ASTRAL

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Abbreviations

LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
IMTA	Integrated Multitrophic Aquaculture
CC	Climate change
OD	Ozone depletion
IR	Ionising radiation
POF	Photochemical ozone formation
PM	Particulate matter
HT-NC	Human toxicity, non-cancer
HT-C	Human toxicity, cancer
AC	Acidification
EU-F	Eutrophication, freshwater
EU-M	Eutrophication, marine
EU-T	Eutrophication, terrestrial
EC-F	Ecotoxicity, freshwater
LU	Land use
WU	Water use
RU-f	Resource use, fossils
RU-mm	Resource use, minerals, and metals

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1 Summary

The prevailing global trend focused on developing strategies to minimize the environmental impact of aquaculture, thereby striving for environmental sustainability, efficiency, and profitability. To assess the environmental performance of IMTA systems and compare them with their monoculture counterparts, LCA study was conducted. This comprehensive LCA study encompassed four distinct IMTA labs located in Scotland, Ireland, South Africa, and Brazil. The analysis scope and data inputs encompassed the cultivation and harvest phases of production, creating a cradle-to-farm gate LCA using SimaPro 9.4.0.2 and EF 3.0 (adapted) methodology to evaluate the environmental performance. The chosen methodology is particularly well-suited and recommended for LCA studies of aquaculture systems, considering a total of sixteen impact categories, including climate change, eutrophication, acidification, and ecotoxicity within the EF 3.0 method. The assessment generated life cycle indicators for one kilogram of biomass across all IMTA labs (one tonne of edible biomass in IMTA lab South Africa), with a specific focus on emissions and nutrient uptake, especially nitrogen and phosphorus, due to their connections with eutrophication. In the Scotland and Ireland IMTA systems, environmental hotspots were identified, pointing towards areas that could be addressed to enhance the systems' environmental profiles. Interestingly, both the Scotland and Ireland IMTA systems exhibited higher environmental impacts compared to their monoculture counterparts. In the case of Scotland, the cultivation phase showed substantial reductions of -10% in climate change and -98% in eutrophication for freshwater, and -70% for terrestrial eutrophication. In the remaining IMTA labs, particularly Ireland, South Africa, and Brazil, the cultivation phase remained the dominant source of impacts, with percentages as high as 97% in the marine eutrophication category. Notably, South Africa's IMTA lab successfully integrated the cultivation of Ulva in the effluents of the urchin system, thereby using the cultivated Ulva as direct feed in the early stages of urchin growth and processing it into formulated feed for later stages. This innovation significantly reduced the overall requirement for formulated feed and led to a substantial reduction of 36-46% in the eutrophication category. The overall reduction in the marine eutrophication category was notable, with reductions of 27.48%, 47%, and 47% observed in Ireland, South Africa, and Brazil in the IMTA system when compared to monoculture, highlighting the efficient nutrient retention and utilization in all the IMTA labs. These findings underscore the substantial value of transitioning to sustainable IMTA systems within the context of a circular bioeconomy. This transition not only enhances the utilization of marine resources but also contributes significantly to the broader goal of fostering sustainability in coastal regions.

2 Life cycle assessment (LCA)

2.1 General description of LCA in aquaculture

Life cycle assessment has emerged as a key environmental accounting tool to quantify the impacts and provide useful information required to improve sustainability of various production systems and process value chains, including aquaculture. Several LCA studies on aquaculture have been performed assessing environmental impacts from fishing, fish feed, and aquaculture systems with different species and different designs (intensive and extensive). In aquaculture, LCA compares different techniques of production of one species and assess the main contributing activities to the total impacts of producing that species (Henriksson et al., 2021; Ziegler et al., 2016).

