Farm to fork, Communities Development and Climate Action
European Research Executive Agency (REA)

INNOAQUA
PROJECT

Document Title:

D2.1 Aligning INNOAQUA's Sustainable Aquaculture Practices with the EEA

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Date of submission:

15.03.2023

This document is the INNOAQUA project deliverable **Aligning INNOAQUA's Sustainable Aquaculture Practices with the EAA** (contract no. 101084383) corresponding to **D2.1** (Month 2) led by **EAS**.

Funded by the European Union under grant agreement number 101084383. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them

Project details			
Project name	Innovative Approaches for an Integrated Use of Algae in Sustainable Aquaculture Practices and High-Value Food applications		
Project acronym	INNOAQUA	**Start/Duration**	June 1st, 2023 48 months
Topic	HORIZON-CL6-2022-FARM2FORK-02-05-two-stage	**Call identifier**	HORIZON-CL6-2022-FARM2FORK-02-two-stage
Type of Action	HORIZON-IA	**Coordinator**	NORCE Norwegian Research Centre AS
Contact person	Dorinde Kleinegris (Project Coordinator) - dokl@norceresearch.no		
Project website	www.innoaqua-project.eu		

Deliverable details			
Deliverable name	Aligning INNOAQUA's Sustainable Aquaculture Practices with the EAA.		
Number	D2.1	**Work package**	WP 2
Dissemination level	PUBLIC	**Nature**	R — Document, report
Due date (M)	M2	**Submission date (M)**	M3
Partner responsible	EAS	**Contact person**	Alistair Lane

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Document History			
Date	**Version**	**Name**	**Changes**
14.08.2023	V0.1	Aligning INNOAQUA's Sustainable Aquaculture Practices with the EAA.	
15.08.2023	V0.2	Aligning INNOAQUA's Sustainable Aquaculture Practices with the EAA.	Internal revision
15.08.2023	V1.0	Aligning INNOAQUA's Sustainable Aquaculture Practices with the EAA.	Final review - Submitted
19.03.2025	V2.0	Aligning INNOAQUA's Sustainable Aquaculture Practices with the EAA. V2.0	Re-submission after review meeting RP1

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List of Acronyms

Abbreviation / Acronym	Description
ABP	Animal by-products
EAA	Ecosystem Approach to Aquaculture
EC	European Commission
EIA	Environmental Impact Assessment
FAO	Food and Agriculture Organization of the United Nations
FPH	Fish Protein Hydrolysates
FTPM C-C	From product to market co-creation
FURG	Universidade Federal Do Rio Grande
IMTA	Integrated Multi-Trophic Aquaculture
PBRs	Photobioreactors
POP	Persistent Organic Pollutants
ppt	Parts per trillion
RAS	Recirculating Aquaculture Systems
SEA	Strategic Environmental Assessment
SRS	Shallow Raceways Systems

Executive Summary

An ecosystem approach to aquaculture (EAA) is a strategy for the integration of the activity within the wider ecosystem such that it promotes sustainable development, equity and resilience of interlinked social-ecological systems. (FAO. 2010).

The development of Integrated Multi-Trophic Aquaculture (IMTA) production systems is not new, although deployment across Europe remains low, despite its EAA credentials. The "classical IMTA" approach, where multitrophic species are grown on the same site to achieve the various advantages of the system has legal bottlenecks and associated challenges.

One of the legal constraints is the use of animal by-products (ABPs) for the production of food and notably Category 2 aquaculture animal by-products that are considered as high-risk material[1]. Revision, including additional definitions, of current legislation and introduction of new legislation forcing circularity in view of environmental protection maybe required. Other bottlenecks may be partially overcome by the "basin-scale" approach to IMTA, where the positive and negative environmental effects, as well as social and economic, may be easier to measure and manage when seen at the whole and larger water system dimension.

INNOAQUA seeks to excel in trophic efficiency through its two demos. It is a fully integrated approach that uses the "natural ecosystem approach" in a predictable and manageable way to fully exploit the fish production waste streams and create high-quality and low carbon-footprint protein and other valuable ingredients from algae. Waste production will be minimised and valorised, for example through upcycling to create packaging solutions. Other solutions will be proposed for waste limitation during both production and processing.

As one of the first deliverables of the project, potential gaps in alignment with the EAA approach are also presented, including the use of native algal species and the potential legal challenges associated with the use of microalgae produced from wastewater streams for use

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[1] **Regulation (EC) 1069/2009** and **Commission Regulation (EU) 142/2011** are the framework within all handling, collecting, processing and trading of animal by-products take place. The main principles are safe sourcing, safe treatment and safe end uses. Category 2 material is defined in Article 9 of Regulation (EC) 1069/2009. Category 2 material is also high risk; it includes fallen stock, manure and digestive tract content. Category 2 is also the default status of any animal by-product not defined in Regulation (EC) 1069/2009 as either category 1 or category 3 material. https://food.ec.europa.eu/safety/animal-products_en

as a feed ingredient, its application as a novel food obtained through biorefinery techniques and potentially the utilisation of algae species not (yet) approved for food.

