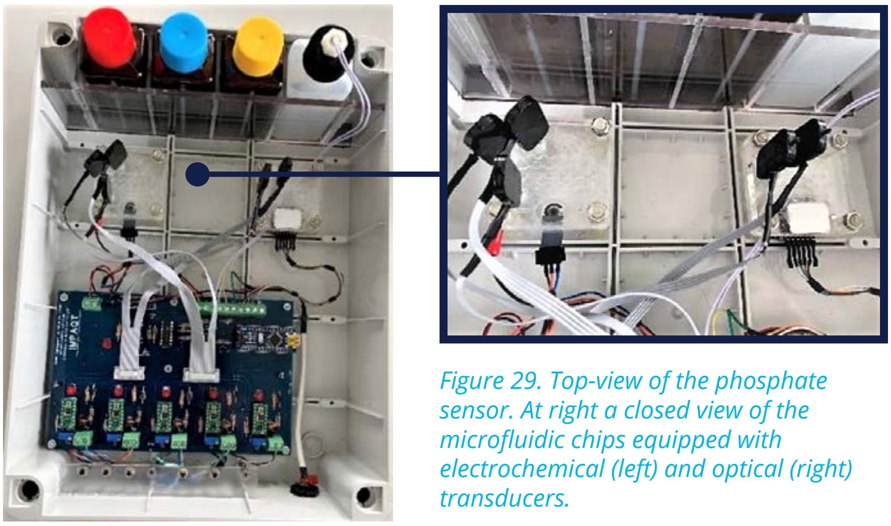


Figure 29. Top-view of the phosphate sensor. At right a closed view of the microfluidic chips equipped with electrochemical (left) and optical (right) transducers.

An 'electronic tongue' was developed for sensing water chemistry. The electronic tongue, by definition, is an empirical instrument and the meaning of the data depends on the application. It can stand alone or be integrated with other developments, e.g., for underwater communication.

LEARN MORE!

o [Find out how the engineered platforms work]

A novel miniaturized low-power, low-cost, acoustic, submersible underwater transmitter node (UWTN) and gateway buoy have been developed to create an underwater sensor networks platform. Each UWTN is integrating accelerometers, temperature and pressure sensors and a unique ID tag, that can be immersed in water and IMTA sites to monitor water flows, seaweeds movements and marine animal activities. It also has an auxiliary sensor interface that can be used to record the external sensors data, such as from nitrites, phosphates, and oxygen level sensors. The gateway buoy logs the received data, performs edge-processing and pushes the results to the cloud by the DAS. The transmitter nodes can be attached to seaweeds, cage nets or left floated in the water.

Figure 30. Attachable seaweed sensor

The goal of the transmitter is to connect sensors data provided by its internal sensors or those externally connected sensor to the gateway buoy using acoustic waves. For this, an acoustic biotelemetry method has been selected as the communication solution because it provides a better robustness comparing to the other communication techniques. The proposed platform enables the collection of sensor data in real-time from an underwater environment which can lead to further knowledge about what is happening beneath the water surface and result in the further development of IMTA sites.

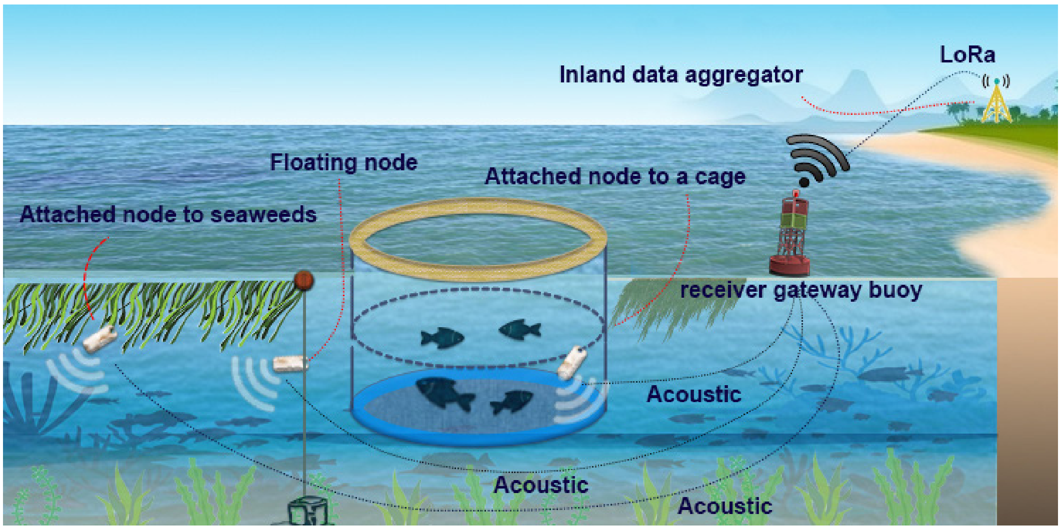


Figure 31. IMPAQT Biotelemetry platform

Biofouling is a phenomenon occurring inevitably in the marine and freshwater environment, causing problems in aquaculture production. When biofouling is established on sensor's surfaces, it disrupts the acquisition of accurate measurements. In IMPAQT the development of biofilms and biofouling on sensors' surface materials was monitored and assessed. This will be described further on in the section about when main project results.

LEARN MORE!

o IMPAQT Acoustic Telemetric Platform factsheet

DAS - Data Aggregator System

The Data Aggregator System (DAS) is the relay point between the IADAS and the cloud system (IMS). It is an edge gateway in charge of interfacing the sensors nodes deployed over the IMTA sites (Ireland freshwater and coastal, Netherland and Turkey) with the cloud platform. Its functionality is to aggregate datasets from all the IADAS and other devices, such as cameras and sensors and communicate validated datasets to the cloud, which is then transferred to the IMS. In some cases, local processing of the data can be made.

Figure 32. Combined DAS & IADAS and EMS inside the data buoy at Marine Institute pilot site

Figure 33. DAS attached on the Netherlands pilot site data buoy. It is located at the right top (white box)

The DAS was designed in such a way to overcome marine context challenges. For example, limited internet connectivity, no energy availability, and other marine conditions that could hinder reliable and resilient performances. Moreover, since pilots have different requirements, a versatile approach had to be chosen for the DAS to allow covering the different use case variations. More information about this can be found in deliverable *D2.4. Final version of Autonomous Data Acquisition and Communication Systems.*

LEARN MORE!

o Learn more about the DAS with this innovation factsheet

EMS – Energy Management System

The Energy Management System (EMS) is a multifaceted device developed to interconnect various components and provide energy to their connected devices such as DAS, IADAS or sensors in a controlled way. Its development answers the need for an efficient energy supply in places that energy resources are limited. The EMS versatility allows various solar panel configurations and different battery capacities to fulfil the power demand, depending on the deployment. It receives power from heterogeneous power sources, which can be by a harvesting solution (renewable solar energy via solar panel), or from an AC power source when a power generator is available, being able to provide reliable energy to the devices.

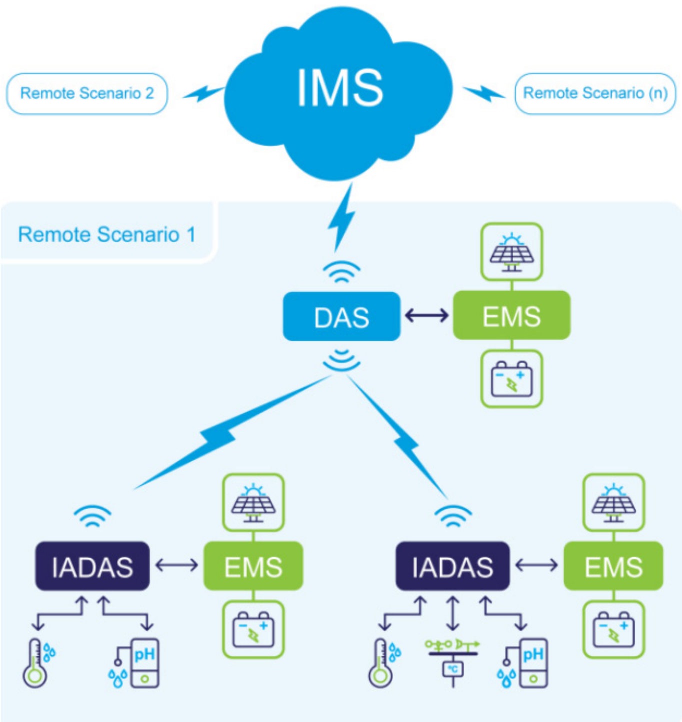


Figure 34. EMS at IMPAQT scenario

During the deployment, it is very important to simplify as much as possible the actions in the field with a bunch of connections to verify such as the ones from the solar panels, battery, IADAS, DAS or the EMS itself. To ease the process, these required actions can be validated using the EMS Visualizer tool. It checks the connection status from the charge controller and the EMS, as well as parameters from the battery, the solar panel and the connected devices represented as load. If the internal connection of EMS fails, the user will see in the lower-right corner a red sign indicating the error. Otherwise the tool indicates
EMS OK status with a green sign (Figure 35).

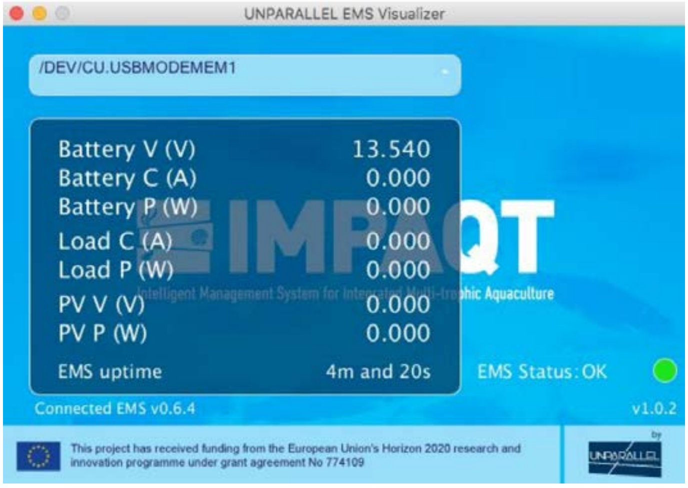


Figure 35. EMS auxiliary visualizer tool with OK status

As in the case of the DAS, two EMS variants were created to fulfil all the pilot needs: a Change Controller Edition, or EMS – CCE, and a Power Channel Edition, or EMS – PCE. The first one is a more complete solution to handle scenarios where a complete energy harvesting solution is required. For the scenarios where is already deployed an energy harvesting system, the EMS - PCE allows to incorporate the functionalities of the EMS concept, but with a low cost, small package size, and low weight as main properties of this version.

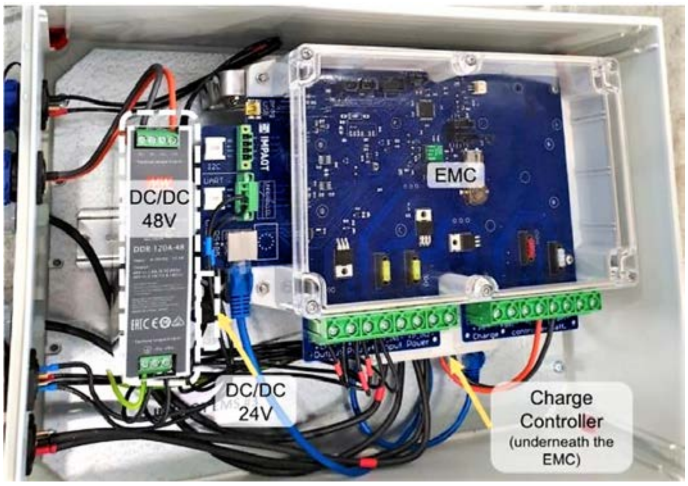


Figure 36. Modules inside the EMS – CCE. The Energy Management Controller (EMC) is a fundamental board to interconnect the other components belonging to the EMS – CCE.

LEARN MORE!

o Check the EMS Innovation factsheet

Satellite radiometry as remote sensing

Satellite imagery has been used for more than twenty years to monitor the marine environment, and to provide invaluable and unique data not only for observation of the climate change (surface temperature and carbon footprint of the oceans) but also in many other fields. Recently,, Earth Observation (remote sensing, usually together with a model output) was also involved in supporting the aquaculture and fisheries industry. For this purpose, data from satellites sensors working in the visible (ocean colour) and infrared (sea surface temperature) part of the electromagnetic spectrum are most commonly utilized.

Earth Observations provide a spatial view of environmental parameters with typical spatial resolution from 10 meters to 1 km, depending on the sensor. The concentrations of chlorophyll-a (Chl-a) and total suspended matter (TSM) are major water quality parameters that can be retrieved using remotely sensed data.

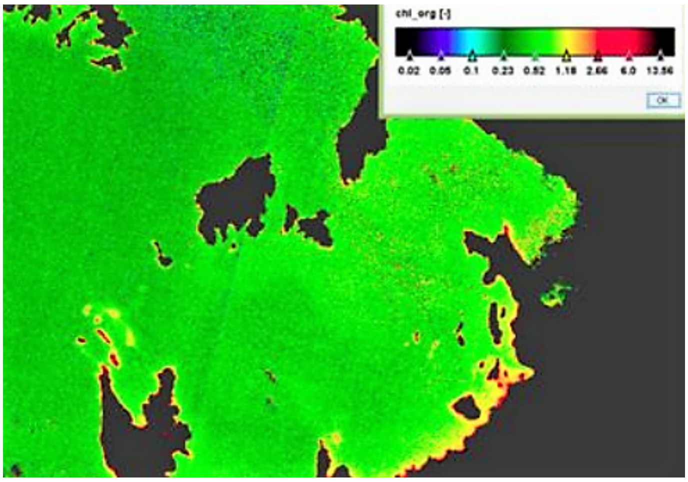


Figure 37. Chlorophyll-a on 2019.05.08

For moderate resolution (300 m, 1 km or more), remote sensing data and model outputs are processed in the "Argans Platform" to generate data, images and metadata available for the IMPAQT platform. Original data are automatically downloaded daily from different providers (CMES/Copernicus, ACRI remote sensing database, spatial agency) and processed at Argans to provide analysed data, images and metadata. The results are made available on a dedicated FTP server and they can be accessed and used by the IMPAQT platform as sensor measurement. For example, statistics can be used in decision trees as the in-situ measures, and visualized in the IMS dashboard. Images can be visualized on the dashboard as well. The same methodology is applied for high resolution data.

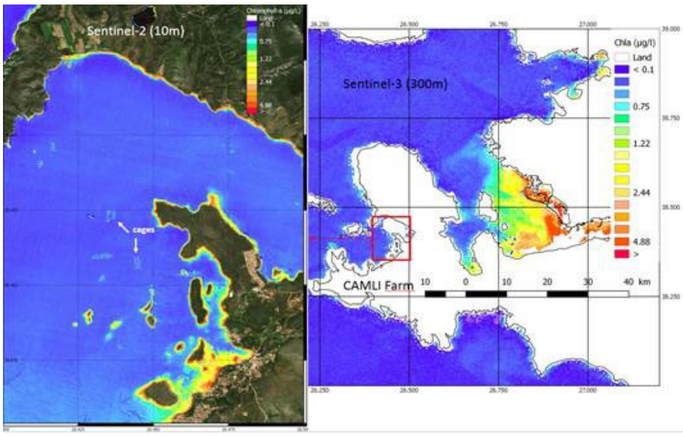


Figure 38. High resolution Chlorophyll-a concentration estimated from satellite imagery at 10m res (Sentinel-2) and 300m (Sentinel-2) for IMPAQT site close to Izmir (Turkey)

European Space Agency through European Union's Earth Observation Programme (Copernicus) as well other national agencies are providing ocean colour satellite data free of charge so there no cost related to these sensors.

LEARN MORE!

o [Take a look to this factsheet about the use of Medium & High-Resolution Satellite imagery in IMPAQT]

Crowd Sourced Data as sensor

The use of participative science in IMPAQT is something rather innovative and its uptake by aquaculture professionals is starting. This means that people, expert or non-expert, are doing observation and reporting, under request or spontaneously, with the help of a smartphone or tablet. The observations could be descriptive (e.g., I see a blue flower) and/or quantitative (e.g., measurements of a noise by recording or coloration analysis by the camera). Observations are time and location-stamped at the right time and location of their acquisition.

Success of an observation network based on this participative approach is generally achieved if the observations made are simple and precise, if the participants are willing or committed to report and, often, if participants feel that they are part of a team sharing the same spirit.

With this rationale, another innovation has been brought to the IMPAQT system by adding a smartphone application. This is used by operators to add observations that could not be easily reported by a classical sensor (e.g., abnormal fish behaviour or presence of predators around cages). Once an observation is made, it is directly sent to the IMPAQT system which uses it as any other measurement as support for decision-making.