The Integrated multitrophic aquaculture (IMTA) approach has been proposed as environmentally sustainable technology compared to intensive monoculture systems (Chopin, 2012). In IMTA, to produce multiple products from a common nutrient flow contributing to improved resource retention and utilisation is the key concept. The relation of this to bioremediation and mitigating eutrophication is yet to be fully understood and needs attention with an environmental perspective compared to a monoculture system. This approach fits well within the global ambition for circularity in food production, which strives to minimise energy and nutrient losses and maximise resource use efficiency, by closing the nutrient loop. LCA will facilitate the comparison of different systems such as monoculture and the IMTA, to understand the environmental performance based on a common denominator (for example per kg of biomass). Many studies focus on the productivity effects of cultivating multiple species from different trophic levels, as well as the nutrient uptake, nutrient recycling, and waste reduction by the IMTA system (Hughes & Black, 2016).

LCA is carried out according to the ISO standards guidelines (ISO 14040 and ISO14044) that includes four defined phases: 1. Goal and scope definition, 2. inventory analysis, 3. impact assessment and 4. Interpretation of the results. Goal and scope definition is the first step of LCA that sets the basis for the assessment. The aim and purpose of the study and intended application of the results are defined. The scope of the study includes the process and system description, function of the system, functional unit, the system boundaries, assumptions, limitations, and data quality. Defining the system boundaries plays a major role in the assessment of environmental impacts associated with inputs and outputs. This is often limited by data and resource availability or focussed to cover the major life cycle stages. Here, all processes included and excluded are clearly defined. The functional unit is defined as the quantification of the function that the product system will deliver and is used as the basis for calculating the potential impacts. This facilitates comparative studies in fisheries and aquaculture, for example between a monoculture and the IMTA system.

Life cycle inventory (LCI) phase includes the collection of data (qualitative and quantitative) for inventory analysis. This is one of the most time-consuming phases of the study where input and output data on mass and energy are compiled based on the defined system boundaries. Life cycle impact assessment (LCIA) phase is where the environmental burden related to the input and output of the processes is assigned to an impact category. The impact categories in an assessment are provided by the method used (such as EF3.0, ReCiPe, CML): the method chosen in the current study and the main impact categories for this project is defined in section 2.2. Interpreting the results is the final phase dealing with the outcomes from the study translating conclusions related to the process that contributed to the impacts. This stage will aid in supporting the decision-making, improvement of novel processing technologies, or lay a basis for government policy making. Performing LCA in aquaculture can aid in the decision-making process by identifying the hotspots in the system, where to reduce environmental impacts, and guide the design of the system and processes.

2.2 LCA approach in the ASTRAL project

The overall aim of this LCA study in ASTRAL is to compare the environmental performance of monoculture and IMTA, to provide possible options for environmental improvement in IMTA, and thereby enable shifting monoculture aquaculture practice towards IMTA. Most aquaculture LCA studies have collected data from the research site using questionnaires, literature data, data from commercial sites or have designed hypothetical farms based on literature data. In ASTRAL, we performed LCA with the data collected during the experiments from each IMTA lab. For LCIA, the European Commission developed a method in the context of the Environmental Footprint (EF) initiative and is the one that is recommended to be used by Product Environmental Footprint Category Rules (PEFCRs). EF 3.0 Method (adapted) V1.03 / EF 3.0 normalization and weighting set assessment methodology was used to assess the environmental impacts in the ASTRAL project. SimaPro professional database includes adaptations to make it compatible with the databases in the software (SimaPro Database Manual-Methods library v4.15 2020). Sixteen impact categories were included:

- Climate change (kg CO_2 equivalent), which aggregates greenhouse gas emissions.
- Ozone depletion
- Human toxicity, cancer
- Human toxicity, non-cancer
- Respiratory inorganics
- Ionising radiation, human health
- Photochemical ozone formation, human health
- Acidification
- Terrestrial eutrophication
- Freshwater eutrophication
- Marine eutrophication

- Land use
- Freshwater ecotoxicity
- Water use
- Resource depletion, fossils
- Resource depletion, mineral and metals

These are the widely used categories for aquaculture systems. A brief description of the main impact categories focussed on in the ASTRAL project are described below.