1. Introduction

The Farm-to-Fork Strategy of the European Green Deal acknowledges the potential of algae to become an important source of alternative low-carbon footprint protein and contribute to improving the sustainability and competitiveness of the aquaculture sector. Nonetheless, the European algae industry is still in an early phase lagging behind the overall increase seen at a global level, mostly driven by Asia. Within this context, the EU project INNOAQUA aims to pave the path towards the upcoming sustainable and diversified EU land-based aquaculture industry by demonstrating and mainstreaming innovative algae-based foods and solutions, based on sustainability, circularity, and digitalization concepts. Moreover, innovative food products based on by-products from seafood processing will be developed, and remaining rest fractions from the algae processing will be processes and upcycled into packaging materials, fitting INNOAQUAs waste minimization strategies.

INNOAQUA will also work on understanding how consumer perceptions and social norms influence the consumption of innovative seafood products by co-creating the products together with end-users and simulating their uptake in digital models of communities to identify effective market deployment and penetration strategies.

Lastly, a multi-level outreaching strategy aims at fostering knowledge transfer and ultimately helping maximize the project's scope and impact and will comprise, amongst other, materials for skills development and activities to foster international cooperation.

The full name for INNOAQUA is "Innovative Approaches for an Integrated Use of Algae in Sustainable Aquaculture Practices and High-Value Food applications". INNOAQUA started on the 1st of June 2023 and will finish by the 31st of May 2027. A total of 17 partners from eight countries are involved in the project, led by NORCE Norwegian Research Centre (NORCE). Total project eligible costs are 7.3 million euros, and almost 6 million of this is funded by the European Union

1.1 Purpose of the document

In the original call from which the INNOAQUA project received funding (HORIZON-CL6-2022-FARM2FORK-02-05), the Commission called for innovative solutions to environmentally friendly, inclusive, safe and healthy seafood production through innovation in the supply chain, through implementation of the ecosystem approach for sustainable management of marine or freshwater fisheries or in aquaculture development.

Work package 2 of INNOAQUA (Sustainable Aquaculture Practices) has five main objectives:

I. the implementation of an ecosystem approach in two demo sites.
II. the demonstration of coupled RAS and IMTA systems for an improved environmental sustainability of aquaculture.
III. the production of algae biomass for new seafood and packaging materials development in the project.
IV. the development of digital solutions for aquaculture.
V. the development of aquaculture sludge valorisation strategies.

This deliverable shows how the approach and demonstrations developed within INNOAQUA fit well within the Ecosystem Approach to Aquaculture (EAA) framework[2]. It also assesses the legal and regulatory bottlenecks to wide scale deployment of IMTA in Europe, as presented in three recent EU projects: GAIN – on green aquaculture intensification; ASTRAL – on resilient value chains from IMTA and IDREEM – on regulatory challenges to IMTA.

1.2 Structure of the document

The document consists of three parts to address the two principal objectives.

Following an introduction of the Ecosystem Approach to Aquaculture and its guiding principles, the first part gives a simple overview of the deployment of Integrated Multi-Trophic Aquaculture (IMTA), describing the "classical IMTA" approach, where multitrophic species are grown on the same site to achieve the various advantages of the system. This is followed by presentation of the constraints to deployment in the EU, as identified by various EU projects. Information is also presented on the "basin-scale" approach that can help to overcome constraints, as it focusses on the whole, and larger water system, where the positive effects may be easier to measure and manage.

[2] FAO. Aquaculture development. 4. Ecosystem approach to aquaculture. FAO Technical Guidelines for Responsible Fisheries. No. 5, Suppl. 4. Rome, FAO. 2010. 53p. https://www.fao.org/3/i1750e/i1750e.pdf

The second part focusses on the two INNOAQUA demo sites and their development. Alignment is presented with the EAA-based KPIs. A final part presents some gaps that the project will fill as it progresses, notably on the use of native algal strains and contribution to legislative bottlenecks.

1.3 Relation to other project deliverables

There is no specific relation to other project deliverables, although the EAA approach underpins the rest of Work Package 2 and especially the development of two demos.

2. The guiding principles of EAA

Back in 2010, the Food and Agriculture Organization of the United Nations (FAO) produced its first set of Technical Guidelines to underpin the Code of Conduct for Responsible Fisheries (CCRF). One of the series is dedicated to the Ecosystem Approach to Aquaculture (EAA) (FAO, 2010) and, as the other publications in the series, it sought to enforce the technical, environmental, economic, and social sustainability of the industry.

> *"An ecosystem approach to aquaculture (EAA) is a strategy for the integration of the activity within the wider ecosystem such that it promotes sustainable development, equity and resilience of interlinked social-ecological systems." FAO. 2010*

The EAA has three main objectives - ensuring human well-being, ensuring ecological well-being; and facilitating the achievement of both through effective governance. As "the" strategy to ensure that aquaculture contributes positively to sustainable development, the EAA is guided by three main interlinked principles:

- **Principle 1: Aquaculture development and management should take account of the full range of ecosystem functions and services and should not threaten the sustained delivery of these to society.** Developing aquaculture in the context of ecosystem functions and (at least operationally), estimating some assimilative and production carrying capacities, and adapting farming practices accordingly. The mix of ecosystem services will depend on wider management practices and the trade-off among different services must be acknowledged. This is especially important in the case of ecosystem functions that are unique, essential, or threatened to ensure their preservation.
- **Principle 2: Aquaculture should improve human well-being and equity for all relevant stakeholders.** This principle seeks to ensure that aquaculture provides equitable opportunities for development and equitable sharing of its benefits. This includes ensuring that it does not result in any undue detriment for any groups within society,

especially the most vulnerable. Both food security and safety are to be promoted as key components of well-being.