The application developed in the project is based on the SIMPLEX™ system initially developed for the jellyfish monitoring and which has progressively been expanded to other types of observations. The SIMPLEX™ system has been parametrized for IMPAQT, for farm operator observations reporting or occasional volunteer observers reporting. It is very simple to use, consisting in a hierarchical collect of information with a maximum of three steps (e.g., “predator yes/no” – if yes then “predator dolphins or jellyfish or ….”, and then a possibility to take and record a picture – see figure 39).

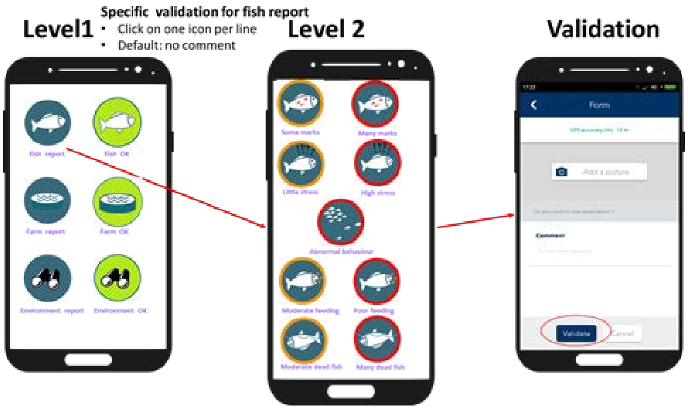


Figure 39. SIMPLEX™ interfaces; example of fish report.

The SIMPLEX™ configuration is now available for IMPAQT for Android and iPhone through the relevant stores in 10 different languages. It has been well appreciated by the site managers and proven to be an innovative, valuable tool to report observation in addition to other measurements.

LEARN MORE!

Two innovation factsheets to learn more about Crowed Sourcing as a sensor:

o [IMPAQT Crowd Sourcing]
o [Use of smartphone application in IMPAQT system]

5.2. IMTA Model and Integrated Management System

The IMTA Model (described in Section 4.) and Integrated Management System (IMS) receives real-time data from two main communication services:

- sensor measurements and camera data coming from the DAS connected to the Internet through a network server, including crowd sourced data (via a smart application)
- and remote sensing and satellite data through an FTP server. The IMS also offers the capability for External Information Systems and Open Data sources (e.g., weather) to be connected.

The IMS is a powerful Decision Support System operating at the scale of an IMTA farm. It is the cloud-based system hosting the IMTA services and providing interfaces to the users (i.e., dashboard) and the different data sources (e.g., satellite imagery, crowdsource data, weather information). The IMS adds value to the data by providing analytics, feedback, context, actuation, and operational guidance.

Taking the data from physical sensors and combining them with production and welfare data (gathered via the developed SIMPLEX App), satellite data, models, and remote data sources, the IMS uses algorithms to provide real-time operation feedback on the condition of the environment, the welfare of the species, and the status of the stocks as well as warnings, alerts, feeding and harvesting suggestions, and feedback on impacts and the 'IMTA'-ness of the operation.

The IMS workflow is based on several subsystems (Figure 40) attending to different business procedures. These subsystems are the already described IADAS, DAS, and Remote Sensing, as well as Data Broker, security system, data management, Device Management Databases, IMS User Interface, dashboard, and IMS Applications and Smart Services.

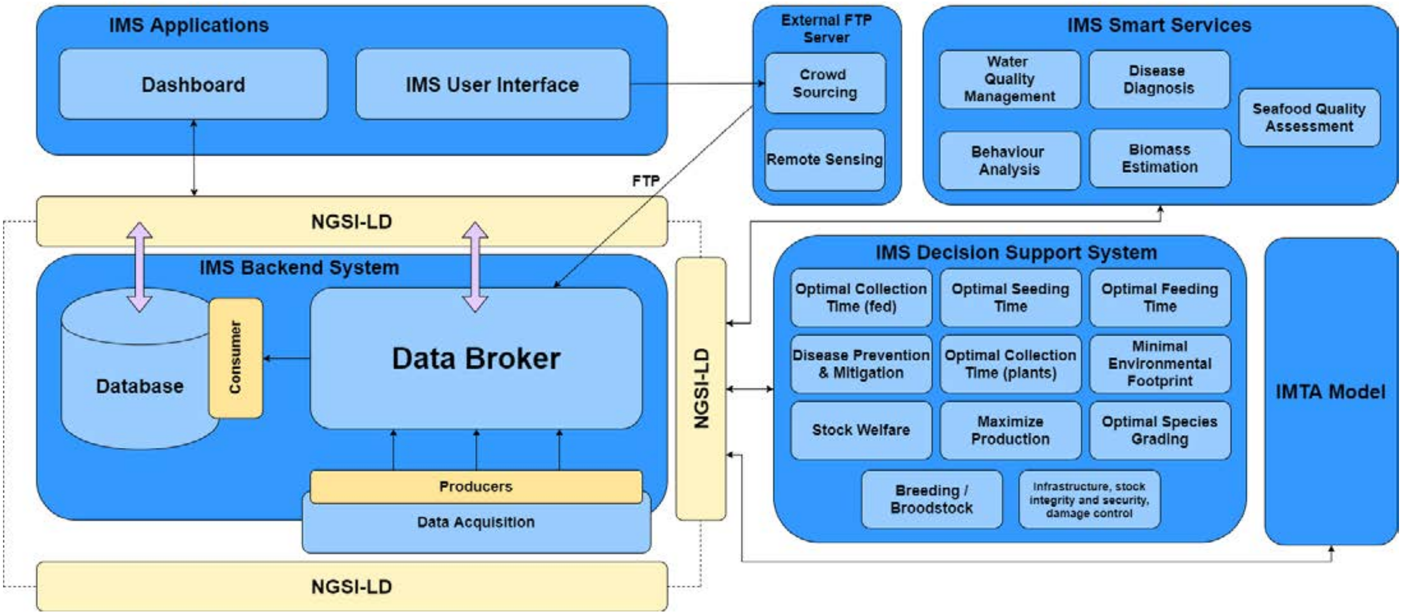


Figure 40. IMS component architecture

LEARN MORE!

o The complete information about the IMS functionalities is very well described throughout the deliverable D3.8. Final version of Integrated Management System.

o An overview of IMS is presented in the IMPAQT Integrated Management System (IMS) innovation factsheet.

The Dashboard is the main access point for the operator to use the IMS. It can retrieve data to visualize by using appropriate APIs to provide, consume and subscribe to context information in multiple scenarios and involving multiple stakeholders. The dashboard allows a complete monitoring with several interactive pages available for:

Environmental monitoring, where the operator can inspect the trend of the different measured parameters by the available sensors and receive relevant warnings, among others functionalities;

Camera monitoring, with camera streaming to selectively check the status of the site via underwater or with on-surface security cameras;

Operations, allowing operational data to be stored and managed,

Stock Welfare Index describes a series of aspects of the farm's status to give a general, quantified overview of the current situation (e.g., condition, behaviour, water quality):

Ecological footprint includes the generation of environmental analytics reports as well as statistics about the site's operation and impact on the surrounding area;

Optimal feeding aiming to optimize the way that the feeding procedure takes place, in terms of timing as well as amount and feed type;

Production planning provides a visualization of the production cycle of the species and the current situation, including graphical visualization of the species' growth curve or biomass increase in time, among others, offering a deeper insight on the site's growing rate;

Disease prevention and mitigation considers a series of protocols that are validated by the operator. A set of parameters and observations are taken into consideration to provide suggestions about common disease situations based on the current status of the site, seasonality etc. Suggestions arrive in the form of messages in the corresponding message boards;

Breeding recording enables the management of the different tagged fish and their matching with suitable mates that are going to provide successful results;

Satellite images can be visualized here showing the latest footage as well as the processing results that estimate specific parameters such as turbidity or chlorophylla;

Tasks regarding maintenance as well as husbandry actions are recorded and visualized in a task board that is the product of the planning algorithms that are executed in the system;

Settings feature allowing to the operator to efficiently manage the site's configuration;

Video monitoring, where any potential cameras that have been installed in the system can be accessed for live streaming or to access previously recorded footage.

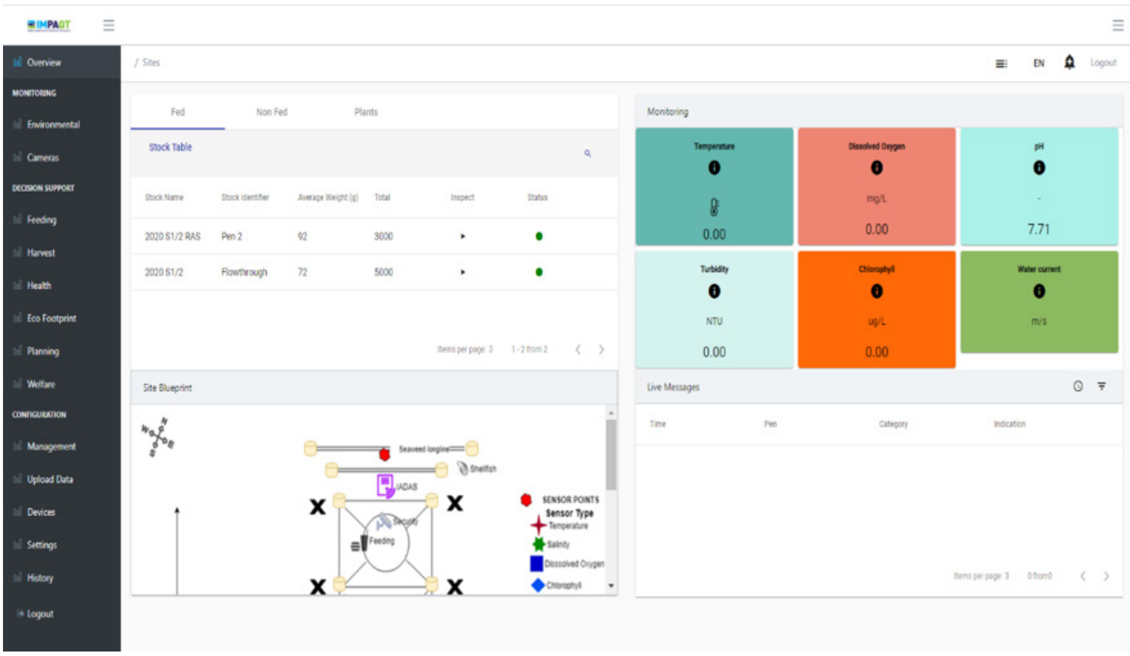


Figure 41-1. IMS Dashboard. An overview of the site is provided, including aspects of the monitoring capabilities of the IMS, environmental and production information. In specific, information is provided for most recent values of specific environmental parameters as well as the active stock information.

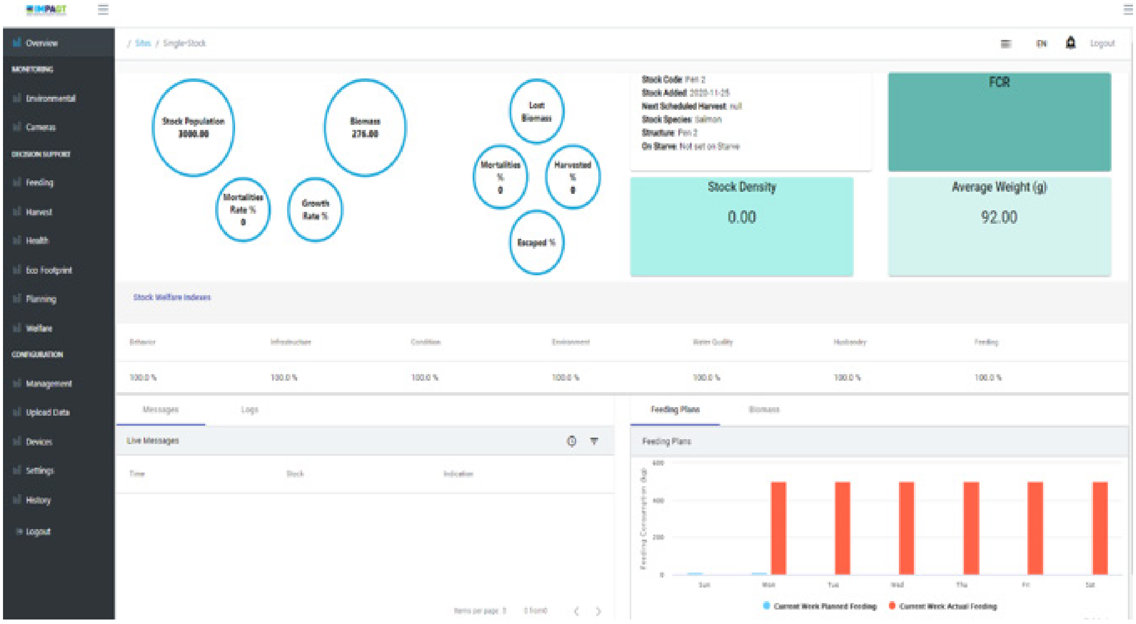


Figure 41-2. IMS Dashboard. Here the operator can monitor the installed IMTA structures (pens, ponds, longlines, mussel units, etc.) and find information on production data such as biomass, average weight, FCR, stock density, species numbers, etc.

The IMS User Interface stores observations into a database at the time of acquisition (the record is time-stamped by the application) and its location. The observers also have the capability to send an image to complement this observation.

The IMS Decision Support System covers the core business and operational needs of an IMTA farm, in the form of Decision Trees, addressing the following business cases: Optimal Collection Time (fed), Optimal Seeding Time, Optimal Feeding Time, Disease Prevention and Mitigation, Optimal Collection Time (plants), Minimal Environmental Footprint, Stock Welfare. Infrastructure, Stock Integrity & Security, Damage Control answer the need of the identification and management of critical events that need to be prioritized in a task-oriented approach where multiple tasks may be overlapped.

Among the Smart Services:

- Behaviour monitoring refers to observing spatial behaviour of fish to monitor fish daily activity.
- Disease Diagnosis addresses early identification of warning signs that may indicate disease in the IMTA population through image processing/comparison and fusion with sensory data.
- Water Quality Management offers functionalities such as the prediction of future instances of parameters and online anomaly detection and categorization.
- Seafood Quality Assessment refers to an extensive list of methods and results from pilot sites available in several project deliverables: D3.1. Specification on individual components of IMS and on their integration, D3.3. First version of Integrated Management System, D3.5. Final implementation of individual components of IMS, and D3.8. Final version of Integrated Management System. Analysis such as microbiological analysis and spectroscopic methods are widely described, and their main results will be presented further on here.

An example of one smart service is provided, i.e., fish disease diagnosis.

Figure 42. Fish disease diagnosis

Fish diseases is one of the factors that are always a concern for aquaculture producers. Outbreaks are to be avoided where possible, or when suitable, efficient treatment should be applied as rapidly as possible. The use of computer vision techniques can be helpful in improving diagnosis and treatment in the coming years.

The main target studied in this component, is the identification of marks or scars in the fish body that may indicate a problem. This identification can give us a prediction in terms of possible disease. For this purpose, the IMS algorithms are analysed in 3 stages:

a. Fish Detection

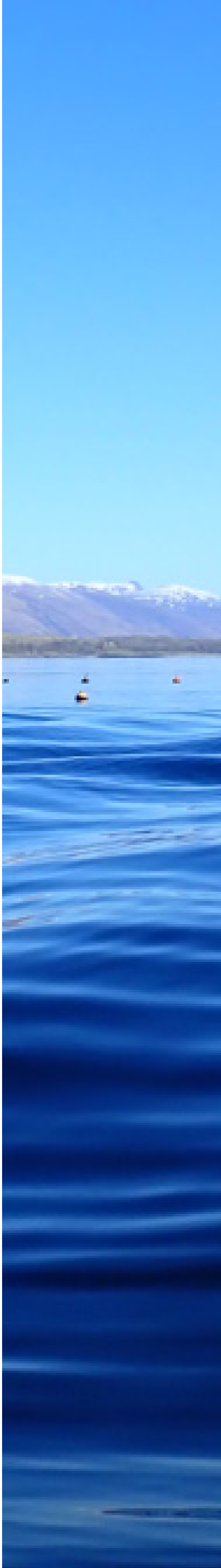
b. Background Reduction

c. Fish Disease Diagnosis

Fish disease diagnosis is the final component. The disease diagnosis algorithm is based on a Neural Network that uses as input an image, the result of the background reduction procedure. Provided that the input of model is an image, the prediction is based on scars, marks, and any distortion in the fish body. The algorithm output is a prediction that represents the probability of infection in the fish (Figure 42), which can serve as an indication of a disease or problem, and alerts the producer to enable prevention. The algorithm's output is also fused with input data from sensors or satellites (e.g., DO, Chl-a) and operator reports and data (e.g., phytoplankton, jellyfish, parasite presence). This work is also extended to other species, like seaweed and shellfish.

Over the course of the project, the IMPAQT IMS has become an important platform providing information and management solutions for producers and regulators alike. The backbone for development has been the detailed assessment of business requirements for each pilot site described in the deliverable D1.3. IMTA system design specifications, from which decision-trees have been generated. Each pilot site addresses the evaluation of the IMS and their interesting results are presented in Section 6.