For the climate change category, an indicator of potential global warming due to emissions of greenhouse gases to the air is expressed in kg CO_2 equivalents. Eutrophication and acidification are measured in kg PO_4 equivalents and kg SO_2 equivalents, respectively. Eutrophication potential is related to the major nutrients (nitrogen and phosphorus) that are emitted to the environment. Acidification measures the potential to form acidic solutions that decrease the pH of soil and water that damage the ecosystem. SimaPro methods manual provides details on the methodology and describes each impact category (website link to methods library). Choice of allocation was performed according to ISO 14044 that has three successive approaches 1. Expand the product system, 2. Allocation via physical relationships (example: mass and energy-based) or 3. Allocation via other relationships (economic allocation).

Aim of ASTRAL to perform LCA.

To help the commercial aquaculture sector to adopt more sustainable production chains and increase awareness to make IMTA systems more environmentally sustainable. Table 1 describes the key characteristics of each IMTA lab studied. Each IMTA lab had focus on key processes such as infrastructure, feed production, energy use, cultivation, and transportation. In the sections below, environmental assessments of each IMTA lab are discussed in detail. To note that not all data are detailed or published in the deliverable to protect data for confidentiality or for future publication.

Table 1 **Key characteristics of each IMTA lab**

Production chain	**IMTA labs Scotland**	**IMTA lab Ireland**	**IMTA lab South Africa**	**IMTA lab Brazil**
Farming system	open system	open system	semi-open system	semi-open system
			partially recirculating system; land-based flow-through system	RAS; land-based flow-through system/ponds
Facility location	Scotland	Ireland	South Africa	Brazil
Monoculture species	Seaweed (extractive)	Salmon (fed)	Sea Urchin (fed)	Shrimp (fed)
IMTA culture species	Urchin, King scallops, oyster	Urchin, Oyster	Seaweed - Ulva	Tilapia (fed), seaweed, halophytes
Functional unit	1 kg of biomass	1 kg of biomass	1 ton of edible biomass	1 kg of shrimps
Impact assessment method	EF v3.0 (adapted in SimaPro	EF v3.0 (adapted in SimaPro	EF v3.0 (adapted in SimaPro	EF v3.0 (adapted in SimaPro
Infrastructure included	Yes	Yes	Yes	Yes

3 Environmental Assessment of IMTA lab – Scotland (SAMS)

In recent years, seaweed cultivation has gained prominence along various coastlines, catering to both human consumption and animal feed industries by providing fresh biomass. These macroalgae, broadly classified as brown, red, and green seaweeds, play a pivotal role in coastal marine ecosystems. As primary producers, they form the foundation of aquatic food webs and contribute to climate regulation by absorbing carbon dioxide for growth and potential for local mitigation of local ocean acidification. By assimilating nutrients like nitrates and phosphates, they mitigate eutrophication. Seaweeds exhibit multifaceted utility beyond environmental benefits. They serve as a resource for energy production, fertilizers, and nutrient-rich animal feed components. Additionally, they contain micronutrient, minerals, vitamins and biologically active compounds like fucoidans and carotenoids (Øverland, Mydland, & Skrede, 2019). Notably, seaweed finds application in diverse sectors, including the extraction of phycocolloids—such as alginates, carrageenan, and agar—which serve as thickening agents in the food, pharmaceutical, cosmetic and many other industries.

Seaweed research and cultivation practises are increasing due to their potential as a feedstock for energy and feed supporting blue growth in Europe (Seghetta et al., 2017). The global seaweed new and emerging market report 2023 by World Bank reports ten global markets that can grow additional USD 11.8 billion by 2030 (World Bank. 2023, http://hdl.handle.net/10986/40187). Cultivating seaweeds is seen as an alternative to land crops as it avoids deforestation, land competition and has high rate of carbon dioxide fixation, bioremediation of eutrophication nutrients (N and P), and climate change mitigation (Oirschot et al., 2017; Ross et al., 2023; Thomas, Potting, & Gröndahl, 2021; Thomas et al., 2020). An IMTA farming system combines organisms at different trophic levels that are linked in the common environment.