- **Principle 3: Aquaculture should be developed in the context of other sectors, policies and goals.** This principle recognizes the interactions between aquaculture and the larger system, in particular the influence of the surrounding natural and social environments on aquaculture practices and results. This principle also acknowledges the opportunity of coupling aquaculture activities with other production sectors to promote materials and energy recycling and better use of resources in general.

The EAA is a wide-reaching approach that can be applied to all aquaculture systems, whatever their technology level and wherever they are sited. For INNOAQUA, the application of EAA is restricted to the concept of land-based Integrated Multi-Trophic Aquaculture (IMTA).

3. Deployment of IMTA

Nutrient extraction (reducing or preventing eutrophication) is the most widely known ecosystem service of macro-algal culture and is at the heart of the Integrated Multi-Trophic Aquaculture (IMTA) concept. One of the pioneers of IMTA, Dr. Thierry Chopin, introduced the concept in 2004, describing it as “The farming, in proximity, of aquaculture species from different trophic levels with complementary ecosystem functions, in a way that allows one species' uneaten feed, waste, nutrients and by-products to be recaptured and converted into fertiliser, feed and energy for other crops, and to take advantage of interactions between species. Farmers combine fed aquaculture (e.g. finfish) with synergistic extractive aquaculture, which utilises the inorganic (e.g. micro- and macro-algae and plants) and organic (e.g. suspension and deposit feeders) excess nutrients from fed aquaculture for their growth. What were previously considered wastes, or by-products, of one species become co-products that can be used by other species, considered additional crops, providing economic diversification in more efficient and responsible food production systems. This is biomimicry, simply emulating what nature does.”

The Aquaculture Europe 2013 conference in Trondheim, Norway took the theme “Beyond Monoculture” and was the first European event to focus on this “new” approach. Since then, several EU projects have further defined and developed IMTA (including with a wide range of species combinations).

3.1 Classical IMTA approach

The classical approach to IMTA was for a single production site in cold-water marine aquaculture. The model was based on sea cage culture of Atlantic salmon with lines of (sugar) kelp and mussels suspended “down-current” of the salmon cages to absorb nutrients. A fourth trophic level (bottom feeders or detritivores such as sea cucumbers) were subsequently added.

In 2016, the Norwegian Leroy Seafood Group and the Bellona Foundation joined forces to form the company Ocean Forest, whose goal was to establish new forms of biomass production linked to aquaculture (https://bellona.org/projects/ocean-forest).

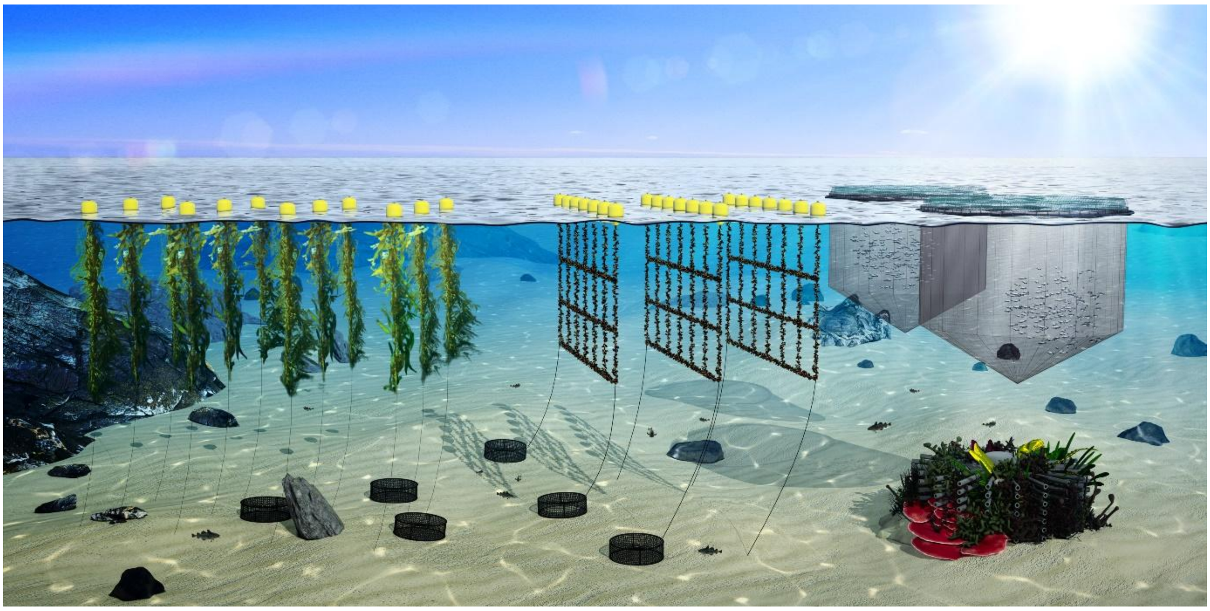

Figure 1. Ocean Forest Concept. Copyright Ocean Forest.