6 WORKING TOGETHER FOR SUCCESSFUL RESULTS



Having presented the methodological aspects and technologies used in the design of the IMPAQT platform, in this section we will focus on its implementation and validation.

To summarise, the IMPAQT advanced management platform for the sustainable development of IMTA production systems used commercial off-the-shelf (COTS) sensors as well as developed and deployed novel sensors and data sources, together with smart systems required for long-term autonomous monitoring of environmental, non-environmental and biotic parameters at the cultivation sites. Besides, the advanced IMTA model provided spatially explicit information on how the different farm components interact with the environment on an ecosystem scale, offering planning decision support to pilot site operators. Finally, the Integrated Management System (IMS), operating at the scale of each pilot site, was developed to enable enhanced and data-driven operational decisions concerning animal welfare, production optimization, environmental protection and product quality.

Even though the advanced management platform seems complex, its functionalities and benefits are very easy to understand. However, this process towards sustainability has to be assessed from different points of view. For example, in IMTA systems, several stakeholders are involved, and the impact of the project results might be slightly different from one to another. Moreover, the assessment of how IMPAQT developments and implementation results are changing the paradigm of aquaculture has to be made at multiple levels.

After the final design of the IMTA system and evaluations of models, as well as product quality and safety analysis performed in the lab; fields trials were the rational step to comprehend the impact of IMPAQT. In this regard, each pilot site provides key results to progress IMTA.

6.1. Clearing the path for IMTA production systems

At the six pilot sites involved in the IMPAQT project, several field trials were made to assess the performance of IMTA, with continuous monitoring and adaptations to overcome different issues. The experience gained at IMPAQT shows both specific and general benefits of IMTA, but also challenges, and thus, although the path towards a more sustainable and efficient aquaculture is not a smooth one, it is much clearer after the project.

Besides the main findings detailed below, the different spatial configurations of the six IMTA set-ups offer interesting insights that can be consulted in the public deliverable D.4.3. Pilot demonstrators and validation results.

At the UK pilot site (PaB), several field trials were performed for seaweeds and oysters. These trials were monitoring programmes that followed key performance parameters of either species group over time, and over consecutive years for seaweed, in conjunction with monitoring prevailing environmental conditions.

The consecutive seaweed cultivation seasons at this site of 2 (*Alaria esculenta* [Aesc] and *Saccharina latissima* [Slat]) and 3 (Aesc, Slat and Laminaria digitate [Ldig]) species showed differences in biomass yield, i.e., for Aesc and Slat were overall higher in 2020-2021, with Slat reaching new record levels of >16 kg/m at this site.

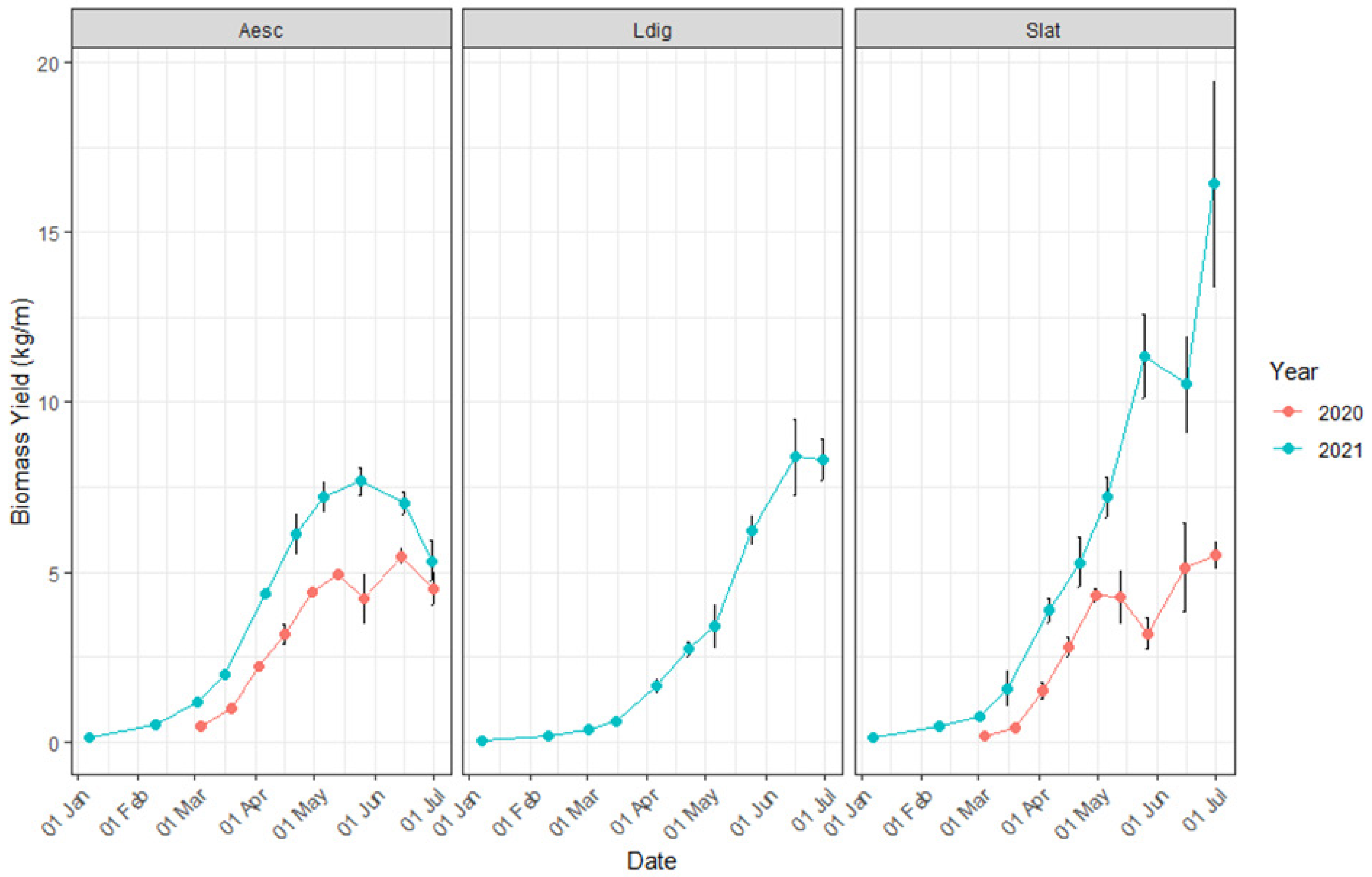


Figure 43. Temporal change in biomass yield (kg/m) of three seaweed species Alaria esculenta (Aesc), Saccharina latissima (Slat) and Laminaria digitate (Ldig), and difference across consecutive cultivation cycles ('2020' = 2019-20, '2021' = 2020-21)

However, this period experienced overall less rainfall, higher nutrient levels and less severe weather over the winter months, as well as warmer days in spring compared to the 2019-2020 stock. This may explain some of the variation in biomass yield observed between the years. In addition, the seaweed seeding method used for the second cycle has improved from previous years, with the seeded twine being deployed more densely onto the growing lines (i.e., more twine turns per linear meter line). More precisely, this optimised deployment technique resulted in a marked increase in sporophyte density, expressed as number of individuals per meter growing line (20/3/20 vs. 17/3/21, respectively: Aesc: 238±14 vs. 305±83, and Slat: 211±62 vs 291±18).

Differences in the timely onset and intensity of biofouling pressure were also registered, with the second season starting two weeks before the first one. Another interesting finding affects the optimum harvest time, a variable of great importance as one has to find the perfect balance between biomass yield and fouling pressure (i.e., high yield but none or low biofouling cover affecting the appearance, composition and application potential of the crop). The UK pilot site team found mid to late May to be the optimum harvest time, and not mid to late June as had been practised prior to IMPAQT.

Hatchery-reared oyster spat were deployed at PaB in co-culture with seaweed (subtidal cultivation), but also at a neighbouring commercial native oyster production site (Lochnell Oysters [LO], 'classic' intertidal oyster monoculture). After eight months of their deployment, the intertidal stock at LO showed on average larger values for shell length than the subtidal stock at PaB, whilst also presenting notable differences in shell shape, i.e., at LO spiked shell edges, at PaB smooth shell edges. Whilst being on average smaller, PaB oysters have a higher meat content relative to their size.

At the NSF pilot site, the IMTA setup showed that both seaweed (*Saccharina latissima*) and mussels (*Mytilus edulis*) can grow well in the harsh offshore conditions at 12 km of the coast in the Netherlands.

Figure 44. Seaweed harvest at the NSF pilot site, after their relocation from coastal to inshore farm due to structural damage of the IMTA setup

Although the harsh conditions of the North Sea and several storms damaged the IMTA setup, structural side improvements were successfully implemented. Seaweed seeded lines deployed at the offshore pilot site had to be moved to an inshore environment but a successfully harvest was achieved. Another cultivation line has been also damaged but underwater footage showed that the seaweed growth was progressing as expected. In the same line, the mussel module was developing mussel spat adequately as seen in the underwater footage.

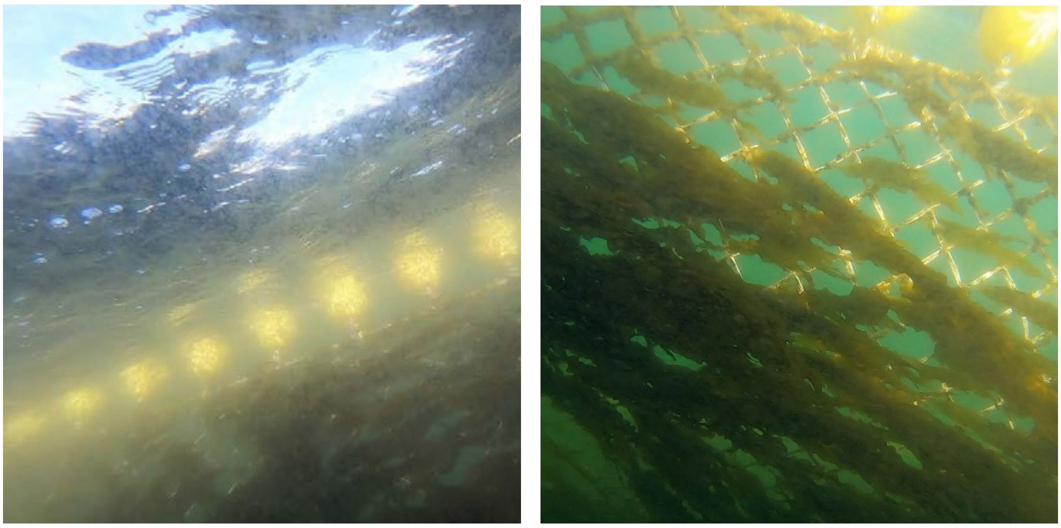


Figure 45. Underwater footage seaweed growth SMAC3.0

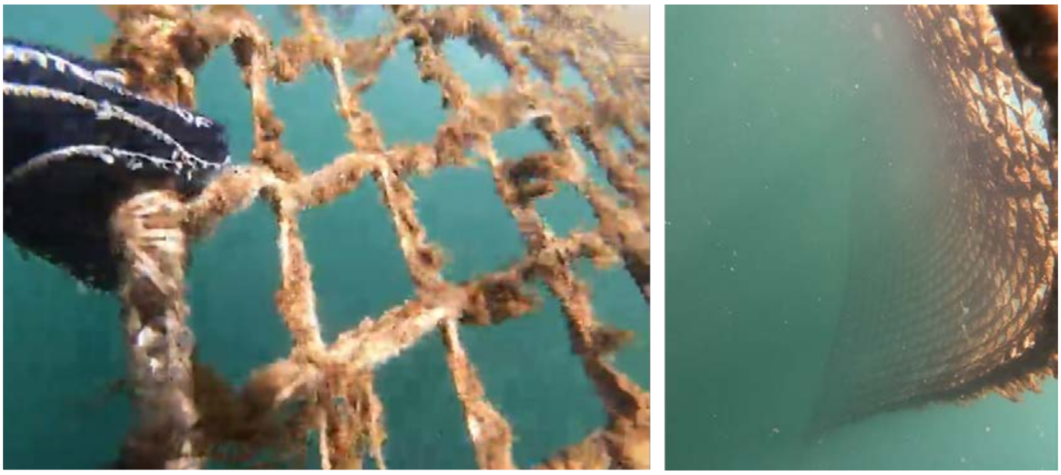


Figure 46. Underwater footage mussel spat at the Mussel Module

A 'typical' IMTA scenario was deployed at the MI coastal pilot site, with a fed component (fish) and two extractive levels (shellfish and algae). Here, 4 pens were stocked with finfish (*Salmo salar*), approximately 12,000 fish in total, 250 m of line was seeded with *Alaria esculenta*, and 580 scallop (*Pecten maximus*) were suspended from the pens in lantern nets.

Figure 47. IMTA species at Lehanagh Pool - Alaria esculenta on longline, scallops, and juvenile lobster (6 months)

In this trial, the decision was made to cultivate these species along with European lobster within the current grid infrastructure traditionally established to hold salmon pens. Two hundred and four lobster individuals were put to sea at stage 5 development. The stock was cultivated in a Sea Based Container Culture units (SBCC) traditionally used to collect and cultivate juvenile shellfish such as oyster. Here they were repurposed for holding lobster and suspended from sea pens. After 6 months at sea, the SBCC have a wide assemblage of organisms providing a feed source for the lobster which was continuing to moult and grow in size. *Alaria esculenta*, seeded to kuralon twine, was deployed and after 6 months the stock was harvested. Scallop were transferred to site at average weight of 18.55 g.

Therefore, this pilot saw the successful installation of 3 new species to a monoculture site establishing an IMTA production system of 4 species (1 fed, 2 extractives and 1 plant species). Moreover, the IMTA installation at the pilot was successful in yielding two crops of *Alaria esculenta* and a small crop of Pecten maximus. Despite the impact of several storm systems, the biomass production on this site was successful in informing the set-out research questions.

Part of the seaweed of an IMTA system was successfully harvested also at the Çamli site, indicating a good integration with sea bass, even though the cultivated seaweed there, *Ulva rigida*, is quite sensitive to strong environmental conditions, such as those found at the Aegean Sea. At this pilot site, sea bass, mussels and seaweed were co-cultivated. The main benefit here was the production of additional 2 tonnes of mussel and 1 kg of seaweed. Moreover, analysis of product quality and safety showed good results.

The YSFRI pilot is a commercial aquaculture bay for IMTA of several species, and the production activities are well regulated with decades of experience and local governmental-environment related policies. It can be considered that here, the IMTA system is already demonstrated as a well working model for aquaculture. They cultivate a combination of kelp (*Saccharina japonica*) and Pacific oysters (*Crassostrea gigas*) for decades at almost the bay scale. Both the kelp and oyster are non-feeding species, which an internal recycle of biogenic element is supposed. Since fall in 2020, to promote the recycle use of natural resource from the large-scale aquaculture, artificial reefs have been deployed in some area of the bay, as to provide shelter for small fish and benthic organisms. Also, sea cucumbers (*Acanthopanax spinose*) are being cultured within these artificial reefs, as to use the sedimentation of the suspended culture animals.

Some of the overall benefits of IMTA, both known and potential, were seen throughout the IMPAQT project. For example, SAMS (the UK pilot site) informs that the transition under IMPAQT from seaweed monoculture to co-culture with shellfish has overall improved the site's seasonal and spatial efficiency. Whilst the site was only in use for 8-9 month per year for growing seaweeds, it is now in operation all year round with native oysters reaching their marketable size after several years.

Moreover, the Marine Institute conclude from their pilot site that IMTA can be perfectly applied to traditional monoculture with minimal costs to the operator. The capital expenses were low due to using non-traditional structures and utilising the mooring structures that are already in place to support the fed species pens. Utilising the existing grid structure successfully yielded a crop of seaweed with maximum biomass of 9 kg/m and provided a culture habitat for scallop and lobster at the Irish coastal site. In this way, the use of materials and the impacts to the seabed are reduced. This also maximises the existing footprint of present infrastructure, and allows co-locating the species in close proximity to each other. A reduced amount of non-recyclable material deployed, supporting a healthy ecosystem status at the site it is also a benefit informed by the PaB site.

The application of low trophic species has little operational expenditure for the operator. The non-fed species do not require a high level of maintenance, only recommended inspection after storm events, some sporadic routine maintenance, or nearing the end of the production cycle to ascertain harvest yield. This can be further reduced by utilising a management system such as the one develolped by IMPAQT, which has in-build intelligence to indicate approximate growth rates and environmental indicators of growth, reducing the need for stock and site inspections. At the IMPAQT pilot sites, less visits were required when the autonomous environmental monitoring was applied successfully. At the SAMS pilot, the performance of both seaweeds and oysters will continue to be monitored after the project ends, and for trialling further shellfish species (e.g., scallops).

As seen in several IMPAQT pilot sites (UK, Ireland coastal, Çamli), an increase of the diversity of crops applying IMTA concept, contributes to the biodiversity and good environmental status of the ecosystem. The biomass increases directly by offering additional crops as well as indirectly by exploiting the synergies between the species groups. Seaweed biomass exceeding previous cultivation years, as happened at the UK site is also due to improved monitoring during IMPAQT and optimisation of growing techniques.

The risk of eutrophication is minimised due to bioremediation of dissolved and particulate organic matter as well as nutrients. The Marine Institute relate how seaweed can act as an important remediation of fish waste in the environment. At the Lehanagh Pool, the potential of *Alaria esculenta* to remediate/remove salmon waste was estimated at 11 -14% of the nitrogen, 17 – 21% of the phosphorus, and 13 – 16% of the carbon. Reduced environmental impact is demonstrated as waste from the salmon at the farm was remediated by the low trophic species added, through nutrient cycling in the kelp and the scallop, whilst the lobster also showed utilisation of salmon waste.

The added trophic species can provide also additional revenue streams for operators. When scaled up to a commercial level in Ireland (commercial sized 6 pen grid) there is a potential to culture over 4 tonnes of high value seaweed as an additional crop during the winter months as well as the extra added value of turning to a more circular production system. There is an increase in commercial biomass produced, along with a diversity of products which spread economic risk and facilitates better cash flow.

6.2. Product quality and safety, the added value

Among several factors affecting seafood quality, the level of bacteria population is of critical importance since this parameter affects several quality characteristics, such as odour and overall appearance. Several Gram-negative microorganisms belonging most frequently to *Pseudomonas* and *Aeromonas genus*, and sulfur-producing bacteria, are involved in the quality degradation of fish and seafood.

Figure 48. Seaweed samples at the lab

There is no doubt about the strong need for seafood quality monitoring and quality assurance through the whole value chain. Therefore, the IMPAQT project looked at the time consuming conventional analytical methods and considered the development of sensitive, low cost, and rapid analytical technologies, and have attempted to simulate the implementation of Process analytical technologies (PAT) in product quality assessments.

In collaboration with Marine Institute, SAMS and Çamli pilot site, the Agricultural University of Athens (AUA) have analysed in the lab several batches of products. Additionally, AUA developed new models for the rapid evaluation of seaweed quality by applying spectroscopic techniques and sensor systems. A detailed description of these analysis and results can be found in several project deliverables, such as: D1.4. Final IMTA system design specifications, D3.3. First version of Integrated Management System, D3.5. Final implementation of individual components of IMS, D3.8. Final implementation of individual components of IMS, and D4.3. Final version of integrated reference platform.

Briefly, both, fresh/frozen and dried samples of seaweeds *Alaria esculenta* and *Saccharina latissima* have been provided by SAMS from consecutive production years (2019 and 2020) and analysed for food safety indices. Overall, results revealed differences in the microbial load as well as community composition and relative proportions between seaweed species and production years, with the latter likely being associated with differences in environmental cultivation conditions between years. The microbiological quality and safety of both wet and dry seaweeds seems to be of a remarkable higher quality in the 2020 harvest than in the 2019 one. This difference might be attributed to three different variables: different time period of harvest (two weeks earlier in 2020), different environmental conditions (such as temperature or salinity), and/or more appropriate handling immediately after harvest.

Seabass and seaweed (dried Ulva spp.) samples from the Çamli pilot site were also analysed. The same rationale is followed, comparing samples from two harvest periods (2020 and 2021). Overall, no important differences were observed between the two periods and species. Nonetheless, seabass harvest in 2021, thus more progress in the IMTA system, showed lower growth rate of specific spoilage microbial groups (e.g., Pseudomonas spp., B. thermosphacta and H2S) producing bacteria.

The Marine Institute have also provided several samples for analysis. A large amount of the work was related to the monitoring of seaweed quality as there is few information about the microbiological quality and safety of seaweed intended for human consumption. Moreover, the impact of IMTA on the microbiological quality of seafood was investigated, as well as the influence of the environmental conditions on the quality and safety of seafood products.

Therefore, AUA studied the spoilage potential as well as the presence of pathogenic bacteria in three different species (salmon Salmo salar, seaweed *Alaria esculenta* and scallops) cultivated in the coastal IMTA system of the Marine Institute. In addition, several nutritional parameters were evaluated so as to provide a preliminary view about the nutritional quality of the products. Nutritional parameters of the 3 different species — together with sub-cases — were analysed. No particular differences were observed in salmon of different harvest seasons, neither in the seabass samples provided by Çamli. The tested nutritional parameters of *Alaria* differed across the years, with higher protein content for the 2021 samples.

The low initial microbial population of the total viable account but also of well-known spoilers, such as Pseudomonas, B. thermosphacta and sulfur-producing bacteria indicate products of high microbiological quality. Additionally, low level of bacteria of Enterobacteriaceae family is found, a quite important parameter for the quality of the products, since bacteria of this family are considered as hygiene indicators.
Different samples of salmon and *Alaria* from different seasons were analysed, so as to record any variability in products quality, related to harvest season (different environmental conditions). Microbial profile of seaweed harvested in 3 different harvest years (2019, 2020, 2021) was significantly differentiated (xx). Products of 2019 were of the lower quality, while in 2021 products microbial counts were at remarkably low levels. On the other hand, different environmental conditions did not affect the microbiological quality of salmon. Finally, pathogenic bacteria were absent in the Marine Institute products, in any of environmental conditions and harvest time.

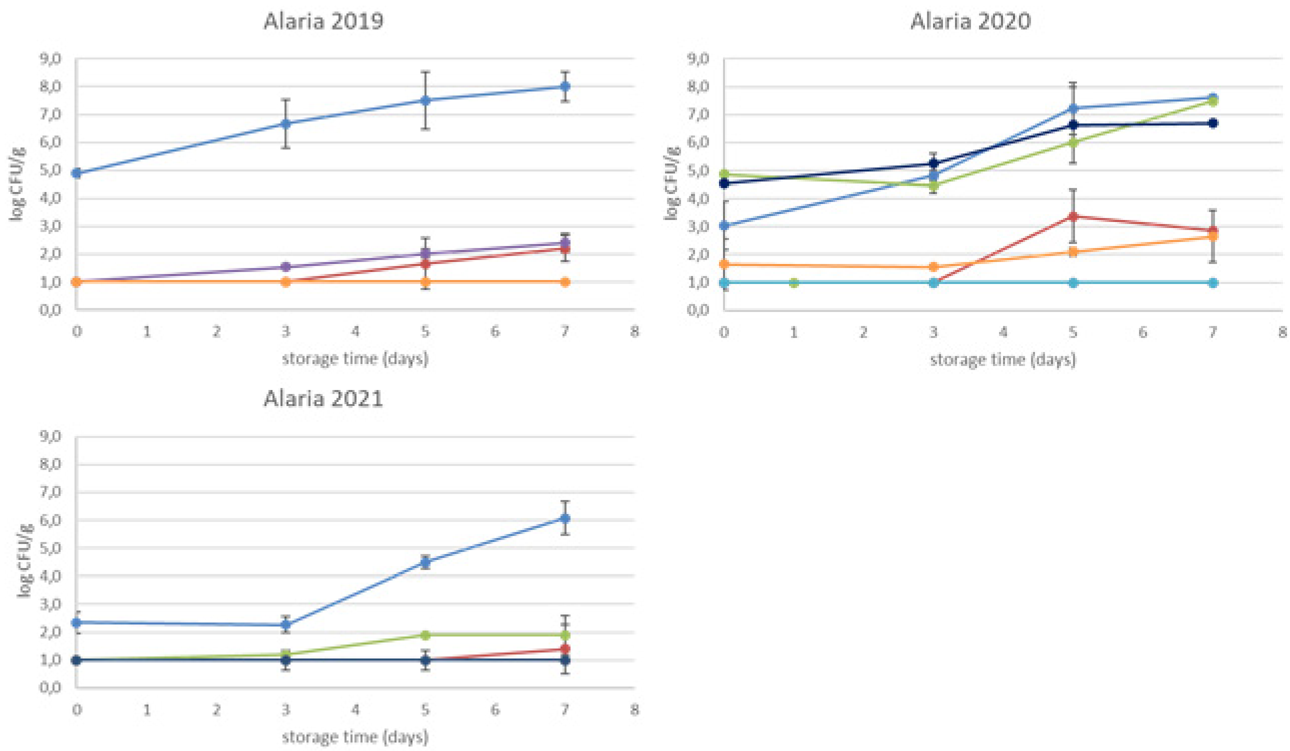


Figure 49. Microbial evolution of Alaria esculenta obtained from MI in 3 different years

6.3. Intelligent Management System performance

Even in countries where IMTA is a well-known practice, the management of large-scale IMTA areas remains challenging. Nevertheless, implementing and applying new/emerging technologies and innovations in monitoring and management systems can provide guidance to adaptively manage IMTA systems to ensure ongoing sustainability.

As described in Section 5, IMPAQT developed several novel technologies and most of them are designed in such a way to be integrated in one multi-purpose, multi-sensing, and multi-functional management platform for sustainable IMTA production. However, for several reasons, such as the difficulties generated by the COVID-19 pandemic (with travelling restrictions), some aspects of the IMPAQT platform could not be fully deployed. This situation significantly delayed the pilot reaching full operational status using the IMPAQT system within a preferred timeframe due to limited access to labs, engineering suites and access to pilot sites, in addition with delays in sourcing components and shipping. Despite these challenges, the IMPAQT team kept working looking for alternatives. In some cases, all the components of the IMPAQT platform were remotely trialled and sent to the pilot owner to be installed by the operators. When this option was impossible, commercial solutions with similar characteristics to the technology developed at IMPAQT were used. Most of the encountered challenges were exceptional and would not happen in a normal circumstances.

Equivalent commercial solutions of some of the IMPAQT platform functionalities were used at the UK pilot site. Using such commercial solution allowed for the inter-comparison with the IMPAQT platform deployed at other pilot sites, and demonstration of the inter-operability of the remote management system (IMS), whilst data were readily available for it and data-driven decision-making therein.

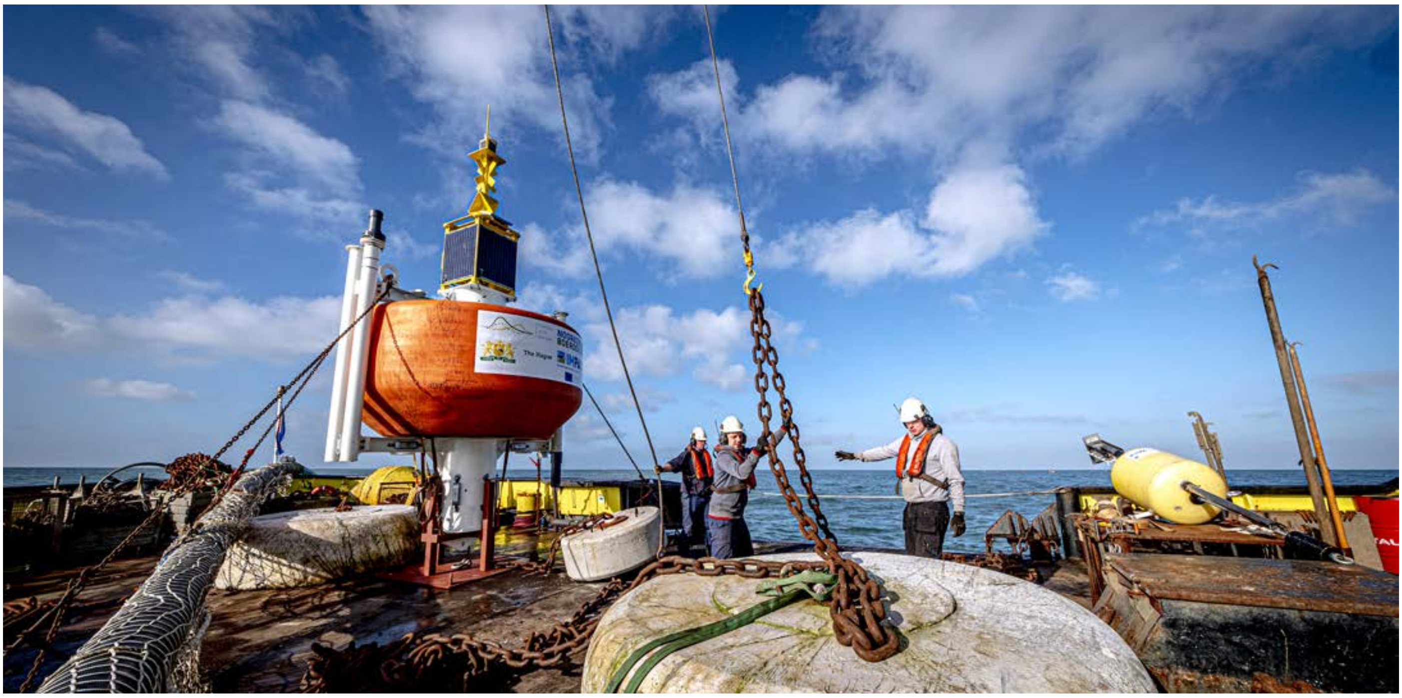
Since deployment at the UK pilot site, the platform worked well with data being recorded and transmitted to the IMS in real-time. The IMS main functionalities exploited at this site were:

- the display of real-time and manually collected data for the cultivation environment and farmed stocks;
- input of historic site data allowing actions such as inter-annual comparison;
- decision support applications by calculating indices of importance for production e.g., stock growth, stock welfare, ecological footprint, and many more. For example, the user can inspect individual stocks, e.g., a seaweed growing line and follow the progression in biomass yield and blade length in conjunction with prevailing environmental conditions and production pressures such as level of biofouling;
- Display of microbiological data (with manual input) such as bacterial count on the seaweed blades, which can be overlaid with the data plot for biomass yield;
- The calculation of a continuous value for biofouling pressure, generated from manually provided categorical data and their correlation to key environmental parameters (e.g., temperature, turbidity).

Although the initial costs for sensors, deployment platform, telemetry, etc., may be high, especially for small-scale operators, the investment pays for itself after a short while by reducing the number of site visits necessary and providing more detailed data to optimize production operations. The work performed at the UK site under IMPAQT with regards to improved monitoring and management as well as progression of the site to multi-species use has attracted a lot of interest from both established and potential future farmers wanting to learn more about cultivation and monitoring solutions.

At the NSF pilot site, the IMS helped in the farming of seaweed and mussels, to make the correct decisions during the life cycle of the farm.

The IMS dashboard was functioning with the real-time data from the big reference buoy of the NSF pilot site. Historical data, retrieved data sets (e.g., vertical current data) and manually collected data (e.g., length of the seaweed) was uploaded and displayed, allowing the farm operator to use it in the daily operation. With the IMPAQT IMS a start was also made in collecting important time-series and defining boundary parameters for future seaweed and mussel farming in the North Sea.



Overall, key benefits regarding technology deployment at this site are:

- Collecting data during the offshore pilot and make it visible in the IMS dashboard was valuable. It showed if the data buoys were still working and if the structures were still in place.
- Gathering data was valuable for further analysis of the performance of the set-up and validation of models.
- Detect specific needs for specific environmental conditions to provide inputs for required adjustments of the technologies. For example, at the NSF pilot site was a challenge to retrieve real-time data on winter due to the reduction of the energy supply the monitoring equipment needs. In response to this, prototypes such as the DAS could be improved with e.g., a plug-and-play system for connecting sensors allowing to add and remove them and reduce the energy consumption).

At the Marine Institute coastal pilot site, the IMPAQT platform provided an appropriate monitor system to efficiently manage the IMTA set-up, and to support deployment of a variety of sensors in a harsh, saline, operational environment, providing onsite communication for remote access to data. As in the other IMPAQT pilot sites, a number of different off-the shelf sensors communicated effectively with the system to provide real-time environmental parameters and ensure the operator is aware of any changes or threats, allowing rapid reaction to ensure stock welfare.

The IMS allowed for the effective management of multiple species, both fed and unfed, making it a useful tool for multi-species farmers. The experience of the Marine Institute at the coastal pilot site focused on the easy graphical access to values and trend plots of parameters allowing to be informed and to recognise changes in trends. Also, the ability to monitor stock status, biomass and to compare different stocks supports optimisation of production.

For example, production data shows the different trophic levels by biomass in order to compare the trophic balance on the site. This is further enhanced using existing literature values to create a visualisation tool to highlight the remediative benefits of using multiple trophic levels. Production data also allows the visualisation of 'active stock' with respect to 'harvested stocks'. Operators can maximise this data archive to monitor stocks between generators to maximise growth performance at their site. 'Compare stocks', a functionality also tested at the SAMS pilot site, allows to compare inter-annual and interspecies biomasses and growth rates.

Visualisation of production with environmental data on site allows the decision making to manage production with respect to any potential trends observed in the environmental data which may cause a threat. For example, increase in water temperatures will alter feeding patterns in fish.