3.2 Regulatory bottlenecks & other constraints

The key IMTA EU projects over recent years (GAIN, ASTRAL and IDREEM) have identified various regulatory constraints that might hinder the development of the sector, especially with regard to licencing.

Existing EU regulation provides the highest standards for food safety and consumer protection through strict regulations on food and feed safety and hygiene and on human and animal health. But these might actually be limiting the capacity of EU aquaculture to valorise (waste stream) resources and develop circular processes.

GAIN produced a white paper on policy/legislation change (Ferreira et al, 2020) where they identified several bottlenecks for application of the circular approach (including IMTA and aquaponics). In summary:

- Legal restrictions: for example, the consideration of Category 2 aquaculture animal by-products (ABPs), that are globally considered as high-risk material, which strongly constraints their options for valorisation. Another example could be the use of fish waste to feed filter- or deposit-feeding invertebrates. In these situations, a revision of in-force regulations to promote changes would be required.

- Some particular processes of aquaculture production may be subjected only to lax legal restrictions, or these may not exist at all, due e.g. to the low environmental impact or to the presence of regulatory gaps. So, it might be appropriate to introduce new legislation forcing circularity in view of environmental protection or encourage it through incentives such as tax benefits or ecolabelling. Examples of this may be water reuse or the discharge of N and P through effluents.
- Policy approaches for commercial IMTA or aquaponics might focus on the support to companies in technology and process development, with tax benefits and environmental certification as possible incentives.

On that first point, and relative to INNOAQUA, is the reuse of aquaculture effluents, where the Circular Economy Action Plan[3] considers the cultivation of algae for the treatment of wastewater and sewage sludge, in the context of the revision of relevant directives. An example is the use of microalgae produced from wastewater streams as a feed ingredient. The microalgal biomass would need to comply with Regulations (EC) No 178/2002, (EC) No 183/2005 and (EC) 767/2009 and Directive 2002/32/EC on undesirable substances on animal feed. Algae are included in the latest version of the catalogue of feed materials, but microalgae are not specifically mentioned.

The GAIN white paper proposed several revisions of current regulations:

1. Authorised uses of Category 2 aquaculture ABPs based on the potential health and safety hazards and the efficiency of authorised processing methods to eliminate those hazards.
2. Definition of Category 2 aquaculture ABPs, since it is too broad and encompasses a wide range of by-products of different origins, characteristics and potential risks. Sub-categories should be created to classify Category 2 aquaculture ABPs and authorised uses should be different for each subcategory, depending on their potential risks and the efficiency of authorised processing methods to eliminate those risks.

[3] https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

3. Design and validate safe and cost-effective processing methods for Category 3 aquaculture ABPs in order to extract high-value products such as protein hydrolysates and peptides.
4. Generate scientific and technical knowledge to evaluate the potential risks for human and animal health associated to the feeding of filter- and deposit-feeder aquatic invertebrates with fish waste in IMTA facilities, in order to frame a regulatory change on Regulation (EC) No. 767/2009.

Concerning the practicalities of implementing commercial scale IMTA, one important constraint is the space requirement. If a starting point for an industry definition were to be how effective the IMTA system is at removing excess nutrients (especially nitrogen) from the environment, the setting of thresholds for industry standards would be crucial to the operation of a certification system. But proof that growth of the extractive species directly offsets nutrient load from the fish farm is difficult to confirm. IDREEM partners suggested that changes in water quality might have a wider variability than could be offset by the extractive species at scales that might be implemented in Europe. They cited estimates that to remove 10% of the nitrogen from a 1000 tonne salmon farm would require approximately 10 hectares of seaweed and their own models suggested that the scales are liable to be larger than this.

3.3 The Basin-scale approach to IMTA

The recent EU Horizon 2020 project, FutureEUAqua assessed IMTA and carrying capacity in a set of deliverables (D4.1 to D4.3 at https://futureeuaqua.eu/index.php/media/public-deliverables/).

Freeman et al. (2022) suggested that IMTA research on the farm as a single unit may be limiting in assessing the environmental and economic advantages of the concept, but that the underlying ecosystem interactions are sound. This has led research to consider integrating different species fulfilling different trophic niches at broader spatial scales – hence the term basin-scale IMTA. Sanz-Lazaro & Sanchez-Jerez (2020) recommended using basin scale nutrient budgets to guide licenses for monoculture operations of finfish and a variety of extractive species, with the potential to overcome limited implementation of IMTA.

Images are often seen of the vast basin-scale IMTA applied in China, for algal production abut also to mitigate eutrophication and dampen climate effects.

Although it is not easy to assess the level of remediation needed at a basin scale, the decoupling of algae and finfish culture in a water basin could improve their environmental quality with multiple sources of dissolved nutrients. The siting of algae production units could also take advantages of other ecosystem services.