Sensor derived data is displayed in the overview page of the IMS Dashboard, where frequency of measurement is observed and sensor faults are highlighted. Time series can be altered to let the user inspect for trends in data such as drift of sensor over time prompting a calibration requirement. The IMS has inbuilt alerts for the user to get an immediate notice if a problem occurs, and it allows the settlement of upper and lower thresholds outside of which alerts are activated. Detection time for real-time monitoring issues is immediate.

The establishment of the IMPAQT platform at the Keywater Fisheries site was made by the installation of 3 in-situ monitoring points. The first one is located where water enters the farm, i.e., the abstraction point. The second one was installed at the treatment sump which is controlled by pumps and with different levels of filtration, and is the main water body that recirculates through the 12 tanks in the nursery RAS. The third is the discharge point, where water leaves the farm, thus at post treatment level and subject to regulation. A multi-parameter probe with an IADAS was located at each of the points. In addition, 3 independent loggers were deployed to the ponds measuring light and temperature, and a weather station was roof mounted on the site office. The DAS is located in the site office. All were connected to the existing monitoring solutions enabled at the site, i.e., Oxyguard system, and the IMPAQT system was integrated with it.

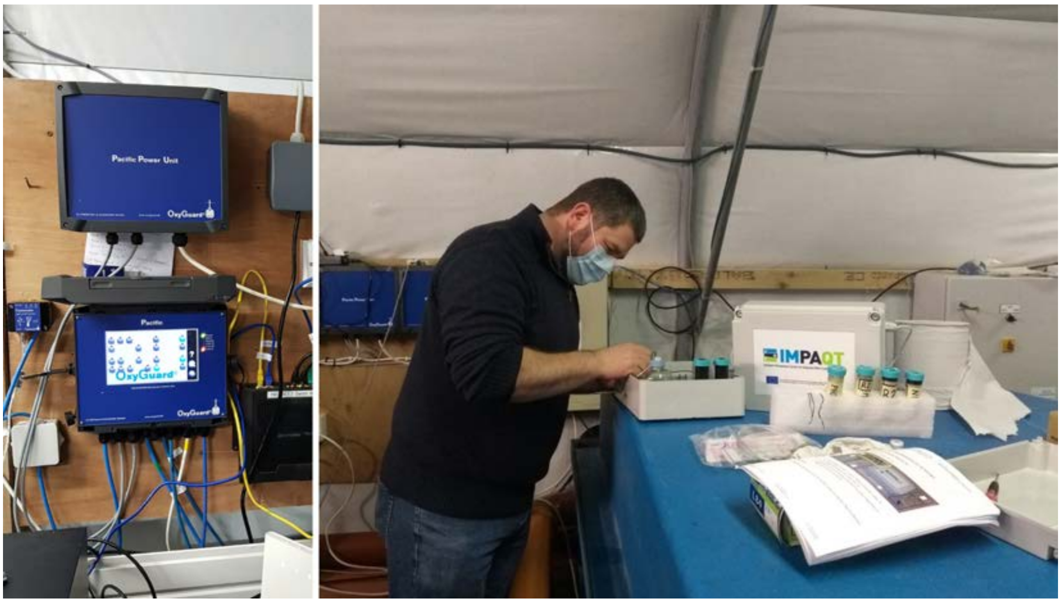


Figure 50. IMPAQT coordinator Frank Kane at the site (right), and site system used in Keywater Fisheries site (left)

Pre IMPAQT the site was monitored primarily in low resolution, with no real-time data using individual logging equipment and taking manual readings and information recordings. Farm management operations (e.g., feeding) were also performed manually. With the IMPAQT platform site observations, records and biotic monitoring were digitised and centralised. This combination of changes sees a significant reduction time spent in monitoring and recording tasks, and a reduction in human error associated with manual data collection and handling. In this pilot, integration of sensors and technology, access to real-time data and smart analytics enabled the operators to be aware of and react quicker to potential stressors occurring in the system.

The Çamli site worked with 3 data buoys deployed and successfully installed. Data buoys were also housing the EMS (batteries and solar panels) and the data transfer devices. The EMS save energy by managing it according to the measurement frequency of the devices starting and stopping very effectively. As at the Irish coastal site, a meteorology station is also available, measuring wind direction, speed, air pressure, and temperature. This meteorology station sends measured data to a computer responsible to collecting data coming from data buoys sensors. Energy is supplied from the power generator for both the meteorology station and the computer. The next step is sending data to the IMS. In this case, IADAS and DAS were not used, but far of being a limitation, it showed again that the IMS can be integrated with other systems.

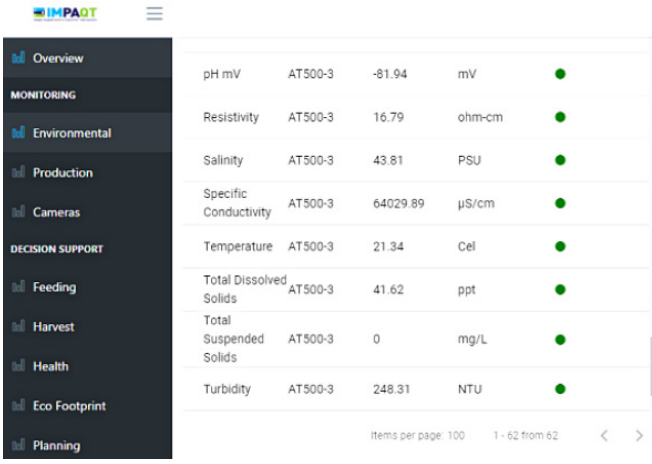


Figure 51. Meteorology station at the Çamli pilot site

Figure 52. Energy supply and bateries

Based on its experience with the IMS, the Turkish pilot site reports an adequate and effective evaluation of the data related to fish and mussel farming by using decision trees. The IMS has been effective in terms of stock development, quality assessment and giving warnings and feedback on the actions to be taken. Before the availability of the IMPAQT system, task such as stock assessment and reporting were made by personnel. Therefore, and as informed at the other pilot sites, the use of IMS was a time saver and prevented wrong evaluations due to human errors and promote correct decision making.

Figure.53. Environmental data page of the IMS

The live video stream and image analysis offered by the IMS was used at the Çamli site to detect morphological disease signs and understand fish behaviour. In the first case, the IMS warns the operator to ask a specialist to evaluate the current situation and start or prevent the disease before most of the stock is infected. In the second case, one example is the swimming behaviour videos before, during and after feeding.

Environmental management of the aquaculture activity was also possible using the IMS. The data from the water quality sensors were found to be useful both in the effective management of the activity and in reducing the environmental impacts.

The pilot in China is a bit different from the EU pilots, as the commercial-scale integrated aquaculture of kelp and oyster have been carried out for tens of years, with the occasionally cultured benthic species (sea cucumber, abalone, sea snails, etc.). Most aquaculture practitioners in this place have their practical experience for production, e.g., the growth condition of cultured individuals or estimation of total production. For the IMS to be successful, in additional to data collection and precaution functions, the application should be able to provide the information for ecological process with aquaculture activity involved.

Due to the political restrictions for on real-time data transmission, the environmental data collected in Sanggou Bay could not be transported directly to an EU server, so a local version of IMS with similar system design from IMPAQT has been developed and deployed in the pilot. The hardware functionalities of the IMS have been mostly done: the display of real-time and manually collected data for the environment around the demonstration rafts; historical data which can be outputted for further analysis; and a lab-module for monitoring water labs by the bay for physiological experiments. A visualisation model based on numerical model results is under test. However, the IMS for YSFRI is not complete yet, and the integration of ecosystem models is still under development.

At the YSFRI site, the monitoring platform was deployed and located near the demonstration culture rafts for kelp and oysters. The platform itself has sufficient energy supply with 8 solar panels and the built-in power system. There is a simple meteorology station being integrated to the platform to measure wind speed & direction and air temperature on site, as well as different sensors. The platform has been working continuously since October 2020 and transmitting data to the local IMS designed with collaboration from Institute of Oceanology, Chinese Academy of Science (IOCAS), which shares the same concept of the IMPAQT IMS.

Figure 54. IMTA Sanggou bay and monitoring platform

Overall, the data storage, visualisation, and analytics provided by the IMS adds to a better environmental, economic, and societal management of a farm, thus addressing all aspects for a sustainable development of aquaculture. The gathered data is not only important for farm operators but can be provided to regulators, consumers and stakeholders, for evidence of aspects like high environmental, and animal health, and seafood safety standards. All the IMPAQT pilot sites wish to continue testing the IMPAQT system beyond the lifetime of the project.

7 HOW ARE WE CHANGING THE PARADIGM?

The new European Commission Strategic guidelines for a more sustainable and competitive EU Aquaculture [1] promote the development of IMTA and lower trophic species to improve environmental performance. Even though IMTA is already known as set of practices with lower environmental impact, it is essential to pair this with its socioeconomic effects.

IMPAQT experts worked together for the best assessment and towards the demonstration of the IMTA benefits. The six IMPAQT pilot sites not only served as diverse testing and development locations for the technologies with bespoke versions of the IMPAQT platform deployed at each location but also as sites to investigate optimal sustainable IMTA development and to quantify the ecosystem services and circular economy principles of IMTA. Therefore, besides the importance of progressing to precision aquaculture, the latter part might be the key that opens the door to a real paradigm changing.

Sustainability can be defined as the process of people maintaining change in a homeostasis-balanced environment, in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations.

In the IMPAQT project, the sustainability of the multi-trophic system is addressed under a holistic perspective, where environmental, social, economic and ecosystem dimensions are included.

7.1. An IMTA circular model

Due to integrated multi-trophic systems, some of the uneaten feed and wastes, nutrients, and by-product are recaptured and converted into harvestable and healthy seafood, which makes IMTA a driver for the sustainability of the sector. It is important to highlight the sustainability attributes associated with multi-trophic systems.

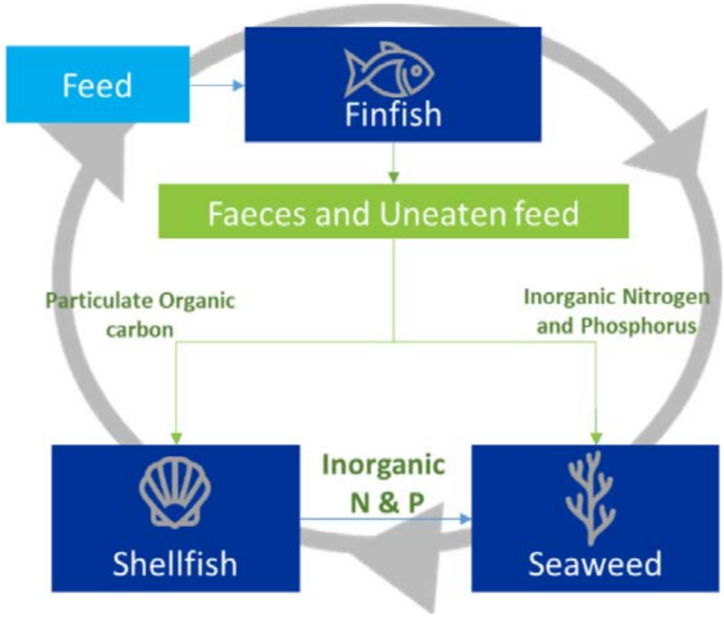


Figure 55. IMTA concept. In IMTA farms the uneaten feed and wastes, nutrients, and by-product are recaptured and converted into harvestable and healthy seafood.

To demonstrate the environmental benefits associated to the implementation of the new aquaculture practices based on multi-trophic systems, **an environmental study is complemented by the incorporation of a circularity approach**, where the new aquaculture systems are studied looking into the circular economy perspective.

The environmental assessment has been carried out through the application of the Life Cycle Assessment (LCA). LCA has been widely applied in the environmental assessment of products and services during the last decades. The LCA carried out in the IMPAQT project is looking at the farm activities and comparing monoculture with polyculture conditions when new species are deployed within the IMTA pilots, quantifying the environmental profile of this aquaculture model.

Life Cycle Assessment is a methodology based on the standard ISO-Framework: ISO 14040:2006 and ISO 14044:2006 [17]), as well as the recommendations of International Reference Life Cycle System (ILDC) Handbook [18] and the Product Environmental Footprint Guideline (PEF6). The methodology implemented consists in 4 phases: goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment, and interpretation of results.

The LCI comprises the data collection and the calculation procedures to quantify the inputs and outputs through the system boundaries: including the resource consumed and emissions to air, water and soil that are attributable to the product or organisation being assessed. Foreground process is the data directly collected from the pilot partners. Whenever this information is not possible to be gathered, data from literature sources is used.

The Life Cycle Impact Assessment focuses on the calculation of the environmental potential impacts associated with inventory flows. The base methodology chosen for the present study within IMPAQT is the Environmental Footprint (EF) Methodology. The baseline conditions are assessed quantifying the environmental impacts associated to the inventory flows, in a number of impact categories, to produce biomass. The impact categories are:

- Climate change (CC) - Radiative forcing as global warming potential (GWP100)
- Ozone depletion (OD) - Ozone depletion potential
- Acidification terrestrial and freshwater (AC) - Accumulated exceedance (AE)
- Ecotoxicity freshwater (ET) - Comparative toxic unit for ecosystems
- Land use (LU) - Soil quality index
- Resource use, energy carriers (RE) - Abiotic resource depletion – fossil fuels (ADP-fossil)
- Resource use, mineral and metals (RM) - Abiotic resource depletion (ADP ultimate reserves)
- Water footprint (WF) - Relative available water remaining per area
- Freshwater eutrophication (EF) - Expression of the degree to which the emitted nutrients reach the freshwater end compartment (phosphorus considered as limiting factor in freshwater).
- Marine eutrophication (EM) - Expression of the degree to which the emitted nutrients reach the marine end compartment (nitrogen considered as a limiting factor in marine water).

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o D5.1. Environmental impacts and circular economy business models at pilot sites

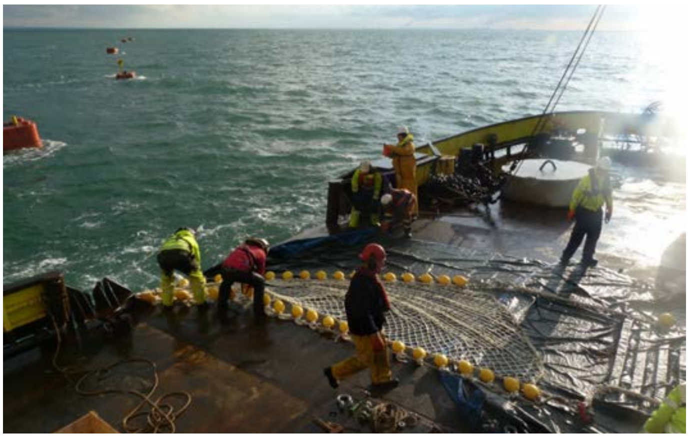
The specific results for each pilot site are fully detailed in the project deliverable D5.1. Environmental impacts and circular economy business models at pilot sites. Overall, the LCA study has revealed an environmental impact reduction of main IMTA products biomass in comparison with the same products produced in monoculture conditions in terms of Marine Eutrophication and under a cradle-to-gate perspective.

However, it seems relevant to investigate the environmental profile of IMTA products in reference to the protein provided. In this sense, IMTA systems performs better as marine eutrophication is reduced in most pilots, albeit the rest of impact categories are not always improved. On the one hand, infrastructure elements have a dominant contribution in the pilots where shellfish and seaweed are developed, mainly due to the use of plastics and nylon structures. On the other hand, feed is the hot spot in fish marine pilots, albeit infrastructure is still a hot spot in the freshwater pilot.

Overall, Life Cycle Assessment analysis studies has revealed that the IMTA systems are environmentally attractive as the impacts caused by the production of biomass can be reduced. IMTA out preforms mono-culture in environmental efficiency when compared, and an IMTA site provides more seafood protein to market while reducing the pressure on the marine ecosystem.In addition to the environmental assessment, circular economy is part of the sustainable scope. Circular economy is the path to contribute to sustainable economic growth, decoupling economic growth from use of natural resources and ecosystems by using those resources more effectively. Circularity concept in aquaculture usually refers to the implementation of actions of waste management oriented to reuse, recycle and valorisation, while the value of the products is maintained. Most of conventional approaches to circularity in the aquaculture sector are based on designing strategies for treating solid waste, wastewater or residues of animal origin. In general, existing initiatives and the development of new innovations are aimed at the valorisation of by-products sourced from the aquaculture value chain.

> IMTA systems are more efficient and environmentally attractive as they produce more seafood protein while reducing pressure on marine ecosystems

In line with standardized practices to address circularity, IMPAQT project has assessed IMTA pilots through the analysis of the inputs and outputs needed for the farm operation. As the project is focused on the IMTA operation, downstream processes are not covered in the analysis of waste impacts. The environmental assessment, previously summarized, integrates infrastructure waste associated impacts in accordance with the defined end-of-life scenarios reported by the pilot's operators.



Implementation of IMTA systems promotes the minimization of nutrient emissions associated impacts, since this stream means an input to produce seaweed and shellfish. In this context, IMPAQT project tackles the circularity through an innovative perspective, since the study provides an analysis of the multi-trophic systems in term of (bio)circularity, providing a framework to support the definition of circular value creation and circular value proposition for IMTA farms.

The multi-trophic production systems have been demonstrated to contribute to circularity in terms of nutrient cycling. Through the multi-trophic systems, some of the uneaten feed and wastes, nutrients, and by-product are recaptured and converted into harvestable and healthy seafood [19]. Nitrogen recycling in IMTA is especially important as nitrogen in the form of plant nutrients or protein is a valuable resource usually requiring high energy inputs to manufacture as fertiliser or convert to protein. IMTA makes use of a free source of nitrogen otherwise wasted. Therefore, the cultivation components have a key role in recycling processes within the IMTA.

Considering circularity from the aquaculture point of view, it is necessary to address the strengths of circularity looking at biological flows. When nutrient flows are recirculated from one species to another, circular economy can be defined as circular bioeconomy. However, more research on nutrient fluxes between trophic levels would be needed to monitor the variation on the circular efficiency within the production cycles. In this sense, having information on optimal harvesting time is a key aspect to ensure the maximum capture of nutrients by the extractive species around fish farms.

IMPAQT platform is also addressed looking into the attributes of circularity inherent to the requirements met during its design. It contributes to the circularity as it monitors key parameters to decision making regarding resource use efficiency and minimization of losses. In this line, the attributes of the platform are prioritized through a quantitative approach to identify the most relevant requirements that promote circularity.

Three main principles that set the basis for the circular economy [20] can be summarized as follows:

1. Preserve and enhance natural capital controlling finite stocks and balancing renewable resource flows.

2. Optimize resource yield by circulating products, components and materials in use at the highest utility always in both technical and biological cycles.

3. Foster system effectiveness by revealing and designing out negative externalities

The qualitative and preliminary evaluation of the meeting points between the circularity principles and the platform attributes are summarized in the table below.

BUSINESS REQUIEREMNTS	Principle 1	Principle 2	Principle 3
BR-01: Structured storage and archiving of IMTA system data	✓	The multitrophic system promotes the circularity at biological level	✓
BR-02: Optimal Collection Time (fed)	✓		—
BR-03: Optimal Seeding Time	✓		—
BR-04: Optimal Feeding Time	✓		✓
BR-05: Maximise production	—		✓
BR-06: Optimal species grading during each growth stage	✓		—
BR-07: Disease prevention and mitigation	✓		✓
BR-08: Optimal Collection Time (non-fed)	✓		✓
BR-09: Breeding / Broodstock (fed/non-fed)	✓		—
BR-10: Infrastucture, stock integrity and security and damage control	✓		✓
BR-11: Environmental and regulatory compliance	✓		✓
BR-12: Minimal environmental footprint	—		✓

Based on the attributes of the IMPAQT platform and the multi-trophic systems, relevant synergies with Circular Economy have been identified. The contribution of the IMTA systems to the circularity of nutrients have been highlighted in the analysis, since it is totally aligned with principle 2 under a biological perspective. The assessment has also revealed that most of the management practices promote the resources consumption and this aspect should be prioritized for increasing the circularity on the aquaculture systems. It has therefore been observed that the solutions provided by IMPAQT are totally aligned with the circular economy concept.

Finally, the study has included a first approach to circular business models, where key messages have been elaborated in relation to the value preposition and the value creation. Particularly, pilot partners have identified resources, activities, and partners potentially relevant to develop circular business models around IMTA systems. Together with this, the circularity of IMTA products has been identified as an interesting attribute for consumers who look for environmentally friendly aquaculture products. Nevertheless, this attribute should be properly communicated and verified.

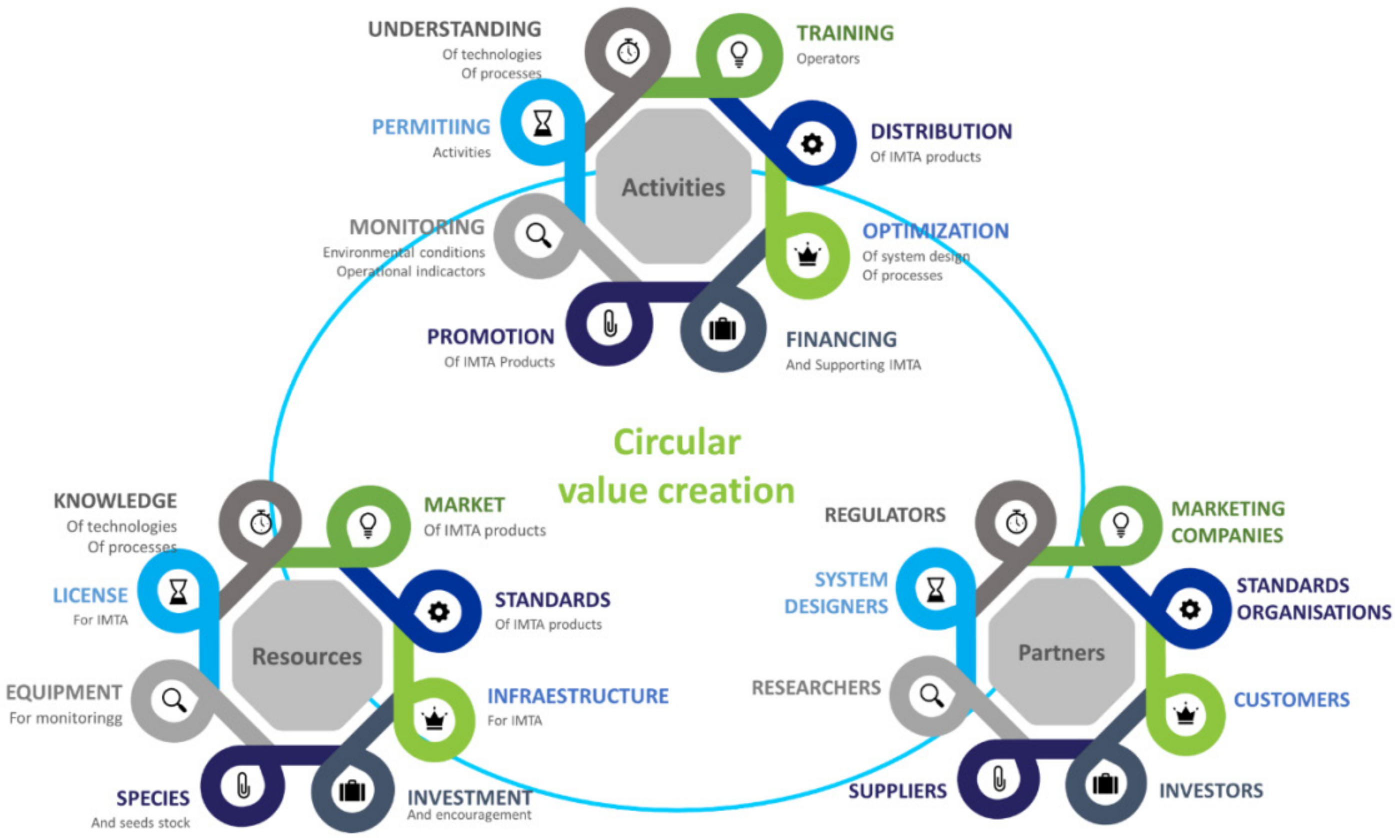


Figure 56. Framework for Circular Value Creation in IMTA system

Under the environmental perspective, ecosystem services are also assessed as part of a holistic approach together with circular economy perspective. Ecosystem Services are a way to assess the socio-ecological connection and resilience of a system [21]. Which services are most relevant strongly depends on the status of the environment and the manner in which humans make use of the natural system. Ecosystem Services Assessment (ESA) can either incorporate a monetary value or focus on the flow of goods and services. The ESA performed as part of the IMPAQT project focus on the flow of goods and services and only in part on monetary value, though incorporation of the "real value" of preserving the natural system can be relevant for the development of business cases.

Within the ESA, the systems are assessed once new species are introduced under IMTA conditions. The analysis combines qualitative and quantitative features through the implementation of a Bayesian Network. To do so, it has first developed a conceptual model to analyse existing monoculture systems and their connections to all delivered marine Ecosystem Services in accordance with CICES classification. Thanks to ESA, IMPAQT project can provide information on the benefits of IMTA to ecosystems in terms of regulating and maintenance services.

The LCA together with the ESA provide a holistic analysis of the benefits associated to the integrated multi-trophic systems, where the environmental impact categories are represented with relevant ecosystem services.

7.2. Socio-economic impacts

There is compelling evidence that affirms aquaculture to be a global economic powerhouse that provides livelihoods and can be a driver of positive social development. It brings jobs to isolated and underprivileged areas in industrial and developing nations and almost universally offers significant societal benefits in terms of access to food, infrastructure, education, and healthcare. Yet, a great deal of contextual variability around aquaculture in communities remains and many important questions are still unanswered. It is important for aquaculture researchers, extension specialists, those who work in international development, and policy makers to understand these benefits and communicate them to the broader scientific and research community.

Aquaculture helps to sustain many farmers and is one of the major sources of income to many households. It also indirectly affects the social and economic aspects of many stakeholders who are indirectly involved in it. The important role and contribution of small-scale fisheries and aquaculture in poverty eradication is acknowledged, as well in ensuring food security and nutritional needs of local communities. Fish can play major role in satisfying the world's growing middle-income group needs, while also meeting the food security needs of the poorest. Thus, a considerable socio-economic impact can be associated with it, in addition to the environmental aspect of aquaculture.

Sustainability of aquaculture not only requires to have a neutral effect on the environment but also to be economically feasible. One of the critical factors that will motivate aquaculture industries to invest on IMTA systems, is general public awareness of sustainable production of IMTA fish and other species and their impact on society and the environment. This will result in consumers that are willing to purchase the end product, and financial gains for all stakeholders in the industry.

In this line, aft er a complete literature review, a Socio-economic Assessment Questionnaire for Stakeholders has been designed, consisting of 26 questions, across five sections (Figure 57).

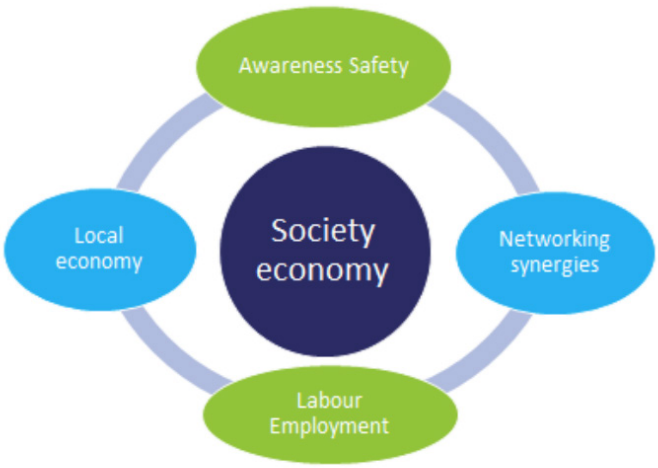


Figure 57. Socio-economic aspects of IMTA

Survey findings and relevant literature [e.g., 22] suggest raising awareness of consumers and business stakeholders about sustainable fishery. A better public image arising with IMTA may lead to easier access to government-issued operating permits and better relations with NGOs and local communities. One study [23] showed that respondents indicated a greater approval for IMTA than for monoculture conditions and also felt that IMTA would improve the public image of the aquaculture industry.

As far as economic issues concern, findings confirm the significant contribution of IMTA to local economy development and these are in accordance with some of the basic IMTA goals: positive local and regional economy impact, avoidance of monoculture seasonality problems, taking into account local fishermen, etc.

The IMTA related networking section indicate that IMTA system offers great potentiality for collaboration through network establishment and synergic action plans. These partnerships can bring together research and academic expert, with business industries, decision makers, people from local sector affected (tourism, restaurant etc.). Most of the stakeholders, are positive of participating in such clustering teams, in order to update their knowledge base, develop new products and R&D methods, and apply new techniques.

In terms of employment, IMTA has a larger positive effect in comparison to monoculture and this is in line with many studies met in the literature. IMTA system offers new labour competences due to the system management demands.

In addition to direct income for fish or shellfish farmers and their employees, sustainable aquaculture can also be a source of additional revenue for other local businesses, i.e., it can increase the area's attractiveness, helping to boost tourism.
Notice that whenever is aimed to identify sustainable solutions, the economic viability needs to be thoroughly explored, so as to motivate aquaculture industries to invest in them. In IMPAQT, the financial aspects and the cost effectiveness of such new integrated cultivation systems are addressed.

Cost-effectiveness analysis has been based on the commerc ial Çamli pilot. Two models have been applied, Activity-based Resources Allocation Model (ABRA), and a Profit/Loss (P/L) model calculating the Net profit derived from the multitrophic against the monoculture conditions. In addition, the first model has been applied to a research scale pilot in Ireland, in order to validate the corresponding results from Çamli.

Significant outcomes reveal that the IMPAQT platform provides time savings for personnel, while the more effective monitoring of the whole on growing process, contributes to a significant finfish survival rate improvement. This essentially leads to productivity rise and consequent higher turnover and profitability, which is further increased due to increasing positive public attitudes towards IMTA and premium sustainable products.

However, in the context of the project, IMTA has been tested on small scale implementations. The system has been up and running on mostly research facilities. Even on the commercial one (Çamli site) the IMTA implementation included just three cages. Yet, to assess the potential benefits, the outcomes of the IMPAQT project application on the industrial pilot have been upscaled, developing a scenario based on the average commercial size of aquaculture facilities in Europe.

The comparison between the Çamli scenario and the upscaling scenario is detailed in table below:

Table 01. Cost-effectiveness analysis for two scenarios

	SITE SIZE (HA)	FINFISH (NO OF CAGES)	SEAWEED (M)	MUSSELS NO OF BAGS)
PILOT SCENARIO	2.1	3	100	75
UP-SCALE SCENARIO	15	60	1000	500

According to this analysis, production volumes increase proportionally to the infrastructure increase which in turn results to linear turnover increase. Moreover, the ABRA model application reveals considerable decrease on the total effort needed, when comparing monoculture to IMTA environments, especially when considering finfish as the prevailing production in terms of both volume and value. Due to economies of scale and automation of procedures such as environmental monitoring and record keeping, labour as a whole is expected to increase from the pilot to the scale up scenario, on a descending rate.

The OPEX (Operational Expenditure) estimation for the scale up scenario shows personnel representing 13% of OPEX in the multi-trophic pilot case, while the rest 87% derives from other resources used. As we scale up by 3 times for instance, all OPEX increase proportionally apart from personnel that increases by 30%. This means that in case of 20 times scaling up, the overall total cost increase just 17,8 times. More about this analysis can be found in the project deliverable D5.2. Cost-effectiveness analysis.

Despite the small IMTA and IMPAQT deployment scale at the Çamli pilot site, significant outcomes came out from the cost effectiveness analysis and the critical review of the available literature. IMTA and IMPAQT systems allow harvesting not to be dependent on one species. Taking into account that the market value may be subject to change, the security of the farm increases by the co-cultivation of seabass, mussels and seaweed. Of course, the capacity factor of processing plants can also be improved by multi-processing of several seaweeds from various seasons.

In addition, the application of activity-based model revealed that multitrophic conditions provide considerable time savings for the personnel to be engaged with other species. In other words, economies of scale and efficient labour management is one of the most significant outcomes of the ABRA model application in the IMPAQT project. Moreover, the automation of specific activities in the ongrowing process provided by e.g., the IADAS platform, such as environmental monitoring and record keeping activities, improve even more such savings.

The IMPAQT platform, allowing a more effective monitoring of the whole on growing process, contributes to a significant survival rates improvement. However, involving all cost elements in the analysis results in increased total operational costs due to additional consumables put in the system (i.e., bag and ropes for mussels, nets and ropes for seaweed, sensors damage and maintenance). Surely, the development of robust cultivation systems, with a high degree of standardisation of the harvesting process will likely reduce operational costs.

In terms of net profit overall, comparing total OPEX with turnover it can be concluded that mainly because of the production volumes increase, the last exceed costs, however the analysis did not include depreciation cost of capital (IMTA & IMPAQT infrastructure), marketing and storage costs. These are very important issues that need to be explored in view of the fact that storage is an essential factor with high impact on costs, while IMTA & IADAS infrastructures are high capital costs investments.

A critical issue to be taken into account is that IMTA infrastructure for co-cultivating multi-trophic species require additional area. This might be limiting in some cases. For example, discussions with industry veterans and researchers revealed that salmon farmers on Canada's east coast would not be willing to reduce their total salmon production to accommodate IMTA since salmon is too valuable for existing operators [22].

On the other hand, after the COVID-19 pandemic era and the climate of uncertainty in the European fish market, prices in the fishery and aquaculture sector are expected to rise. This, together with the improved survival rates provided by the IMPAQT platform and the increasing positive public attitudes towards IMTA and premium sustainable products, can further increase the profitability of adopting IMTA.