3.4 INNOAQUA IMTA – land based and climate proof.

Land-based IMTA systems are not new. Production prototypes were developed in Israel in the mid-90s (Shpigel and Neori, 1996) and various models have been tested for a wide range of species mixes.

The IDREEM project had a pilot in Ardtoe on Scotland's west coast using raceway systems to produce *Ulva* sp. (commonly called sea lettuce) grown on nutrient rich water coming from tanks containing turbot (*Psetta maxima*), cod (*Gadus morhua*) and sea bass (*Dicentrarchus labrax*). The harvest of sea lettuce was then used to feed sea urchins (*Paracentrotus lividus*). After several refinements to the system, it was estimated that the company could produce enough *Ulva* to support sea urchin production of 100-200 adult individuals/m^2 to commercial size. (IDREEM, 2016). ASTRAL and AquaVitae have land-based IMTA with biofloc system in, FURG and University of Santa Caterina, respectively. FURG has an IMTA chain using as fed specie white shrimp, tilapia, oyster, seaweed (ulva) and salicornia. In addition, ASTRAL has in-land IMTA in South Africa with 2 chains: abalone-ulva and sea urchin-ulva[4].

INNOAQUA takes an innovative approach by developing integrated RAS/IMTA systems for salmon and microalgae and for sole and macroalgae to produce purified algal products and fish processing waste into innovative seafood products.

[4] https://www.astral-project.eu/imta-lab-brazil, https://www.astral-project.eu/imta-lab-south-africa and https://zenodo.org/communities/astral_h2020/?page=1&size=20

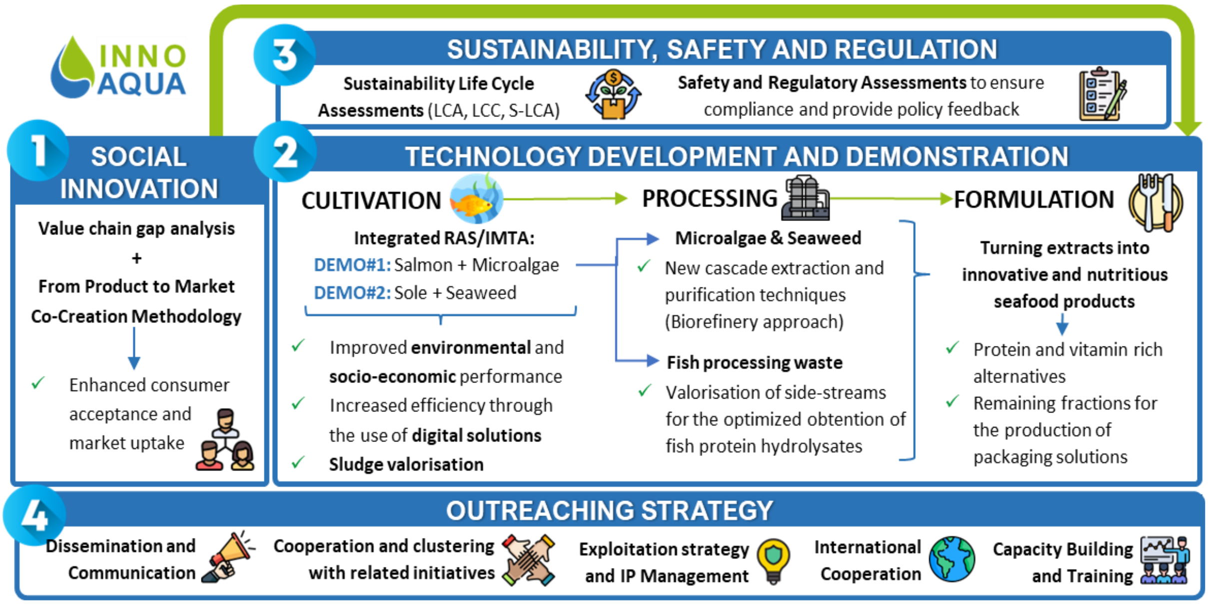

Figure 2. INNOAQUA's overall concept

Land-based systems offer significant advantages over coastal cage culture, including improved management and production predictability, mitigation of environmental interactions and the potential to be sited "close-to-market." They are also considered to be more climate-proof, with regular water quality, light and temperature.

4. INNOAQUA Practices

As stated before, land-based seaweed production is not a completely novel concept. Several systems and prototypes have been developed since the initial works by John Ryhter et al. (1975) passing through the establishment of a commercial land-based seaweed farm in Canada and, closer to the EU, the developments in Israel by Shpigel and Neori (1996). However, while seaweed production has been increasing significantly over the last decades, the contribution of land-based production to this is virtually insignificant. Several factors can contribute to this, but one is certainly the lack evolution of these land-bases systems when compared to those early days.

One of the main differences in favour of land-based algae production is the higher degree of control, when compared to sea-based production, but the truth is that we haven't been able to harness all that differentiation potential. Adding to this, large near-shore areas with access to good quality seawater are not so abundant in Europe, either for practical reasons but sometimes also due to regulatory, economic, or political reasons. A possible way to overcome this is the adoption of IMTA concept in new or already existent land-based fish farms. This means access to territories already assigned to uses by the aquaculture industry and access to good quality water for algae production (meaning nutrient rich and pollutant free). In this case, the challenge is for a fish-farm to adopt algae production technologies, without needing to become an expert. That should be possible through the adoption of technologies for monitoring, prediction, and management (including aides to decision making or actuation), such as it happens already in other sectors, including for instance hydroponics or the microalgae production sector itself.

4.1 Integration of RAS Atlantic Salmon aquaculture with microalgae cultivation.

At first, NORCE will place two small (~25L) tubular photobioreactors (PBRs) at RASLAB facilities, integrating and optimising microalgae production process directly with the RAS system, showing proof-of-principle. RASLAB has 12 independent 2500L RAS systems, each of them automated and self-contained with a biofilter, drum screen filtration, solids collection and UV disinfection to maintain Atlantic salmon in fresh or seawater up to a production density of 75 kg/m^3 and operating at <5% water exchange. Water from RAS with salmon in various life stages (freshwater (1-3 ppt salt), brackish (10-20 ppt salt), seawater (35 ppt salt) will be tested for the production of *Chlorella sorokiniana* (1-10 ppt salt), *Phaeodactylum tricornutum* (15-35 ppt salt), or *Nannochloropsis oculata* (35 ppt salt). Replicate systems will be used to determine system variability in RAS and allow to a simultaneous assessment of culture conditions (temperature, salinity, nitrogen load, other nutrients (P, minerals, vit. B12 concentrations in water), as well as contaminants (heavy metals, POPs, etc.) on the production of microalgal biomass and its quality. Fish growth and performance as well as welfare will be checked while under production. Smart online monitoring using novel technologies based on optical spectroscopy such as multispectral turbidity, nutrients and biomass content will allow steering for example optimal retention times and biomass concentration. The data obtained from this proof-of-principle will form the basis for a scaled-up optimal process design of a microalgae-RAS at commercial scale (50 m^3) and automated digital control system that will be demonstrated at VA's facility (Gulen, Norway).

4.2 Integration of RAS Sole aquaculture with seaweed cultivation following a Smart-IMTA approach.

A4F and SEA8 will pilot at a relevant pre-commercial level a SMART-IMTA (System for Monitoring and Adaption in Real Time for Integrated Multi-Trophic Aquaculture) land-based system that enables enhanced seaweed biomass (*Ulva*, *Porphyra* and *Gracilaria*) and fish production. The demo site will be installed at a commercial Sole (*Solea senegalensis*) aquaculture facility (Safiestela S.A.) owned by SEA8 in Póvoa de Varzim (Estela, Portugal) and operated together with A4F personnel experienced in seaweed cultivation. This SEA8 facility currently produces 2.5 million juvenile sole per year and uses the latest production techniques and farming systems, such as Shallow Raceways Systems (SRS) and Recirculating Aquaculture Systems (RAS). RAS systems are essential for a sustainable aquaculture production, by re-using the water, they reduce the volume of solids and nitrogen released into the environment, and they use 36% less water than a conventional, semi-intensive aquaculture. Presently, however, this is done through mechanical or biological methods without any added value to the system. SEA8 systems usually generate 20-60 m^3/h in effluent rich in organic matter and nutrients such as nitrogen and phosphate, and part of this will be used to supply water to the different seaweed production systems (flow-through systems in free-floating conditions).

This Demo will identify the operational and system specifications to select, adapt and/or develop the digital solutions (further explained in the next epigraph), which will allow to reach an improved IMTA system with monitoring for detecting any problematic changes with culture, but also with automation to improve the efficiency of the process, ultimately helping the fish technician to focus simultaneously on animal production and the management of the seaweed.

Currently, IMTA systems typically focus either on biomass production, compromising the biofiltering performance or, instead, on the later, compromising algae biomass yield. This is mostly due to the lack of capacity to generate, treat data and act in due time (in terms of water and biomass management) to maximize both aspects. For this purpose, INESC-TEC will develop tools that allow the capture, storage and processing of data obtained by sensors to extract information and reach adaptive capabilities of systems, acting in real time in production using data collected and establishing and validating the digital architecture of suitable systems.

On one side, innovative optical sensors for the measurement of different parameters such as dissolved carbon dioxide, nitrates, spectral turbidity, light and temperature will be developed and combined, together with commercially existing ones, in a detection Multisensing Module. This module will have signal processing and communication capabilities to send real-time data to the central control system, being easily replicable for the monitoring of several distributed points and open to the inclusion of new sensors for the measurement of other parameters. These innovative sensing parameters will bring added value in terms of the algae production by supporting a dynamic control of parameters in the fish-algae symbiosis and providing valuable data to develop control systems and algorithms that, in the future, will be able to optimize these complex production systems. Moreover, an innovative Digital Twin Backbone will also be developed, consisting of several blocks or components that will facilitate the ingestion, transformation and storage of data flows coming from the sensors installed in plant, making this data accessible to other interested parties, such as the intelligent Operations and Maintenance functions, in near real time, through a set of pre-defined public Application Programming Interfaces.