> In addition to increasing productivity, employment and resilience for aquaculture operations, IMTA provides a more sustainable and circular product desirable to consumers

These assessments show that IMTA offers actual social and economic benefits by increasing the productivity and increasing employment to operate the systems, while providing a more sustainable and circular product which is desirable to the consumers. IMTA facilitates time saving economies of scale by providing greater production for similar effort. The profitability is increased from multiple species, either separately through increased biomass or in combination with waste mitigation. The diversification of stocks increases the resilience of the operation. These factors and the demonstration of the socially responsible approach builds confidence in the sector and increases the social licences of aquaculture.

Overall, the significant results from both socio-economic assessment and cost-effectiveness analysis reveal the positive prospects of the IMTA systems through collaborative action for the promotion of sustainable fishing practices. Moreover, they contribute to the sufficient understanding of the critical factors in the area of efficient resources management in an IMTA environment, since the innovative use of activity-based method in this analysis allows the effective re-engineering of the activities and their continuous improvement.

7.3. A message for policy, regulation and standardization

The European Union acknowledges the potential of the aquaculture sector and helps to its progress to ensures the supply of nutritious, healthy and tasty food with a low environmental and climate footprint, to create economic opportunities and jobs, and to become a global reference for sustainability and quality. Specifically, the EU policy aims to:

- building resilience and competitiveness
- ensuring the participation of the sector in the green transition
- ensuring social acceptance and consumer information on EU aquaculture activities and products
- increasing knowledge and innovation in the EU aquaculture sector

Each of these objectives are addressed by the IMPAQT project, through its developments and analysis, as well as targeted communication and dissemination activities. Moreover, synergies with other initiatives funded under the Horizon 2020 programme allowed a wider reach to stakeholders and rising awareness of the social and economic relevance of aquaculture.

To achieve a more sustainable development of the EU aquaculture, the European Commission adopted in 2013 non-binding strategic guidelines, which served as the basis for the development by EU countries of specific national strategic plans for aquaculture. Moreover, the European Maritime and Fisheries Fund has provided specific funding to support the sustainable development of aquaculture in the EU.

Recently, the Commission has adopted new strategic guidelines [1] and EU countries have reviewed their national strategies in light of these. Through the Strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021-2030, the Commission provides a common vision for EU countries, the aquaculture sector and other stakeholders to develop the sector in a way that contributes directly to the European Green Deal and the Farm to Fork Strategy. Therefore, the sector is working towards a green transition in the blue bioeconomy by promoting research and innovation, precision aquaculture systems, organic aquaculture, as well as production concepts away from monoculture such as IMTA.

A key concept and framework for sustainability is the Circular Economy approach, fully involved in the IMTA concept. As Circular Economy in the aquaculture sector can be tackled under different perspectives, a common approach may be a key step before progressing further models, strategies, or plans, and as the basis for future recommendations toward circular economy business models in the aquaculture sector. In this context, the IMPAQT partner, LEITAT, in collaboration with the H2020 European projects **AquaIMPACT**, **ASTRAL**, and **iFishIENCi**, has participated in the European consultation regarding the update of the before mentioned strategic guidelines for sustainable development of EU aquaculture.

Two needs have been communicated to EU through this participative process. First, to discuss and share views on a common way forward in relation to how circularity in aquaculture should be addressed and measured. There is a need to discuss and identify ways forward in which circularity can be developed within production and to help ensure sustainability. Second, to stress the value of having a joint and coordinated contribution from relevant H2020 projects to the revised Strategic Guidelines for the sustainable development of EU in relation to circularity. As part of the coordinated actions among these projects, a circularity definition is given, where the importance of biological flows within aquaculture is mentioned. From these EU projects perspective, the circular economy is defined as the action plan in which the value in aquaculture aims at producing renewable biological resources, facilitating the conversion of these resources and waste streams into value added products.

IMPAQT project has made a relevant contribution to stress multi-trophic systems as a sustainable solution for the aquaculture industry, highlighting the circularity embedded. Therefore, IMTA systems shall be considered as a circular economy practice in the aquaculture sector. Future synergies and cooperative actions are planned to encourage the transition to circularity, fostering the concept in the coming strategies for the sector. In this context, the outcomes obtained from IMPAQT project are a relevant contribution for this process.

Overall, IMTA development in Europe is largely driven by research initiatives but yet relies on the transition from scientific evidence to a practising community, for large-scale commercial systems in particular (ref + nr Falconer et al., 2019). Previous pan-European projects have implemented IMTA sites demonstrating the benefits and identifying challenges for its uptake (e.g., **IDREEM project**), as well as developing learning materials such as IMTA best practices or functional technical description, to promote knowledge exchange and communication with regulators (i.e., **INTEGRATE project**). As a research and innovation initiative, the IMPAQT project worked in this same line. With sustainability, efficiency and productivity being intrinsically linked, the IMPAQT project adopted a holistic approach to investigate the environmental, economic, and societal impacts of transitioning to IMTA production systems.

Important identified barriers for the EU aquaculture growth are the administrative [1]. Licensing systems differ across most EU Member States. They are complex and lack predictability in terms of processing time and expected outcome. Applications include aspects of site location and scale, production type, species in culture, environmental impact, social acceptability, and many more. Fully commercial systems generally undergo more extensive requirements as compared to solely experimental sites because seafood production for the consumer's market have to address concerns to animal welfare and food safety. Seaweed cultivation, whether experimental or commercial, remains novel for many EU countries, causing uncertainty in licensing procedures and even more so when applying for non-monoculture systems, such as LTA or IMTA.

The IMTA challenges identified by IMPAQT also concern regulatory burdens as well as site management and investment decisions, being largely consistent with findings of the before-mentioned pan-European IMTA projects. In general, regulation related to IMTA is lacking, as is a harmonization among different national regulatory frameworks.

Whether it is research or commercial activity, it all starts with licensing, which if often a complex and time-consuming application procedure. There is no IMTA license, and even for small-scale experimental sites, IMPAQT found that amending an existing license for inclusion of another species group is not as straight-forward, e.g., adding seaweed to a shellfish site was overall simpler than vice versa, as the UK pilot site experienced. Moreover, many entities are involved in this process, making it more complex (e.g., several entities involved for the SAMS pilot site, such as Crown Estate Lease, Marine Scotland Licensing, FHI, Argyll & Bute Council, etc.). Therefore, whilst it may be possible to obtain permission for small-scale experimental IMTA systems, the regulatory framework in most EU Member States represents a significant barrier to the development of commercial-scale IMTA operations [24].

One of the key messages for policy and regulatory decision-makers is that administrative procedures for aquaculture need to be simplified on a national level, especially with a view to the transition to multispecies systems for the sustainable development of the sector. Responsibilities and processes should be streamlined and harmonised, by for example providing a single platform accessible by all authorities, including the applicant, to inform about the next steps and information required and track progress. More specifically, IMPAQT remarks several recommendations to the policy approach:

- Generate **knowledge exchange centres** and education material for IMTA, and promote social licensing;
- Allow for a '**flexible definition' of IMTA**, i.e., minimum of two species groups but not bound to include fed aquaculture species;
- Lower regulatory burdens, i.e., **streamlining licencing procedures on a national level**;
- The change of procedure (e.g., licensing) requires information on what IMTA and LTA bring to the sector. This again requires knowledge and data sharing, among others.
- **Promote experimental IMTA systems** to address knowledge gaps (e.g., Life Cycle Analysis of IMTA systems), informing producers and regulators;
- Develop **best practice guidelines for IMTA production** addressing aspects of site and species selection and configuration;
- Promote **research and innovation for IMTA development** in EU.

Rapid aquaculture growth presents challenges such as the environmental concerns related to fish farming (habitat destruction, organic and chemical pollution of nearby aquatic and benthic ecosystems, disease and parasite transmission to wild populations). Stakeholders and consumers are not oblivious to these concerns and must be taken into account when designing and implementing policy, regulatory and standardisation actions.

Therefore, besides the huge relevance of policy and regulation for sustainability among all economic sectors, including aquaculture, the stakeholders' involvement — from diverse enterprise profiles to the general public — is somehow guided by policy and regulation frames applied at the national level after their promotion and implementation at the international level. Their involvement in the policy and regulation frames matters not only with respect to their behaviours in the society but to design the best strategies too. The impact of stakeholders, including consumers, in the progress towards more sustainable aquaculture is not independent of policy and regulation issues.

For example, evidence on consumers' willingness to pay for more sustainable products shows that customer participation improves even when consumers exhibit low sustainability-oriented motivation (environmental concern) and ability (eco-literacy). However, although the willingness to pay might be high, it also might depend on the confidence that sustainability is demonstrated and well regulated, ensuring the product quality. For bio-based products, it was underlined that certification might play a key role in purchasing decisions, especially for food and nutrition and personal care products [25]. Social involvement is necessary to make certification an informative tool for consumers to encourage them to make 'green' purchases. Therefore, certification becomes the visible output to consumers of the real sustainability of these products [26].

Developing carefully defined aquaculture standards and rigorous certification processes is key to sustainable aquaculture progression and growth. Aquaculture standards and certification schemes provide practical and functional sustainability benchmarks, thus giving consumers more accurate information on sustainable production methods of their seafood choices.

In this regard, IMPAQT supports the development of standards for algae food products as well as certification for seaweed farm operations. The European Committee for Standardization (CEN) has established a Technical Committee focussing on algae and algae products, in which future standards for the European algae sector are being prepared. The Technical Committee consists of several different working groups, such as Algae processing (WG3) or Specifications for food/ feed sector applications (WG4). IMPAQT partner Stichting Noordzeeboerderij (North Sea Farmers, NSF) is a member of this committee (WG4) to advocate the sector's interest. This way, NSF is able to provide input for the future European norms. Contamination, traceability and sustainable seaweed cultivation, among others, are widely discussed in the different working groups. Future standards will also serve as a guideline for seaweed farmers.

A seaweed standard for food could guarantee the quality and future-proof growth of the sector and production method by setting conditions around challenges such as biodiversity, animal welfare and ecology. NSF decided to explore the possibilities of a GLOBAL G.A.P. certification for the North Sea Innovation Lab. GLOBAL G.A.P. is an internationally recognized standard for farm production. The certification covers:

- Food safety and traceability;
- Environment (including biodiversity);
- Workers' health, safety and welfare;
- Animal welfare;
- Integrated Crop Management (ICM), Integrated Pest Control (IPC), Quality Management System (QMS), and Hazard Analysis and Critical Control Points (HACCP).

At the moment, there is no GLOBAL G.A.P. certification for seaweed farms yet. Therefore, NSF and Global G.A.P. are working together to explore what is needed to certify the North Sea Innovation Lab. The pilot site and data collected from it in conjunction with the IMPAQT data buoy are precious inputs in this process. NSF and Global G.A.P. have undertaken a trial to identify the gaps in the current standards and which one that would be suitable for seaweed production in an IMTA setup.

By developing a tailored standard as part of the GLOBAL G.A.P. framework, we hope to pave the way for future commercial seaweed/IMTA farmers to have their products certified and supply the food markets in Europe is an essential step towards the blue economy.

In general, standardization may be applied either to the production practice (i.e., farming) or to the product derived (food and feed products). Two examples are detailed below.

For the seaweed production (farming), the Aquaculture (ASC) and Marine Stewardship Council (MSC) produced a joint standard, the ASC-MSC Seaweed Standard for environmentally sustainable and socially responsible seaweed production. It sets out requirements for seaweed harvesting and farming practices offering certification for seaweed suppliers and seaweed operations. Currently four producers worldwide have achieved ASC-MSC seaweed certification, the latest being the WANDO eco-friendly seafood cooperative of 11 seaweed farms in South Korea, producing *Hizikia fusiformis* and *Saccharina japonica*, now targeting European markets.

MSC-C-54462 ASC-C-00597

Figure 58. MSC and ASC labels, for wild fish responsibly caught and traced back to a certified sustainable source, and responsibly farmed seafood, respectively.

In the same line, Friend of the Sea (FOS) provide a series of sustainable standards of certification for aquaculture that minimises the negative effects of aquaculture operations. FOS Sustainable Aquaculture Certification must meet requirements related to: management system, legal compliance, biomass and environmental impact assessment (EIA), water and emission monitoring, waste and energy management, social accountability and traceability.

Regarding products, the Soil Association Seaweed Standards [27] regulates organic standards encompassing EU Organic Regulations: defining aims, objectives and principles of organics (EC 834/2007; amended by EU 2018/848 from 1st Jan 2022), and detailing organic production, labelling, control [(EC) No 889/2008] and import rules [(EC) No 1235/2008)]. These form the legal basis for the control of organic farming, food processing and organic labelling within the EU.

LEARN MORE!

o The ASC-MSC Seaweed Standard brochure

Also relevant to mention is that during the course of the IMPAQT project and based on it's the pilot experiences in the offshore North Sea, NSF has used this knowledge to develop a procedure that will help other multi-users to develop their multi-use concept in wind farms. The procedure is available and usable for any type of multi-use, such as IMTA systems. As such, it forms a predictable and transparent process towards a successful permit application for all stakeholders involved. Offshore wind farms are complex industrial areas with many regulations to ensure safe and predictable production. For a multi-user to be able to operate in this area, careful alignment with the wind farm operator is required. This will help both parties to work safely, to have a viable commercial business and to operate in balance with the ecosystem, providing a clear overview of the steps that need to be taken, the conditions that have to be met and in a language that all stakeholders can understand.

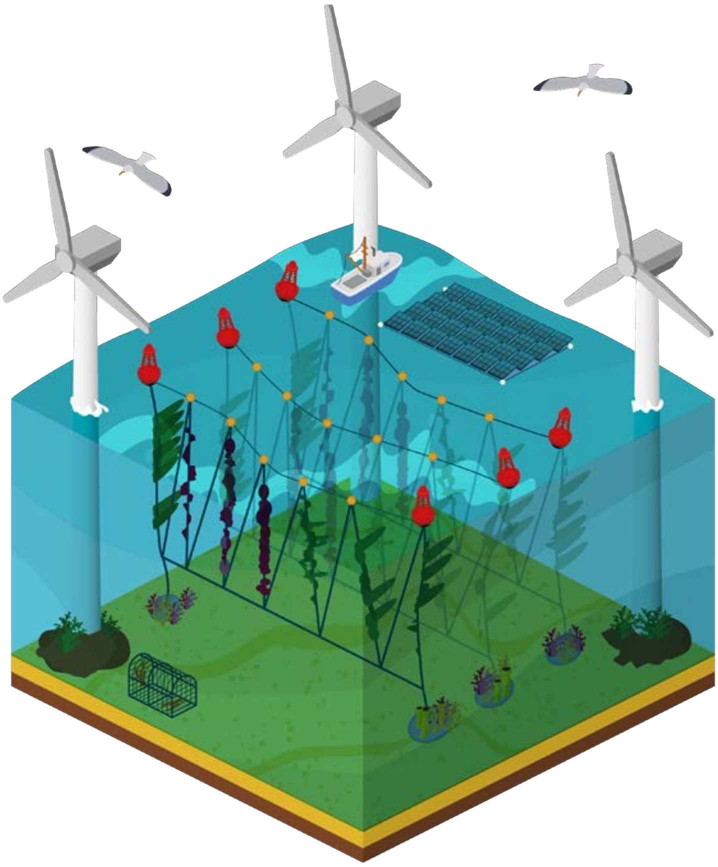


Figure 59. NSF offshore seaweed/IMTA farm

IMPAQT is in contact with the Dutch government to include this procedure as part of their multi-use policy, given the interest shown by the commercial offshore wind farm sector to adopt such an approach. In the meantime, the procedure is being improved in subsequent research projects to enhance its usability across Europe. NSF anticipate a Belgian and UK-version to become available in the course of 2022. This should support any future IMTA users in those countries as well to start their operation inside offshore wind farms.

LEARN MORE!

o [Check this brochure about the NSF training system for multi-use]

7.4. Training for a more sustainable future

An innovative aquaculture sector also demands the development of appropriate skills. This can be achieved through the promotion of specialised curricula and knowledge on aquaculture, as well as life-long training for farmers on innovative approaches for the aquaculture sector [1].

Answering this demand, IMPAQT launched an online training in MOOC format, organized under 4 modules, covering the main areas of IMTA practises, the IMPAQT platform, monitoring technologies, seafood quality and pilot sites, and policy areas such as the sustainability and circularity of IMTA. The course was designed and made available on the OpenLearnCreate platform, a free user-friendly platform, belonging to the Open University, partner of the IMPAQT project. It requires approximately 8 hours of study, but there is no time limit to complete it.