In parallel to the physio-chemical control described, both demo sites will also include monitoring of the microbiome associated with the algae systems. Even though fish-farmers understand the potential sustainability and economic benefits of IMTA systems, they still need to be comfortable on the microbiological safety of the re-used water. With that in mind, the microbiome (bacteria, viruses, eucaryotes) will also be monitored in all systems to understand how these might be related between fish and algae, how they affect quality or cause culture crashes and how to prevent negative effects by for example mechanical treatment in between both processes and other pest control strategies in the algae cultivation.

5. Alignment of EAA “pillars” and the INNOAQUA approach

In an article for the World Aquaculture magazine in 2021 (Costa-Pierce, 2021)), Barry Costa-Pierce, a well-known author of ecological and EAA aquaculture research, described 6 fundamental pillars of “ecological aquaculture”. While they are not the “formal” pillars that are proposed by FAO in its EAA publications, they do enshrine the EAA principles in an interesting way.

Below each is a short description of how INNOAQUA fits those pillars.

1. Ecological aquaculture systems are “aquaculture ecosystems” that mimic the form and functions of natural ecosystems, resulting in accelerated environmental profits.

   INNOAQUA will demonstrate at a precommercial level the integration of fish and algae cultivation in coupled RAS/IMTA systems, aiming to minimize energy and nutrient losses and thus reduce the eutrophication potential in cultivation environments, while simultaneously maximising resource efficiency by closing the nutrient loop. Wastewater from the fish production systems will directly feed into the algae production systems, whereas the fish sludge first will be treated to liberate valuable nutrients for algae production. The KPIs shown in Table 1 below show the % recovery rates of the various activities foreseen.

2. Ecological aquaculture results in accelerated economic profits by practicing trophic efficiency to ensure that aquaculture is humanity’s most efficient protein producer.

   INNOAQUA seeks to excel in trophic efficiency through the two demos. INNOAQUA is a high-tech, fully integrated approach that uses the “natural ecosystem approach” in a predictable and manageable way to fully transfer the fish production waste streams and create high-quality and low carbon-footprint protein and other valuable ingredients from *algae, allowing for diversification and increase in biomass production (fish + algae) per used raw materials. INNOAQUA will contribute to maximising the exploitation of algae by allocating all the valuable extracts to different food/food supplement markets with high added economic value, while minimising waste production by valorising or even upcycling (as is the case of the packaging solutions developed within the project) left-over residuals into other (lower) sectors. Moreover, INNOAQUA will also provide other tools to limit waste during seafood production and processing.*

3. Ecological aquaculture results in accelerated social profits by integrating aquaculture developments into long-term global fisheries, food and poverty alleviation industries and programs.

   From product to market co-creation (FPTM C-C), as a novel market-oriented strategy, will combine techniques used in consumer-led Novel Product Development with agent-based modelling and simulation to guide the producer's decisions along the entire process of introducing a new seafood product to the market.

4. Ecological aquaculture results in accelerated local/regional social/economic profits by integration with communities to maximize local and regional economic and social multiplier effects in order to provide maximal job creation and training within the region.

   INNOAQUA will employ a novel combination of socio-scientific and technological research to offer (novel) seafood producers guidance on increasing consumer acceptance. NORCE, through its Center for Modeling Social Systems, will lead the development and testing of the From product to market co-creation (FPTM C-C) methodology. The methodology is rooted in the necessity to develop products with active consumer involvement in collaborative design and in taking advantage of naturally occurring processes of innovation diffusion in communities.

   Moreover, INNOAQUA will carry out specific dissemination activities aimed at promoting international cooperation in aquaculture related R&D activities. To do so, EAS, in *collaboration with the rest of the partners will lead the organisation of yearly webinars/workshops to disseminate the project results and foster cross-fertilization and replication of developed solutions and to perform analyses of aquaculture industry in different regions worldwide. Moreover, within the project specific capacity building activities will be organised to facilitate technology and knowledge transfer from the participants to the partners and external parties.*

5. Ecological aquaculture uses native species/ strains and does not contribute to "biological" pollution.

   INNOAQUA will test amongst others native strains such as the locally isolated Phaeodactylum tricornutum strain in Demo 1, combined with the brackish and saltwater stages of Salmo salar. (Demo 1: Salmo salar, Chlorella sorokiniana, Phaeodactylum tricornutum, Nannochloropsis oculata. Demo 2: Solea senegalensis, Ulva, Porphyra and Gracilaria), but also cultures them in highly managed land-based systems that allow no escapes or interaction with the surrounding ecosystem. Seaweed species to be used are commercially well-known species, listed for instance in the EU as approved algae for human consumption. All three have a market, both in the EU and worldwide, being Porphyra (ingredient in Sushi rolls) and Gracilaria (source of agar) the most noticeable. Porphyra=Pyropia (the asian species) is the most valuable seaweed genus in the world today. In all cases, native strains of the seaweeds will be selected and used throughout the project.

6. Ecological aquaculture is a global partner, producing information for the world, avoiding the proprietary.

   INNOAQUA outputs will be published in various forms and formats, allowing full transparency and access to detailed information. Its Dissemination, Exploitation and Communication strategy will adequately mainstream and exploit the project's results, including the development of educational support materials for skills development and activities to foster international cooperation. Project results are owned by the partner that *generates them. Jointly owned results will be allowed to be used for non-commercial research and teaching activities by its owners on a royalty-free basis.*

With regard to pillar 1 above, the various activities and associated KPIs of WP2 of INNOAQUA are listed in the following table. Targeted capture and removal of excess nutrients, increased protein levels of algae and protein recovery from fish processing waste, are all provided and show clearly the quantitative trophic efficiency to contribute to the knowledge base that aquaculture is humanity's most efficient protein producer.

Table 1 INNOAQUA KPIs to implement an ecosystem approach to production. Source INNOAQUA proposal.

Activity	KPI
Demonstration processes for full integrated algae production from fish cultivation water effluents at two precommercial level demonstration sites	DEMO#1: (i) >90% capture of dissolved N and P from RAS production of Atlantic salmon and; (ii) reduce the environmental footprint of a land-based commercial salmon grow-out facility, while producing an additional valuable product (25% less environmental impact of the combined (optimised) processes compared to baseline separate processes, through decreased water, oxygen, and fertilizer consumption as well as improved biomass and product productivity. DEMO#2: (i) increase biomass production and decrease wastewater volume by the integration of seaweed in a sole production facility; (ii) increase by 25% the protein content of IMTA seaweed when compared to other origins; (iii) treat 90% of the water exchange by SEA8, removing 30% of the dissolved N and P from one of the fish production streams and (iv) annually remove the equivalent to 55kg N and 3kg P.

Culture microbiome and virome monitoring at both DEMO sites will provide an overview of pests / contamination and thus water and biomass quality.	Water quality sufficient for re-use within both IMTA systems. Biomass quality sufficient for use as food ingredients. Ensure the losses in algae biomass productivity due to crashes are below 5% of annual productivity
Development and implementation of a Multisensing Module and a Digital Twin Backbone to capture, store and process real time data from the processes to support the decision making and system actions	(i) Water Multisensing Module to measure in real time dissolved CO_2, nitrates and water turbidity. (ii) Digital Twin Backbone to capture store and process real time data to support the decision making and system actions.
Demonstration process for the valorisation of dewatered RAS sludge into medium ingredients for algae cultivation	Recovery of 30% N and 10% P from RAS sludge.
Demonstration process to produce functional fish protein hydrolysates (FPH)	Over 70% protein recovery from fish processing waste. Equivalent or improved bioactivity compared to analogue commercial protein hydrolysates obtained from whole fish/fish muscle (PeptACE® or Vasotensin®).

6. Gaps – and how these may be narrowed

6.1 Use of native strains

The species currently chosen in INNOAQUA have been mainly chosen due to their high potential as ingredient for innovative seafood. This is both based on their interesting biomass composition for product development, as well as legislative status regarding use in food. Once shown to be successfully used within this IMTA approach, the step to producing other algal strains on the wastewater from aquaculture should not be too difficult. The developed smart Multisensing Module and Digital Twin Backbone that are used to capture, store and process real time data from the processes to support the decision making and system actions can be adjusted to other species used in the IMTA systems.

6.2 Legislation

As presented previously (and documented by the three reference EU projects), the legislative constraints and challenges for IMTA also apply to INNOAQUA and may actually be amplified using this concept.

INNOAQUA will add to the knowledge base, by studying and collecting data on the regulatory status of products for human consumption derived from IMTA algae cultures grown on fish farming effluents and its application as novel food obtained through biorefinery techniques. The utilisation of algae species not (yet) approved for food will also require a solid application dossier and the studied required to gain market access will also be performed.

More specifically, this will imply the application of isolated extracts from algae to be used as food ingredients as opposed to the whole algae. Moreover, the safety and health considerations of using seafood/fish processing by-products to produce functional protein hydrolysates will be further explored.

All information will be gathered in a comprehensive report on the legal analysis, identifying applicable legislation, steps in the regulatory process that may be improved with the proposed techniques and, in case of uncertainty, different regulatory options. The main findings, in particular bottlenecks due to gaps/overlaps in legislation and recommendations on how these might be overcome will be summarized in a policy paper.

Providing data on potential health and safety hazards of land-based IMTA and the use of fish production wastewater for algae cultivation is not easy to "frame." To simplify, it may be a matter of terminology. For example, if the production of fish is certified as organic, the "effluents/wastes" are also – and, logically, so is seaweed biomass. Of course, being certified as organic does not mean it is safe for human consumption *per se* and especially if it does not fit into a specific legal classification, but in any case, there are values and thresholds for microbiological and toxicology safety that the algal biomass must meet.

In conclusion, INNOAQUA is demonstrating a new and circular production system that could mainstream innovative algae-based foods and solutions, based on ecology, circularity, and digitalization concepts. Innovative food products based on by-products from seafood processing will be developed, and remaining rest fractions from the algae processing will be processes and upcycled into packaging materials, fitting INNOAQUAs waste minimization strategies.

This enshrines the principles of the Ecosystem Approach to Aquaculture, even though there are challenges and potentially legal bottlenecks to market.

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