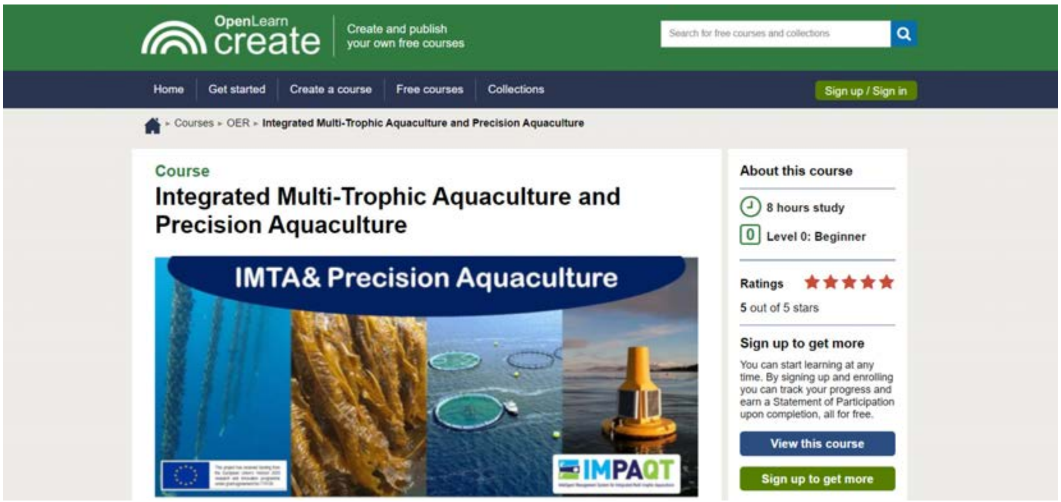


Figure 60. IMPAQT course main screen

Thanks to the collaboration of all project partners, and curated by the Marine Institute, this training makes most of the project results accessible in a comprehensive and dynamic format. It aims to aquaculture producers, operators and end users, intermediary worker trainers, regulatory bodies and policy makers, and national and pan-national organizations for the development of aquaculture.

The short initial module gives an introduction to the course, its content, and to the IMPAQT project. The structure is clearly outlined in tab format so the student can identify sections of interest and can access individual sections discretely. There is a tick box on each item so students can mark as done and keep track of their progress.

The IMTA section contains details on aquaculture and its socio-economic value. IMTA's benefits and challenges are outlined, as well as information related to species. The next step is to learn about sustainability and Economics, focusing on the IMPAQT IMTA model, IMTA's environmental and socio-economic impact, ecosystem services, sustainability and circularity, all framed into the work of IMPAQT pilot sites.

Last but not least, the Precision Aquaculture learning session addresses the innovative technologies developed in the project, some of their main functionalities and relevant applications on the pilot sites to manage and monitor their IMTA system. Sensor biofouling and seafood quality are also briefly described in this section.

Each section has a quiz to test learning outcomes for the course. Moreover, to provide wider information to learn about this sector, references to several materials are facilitated.

Figure 61. Outline of Module 4. Precision Aquaculture

Overall, studying the IMPAQT course provides learners with understanding of IMTA concept, including its benefits and challenges. It allows to reach familiarity with IMTA farm operations and the key functionalities of the IMPAQT platform. It facilitates the proper context through topics such as sustainability, ecosystem services and economics of IMTA, as well as the importance on environmental monitoring and reliable information to operate successfully.

Throughout the project, many other actions were carried out both for IMPAQT team and stakeholders training. For example, UNPARALLEL have designed a ticketing system to support pilot managers in implementation, management and monitor processes with a service similar to a helpdesk, where pilot managers can generate a ticket to ask for help and keep track of any occurrence. This ticketing system allows the creation of a knowledge base for further search and consultations, besides the provision of an agile communication process. Moreover, when possible, several actions of on-site training had been carried out, e.g., to learn how to use the IMPAQT technologies, such as the SIMPLEX application.

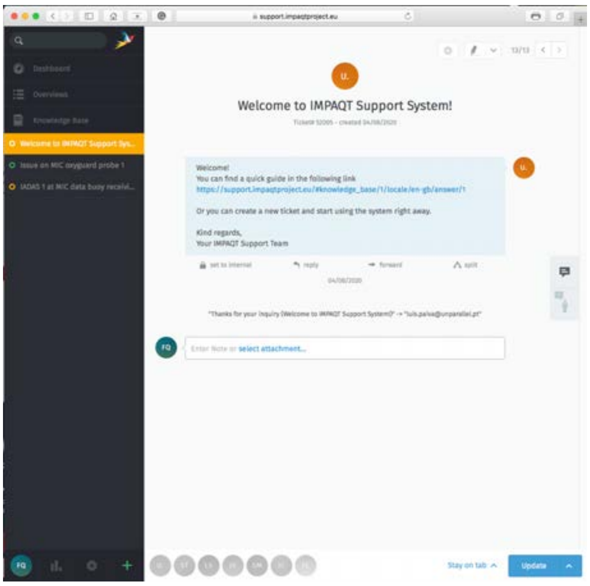


Figure 62. IMPAQT Support System main screen. It has several menus (left column) and below tickets are listed for quick access.

For stakeholders training other than the IMPAQT MOOC, an example is the North Sea Farmers training system for multi-use aimed to seaweed farmers and wind farm operators to enable seaweed and/or mussel cultivation in wind farms in the North Sea.

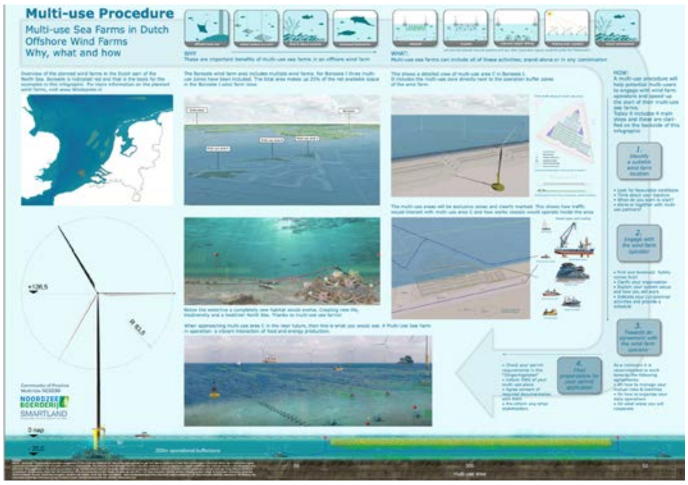


Figure 63. Multi-use procedure to support start-ups of multi-use/ IMTA operations in Dutch wind farms.

The complete information regarding IMPAQT training actions is presented in D6.5. Report on training activities.

LEARN MORE!

Enrol in the IMPAQT MOOC and have an exciting journey to the future of IMTA and Precision Aquaculture

8 MAKING AN IMPAQT

Key Performance Indicators (KPI) embody strategic objectives and measure performance against a specific target. As they are essential, in IMPAQT, several KPIs were established at the beginning of the project to assess the degree of achievement of each the project objectives.

Objective 1 - To design and implement new/emerging efficient and cost-effective technologies in monitoring and management systems for IMTA production.

This objective was established as an answer to a specific but wide issue. The management of large-scale IMTA areas remains difficult due to limited knowledge of mutual interactions among components and understanding of impact at ecosystem level. Routine monitoring of health and welfare is usually based on sampling and inspection outside of normal environment, which is itself a stress event and in some cases inefficient (due to sampling). Environmental monitoring relies on either water sampling or utilization of basic sensors, having impact on operational expenditure and efficiency/cost-effectiveness for large scale deployments. Information fusion remains underutilized. Besides the lack of data availability (or its consequences), there are not sufficient tools to assess the factors affecting IMTA production and to enable real-time response to production challenges, including environmental impact and fish and seafood quality.

Therefore, the achievement of this objective was evaluated based on the delivery of the technologies developed within the IMPAQT platform and their assessment in relation to efficiency and cost-effectiveness.

KEY PERFORMANCE INDICATORS (KPIS)	TARGET VALUE/MEASURE OF SUCCESS	STATUS
Frequency of measurement	From 1 or 2 readings per day to hourly or more frequent readings	★
Response / detection time versus unexpected issue	Latest at the same day	★
Accuracy/reliability of response (reliability of prediction of IMS, including reliability of measurements on which the prediction is based.)	90-95%	★
Average Trophic index (TRIX), 1-10, where values below 4 means low risk on eutrophication, and values higher than 6 means high risk on eutrification. An alternative might be the use of remote sensing/satelite data on eutrophication: organic material, chlorophyll-a and particulate matter	Decrease of at least 25% at and around IMTA platform	★
Environmental impact reduction, comparing 1 single trophic aquaculture system with a multi-trophic aquaculture system	5% increase in carrying capacity of systems for fish farms (i.e., without increasing the net nutrient loading)	★
Sediment dynamics	Statistically insignificant increase in the bottom sediment	⯪ [1]
Feed loss	Decrease by 10%	⯪ [2]
Growth Rate	~ 0,78 in 20 months for sea bass; ~ meat yield mussels > 45%; ~ seaweed growth (blade length) > 1.5 cm/day during peak growth season (Mar to May).	★
Survival rate (100 – mortality rate)	85-90%	★
Annual average ratio of monthly biomass increase for fish vs. monthly feed distributed	~ 0,13-0,17 with Coef: Var~60% for 1st year ~ 0,4-0,5 with Coef: Var~25% for 2nd year	★
Biomass production	Improvement of 6-7%	★
Production costs (OPEX and CAPEX)	~ Reduction of 10% in OPEX (in terms of monthly Person Month) ~ Reaching 20% reduction in production costs (OPEX and CAPEX) for some of the pilots	⯪ [3]

[1] Partially met at MIC. Statistic quantification was not assessed however, the effect is negligible due to the scale of the pilot. No culture structures were housed on or close to the seafloor. Utilising the existing grid also reduced the number of anchor blocks.

[2] Partially met at Çamli. There isn't a feed trap in the pilot site but the camera system and IMS is used to help manage the feeding; when the fish are ready, feeding is started and when they are full, the feeding is stopped to reduce feed loss. This is observed by direct monitoring of camera images through the IMS. At the MIC and MIF pilot sites there are no floc traps or cameras to monitor feed loss.

[3] Utilising the IMPAQT platform reduces operational hours for Salmon production by 6.6% compared to baseline monoculture scenario at MIC. At the Çamli site, the ABRA model shows a 8.1% decrease in total operating effort. For further details see D5.2 Socioeconomic impacts and cost effectiveness of pilots.

Objective 2 - To validate the IMPAQT systems and IMTA model in-situ and the fish/seafood product in laboratory.

IMPAQT aims to achieve better estimates of the overall costs and benefits of IMTA to production, the ecosystem and the fish/seafood product. This should be provided to create financial and regulatory incentives for industry and government to invest in the IMTA approach. IMPAQT IMTA set-ups and IMPAQT platform will be validated in six (6) pilots, covering geographical differences throughout EU and China and different scenarios from inland and coastal to offshore aquaculture systems. The project will pay special attention to fish/seafood quality and safety.

KEY PERFORMANCE INDICATORS (KPIS)	TARGET VALUE/MEASURE OF SUCCESS	STATUS
Number of achieved pilots with IMTA setups and IMPAQT platform installed	6	★
Production systems in IMPAQT pilots	1 inland, 3 coastal, 2 offshore	★
Multi-species compatibility within a site or with mutual benefits	At least 2 different trophic species	★
	Fair growth rate for all species (fish, bivalve, seaweeds)	★
Number of IMTA models validated	At least 2 (1 pilot specific and 1 generic/blueprint)	★
Food quality and safety related to AUA.	100% Safe fish/seafood production for human consumption, disease free, chemical residue free, nutritionally enriched	★

Objective 3 - To demonstrate an optimal sustainable IMTA development in a holistic perspective based on ecosystem services and circular economy principles.

IMPAQT aim to demonstrate the eco-intensification of EU aquaculture based on real data coming from the five (5) pilots in EU and the pilot in China, with the latter used as reference, by demonstrating the eco-efficiency and the environmental impacts minimized, the socioeconomic benefits enabled, including the specific benefits that people could obtain in terms of ecosystem services. These services can be the direct provisioning services, such as optimising the yield of food and other products from ecosystems, but also regulating and supporting services, such as optimising nutrient recycling, thereby boosting water quality and ecological status of ecosystems. Moreover, the project will contribute to the transition from linear to circular economy in EU aquaculture, involving definition of measures to cut resource use, reduce waste and boost recycling in aquaculture. As before, the following table gives insights on KPIs and indicative targets for assessment.

KEY PERFORMANCE INDICATORS (KPIS)	TARGET VALUE/MEASURE OF SUCCESS	STATUS
Production costs (OPEX and CAPEX). See objective 1	Reduction of 10% in OPEX (in terms of monthly Person Month) Reaching 20% reduction in production costs (OPEX and CAPEX) for some of the pilots	
Biomass production	Improvement of 6-7%	
Product diversification	At least 15% contribution of diverse products (shellfish and seaweeds) to monthly, seasonally and or annual income (sells) or to cost coverage	[4]
Market supply	Ability to supply market with at least 3 size grades (out of 5 grades) of fish during 9 months of a year	
Average Trophic index (TRIX)	Decrease of at least 25% at and around IMTA platform	[5]
Environmental impact reduction	5% increase in carrying capacity of systems for fish farms (i.e. without increasing the net nutrient loading)	
Socioeconomic benefits	Demonstration in at least 1 pilot site	

[4] Not relevant for non-commercial pilots. At the Çamli commercial pilot site the models predict a harvestable tonnage of 102 tn of seabass, 5.1 tn of mussels, and 12 tn of *Ulva*. This leads to a volume increase of 14% (for further details, see deliverable D5.2.).

[5] Çamli pilot site TRIX value has decreased to 5.34% and there are ongoing analysis for 2021.

Objective 4 – To promote an effective transfer of knowledge derived by IMPAQT activities to the EU aquaculture.

The presence of a well-educated workforce can be a competitive advantage for the EU aquaculture industry. As technology and knowledge improves, the maintenance/improvement of skills and knowledge in the aquaculture workforce is essential. For that purpose, networks of knowledge/best practice transfer are highly required and the promotion of life-long learning needs support. This statement stands essentially for the IMTA case, since as stated before, there has been very little adoption and knowledge of this technology in Europe. IMPAQT will focus on the active engagement of aquaculture market actors, including employees and executives of aquaculture production facilities. In addition to the standard dissemination, business development and exploitation activities, training activities will be implemented in person and online in the form of Multi-user Open Online Courses (MOOCs), in order to facilitate the effective knowledge transfer of the project's results to aquaculture stakeholders.

KEY PERFORMANCE INDICATORS (KPIS)	TARGET VALUE/MEASURE OF SUCCESS	STATUS
Number of training courses,	3 sessions in person, continuous courses for MOOCs - focus on MOOC, due to COVID-19, every pilot owner give a short presentation on lessons learnt	
Thematic areas,	At least 4 thematic areas about Overarching policies, IMTA practices, IMPAQT platform and pilots, Food quality and safety	
Stakeholders to be trained, link to the activity on the MOOC, provide information to the stakeholder board. MOOC's will be wider distributed. WP6 is in charge, they should contact the pilot owners for input.	At least the stakeholders linked to the Stakeholder Board and those connected to the project as supporters	

This objective is complemented by the results obtained in Work Package 6 - Dissemination, communication, exploitation and training activities of the project. The communication and dissemination activities performed by the partners have overall far exceeded the communication and dissemination KPIs set during the initial stages of the project.

IMPAQT has reached and audience of approximately 85.000 stakeholders through its different actions and channels, and its impacts go beyond the duration of the project. In this line, several partners are already involved in upcoming events, papers submission processes, and other dissemination actions. During the four years of the project, IMPAQT consortium participated in more than 50 national and international events and workshops, and have submitted more than 30 scientific papers. Thanks to our well-designed strategy and the active collaboration of all partners and European projects, we have achieved very good coverage in media, with more than 100 media appearances both at the national and international level, interesting synergies and knowledge exchange. Moreover, our legacy to bring IT to aquaculture and progress to its sustainability comprises more than 100 attractive materials, such as videos, innovation factsheets, deliverables, interviews and much more.

SCIENTIFIC PUBLICATIONS	EVENTS & WORKSHOPS	SYNERGIES WITH OTHER PROJECTS	INNOVATION FACTSHEETS
+30	+50	10	16

MEDIA APPEARENCE	SOCIAL MEDIA FOLLOWERS	WEBSITE VISITORS	COUNTRIES REACHED
+100	+1300	+70000	50

The impact of initiatives as the IMPAQT project should always go beyond. In this regard, all partners will keep disseminating the project results and looking actively for further collaborations, knowledge transfer and exploitation of the IMPAQT outcomes. This year you can interact with some of our partners at Aquaculture Europe 2021 (Madeira, Portugal), the 35th EFFoST International Conference 2021 (Lausanne, Switzerland) or the International Conference on Life Cycle Management 2021 (Stuttgart, Germany), among others.

There is still a lot of work to do to achieve an efficient and sustainable aquaculture sector, able to make a decisive contribution to the urgent ecological transition in Europe and the world. With the knowledge gained in these four years, we hope to have paved the way a little more. We will continue along it to turn into reality what was only a horizon before.

LEARN MORE!

o Our presence, Knowledge Center, and News are great sections for learning more about our Communication and Dissemination actions.

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 774109