IMTA is a promising approach for the sustainable development of aquaculture. Organic and inorganic wastes from the fed species are utilized by the lower trophic species as nutrients for growth. Seaweeds extract dissolved inorganic nutrients (especially the major nutrients N and P), filter feeders remove finer organic particles and deposit feeders recycle larger particles like the uneaten feed and faeces. From an environmental perspective, advantages of combining the species in IMTA system can mitigate the impacts in eutrophication and climate change categories due to the uptake of nitrogen, phosphorus, and carbon. Carbon capture is estimated at 39,6 kg of carbon that relates to mitigate 145kg CO_2 equivalent; uptake of 4.08kg nitrogen and 0.4kg phosphorus relating to a reduction of 2.82kg PO_2 equivalent in the eutrophication mitigation category all corresponding to per tonne of fresh harvested seaweed biomass. This results in net negative impacts in climate change and eutrophication impact categories (Seghetta et al., 2017; Thomas et al., 2020).

Accounting for carbon cycle in seaweed is being extensively studied. Several studies have conceptualised the capacity of seaweed as a carbon sink where CO_2 from the atmosphere is sequestered by seaweed and can act as a carbon sink in deep oceans and marine sediments (Macreadie et al., 2019; Yong, Thien, Rupert, & Rodrigues, 2022). Here, we consider seaweed as a potential source that fixes CO_2 from the seawater to biomass. One tonne of dry seaweed biomass can absorb approximately 960 kg of CO_2 apart from nutrient uptake, such as phosphorus and nitrogen (Duarte, Wu, Xiao, Bruhn, & Krause-Jensen, 2017). In this study, the system boundary is at the farm-gate and the use and end-of-life phases are not considered. Carbon uptake at the time of harvest is accounted up to the production of seaweed biomass. Future research is needed to study the contribution of seaweed cultivation to organic carbon sequestration that provides the opportunity to mitigate climate change. More studies are required to identify the knowledge gaps in the seaweed carbon cycle, carbon sequestration from seaweed during cultivation, emissions from further seaweed processes and sinking of seaweed to deep sea to sequester CO_2 (Ross et al., 2023).

Overall, in IMTA lab Scotland, we study the environmental performance of a coastal inshore IMTA system in comparison to its monoculture equivalent in terms of biomass yield, nutrient flux, and infrastructure.

3.1 Goal and Scope Definition

This chapter provides a clear statement of the purpose of the study. Scope defines the functional unit, system boundaries, the impact assessment methodology, impact categories, and allocation used in this study.

3.1.1 Goal and scope

The goal of this LCA was to quantify the environmental impacts of the monoculture production of seaweed - *Saccharina latissima* and *Alaria esculenta* and compared to the production of the same with other low trophic species such as native oysters (*Ostrea edulis*), king scallops (*Pecten maximus*) and sea urchins (*Echinus esculentus*). In IMTA lab Scotland, we focussed on the infrastructure elements to identify and reduce environmental impact incurred from aquaculture production systems.

3.1.2 Site and Process Description

The Scottish IMTA lab 'Port-a-Bhuiltin' (PaB) is an open coastal aquaculture site located 200 m off the mainland shore in the Firth of Lorn-Loch Linnhe estuarine system, West coast of Scotland (56° 29.176 N, 5° 28.315 W). Since 2014, this site has functioned as an experimental seaweed cultivation area managed by the Scottish Association for Marine Science (SAMS). Marine Scotland has granted a license for seaweed cultivation at the site, and with a subsequent update in 2020, the license was extended to include the experimental non-commercial co-cultivation of selected shellfish species. Being a research site, cultivated species and production scales vary from year to year depending on various research projects interests and requirements, but have focussed mainly on the cultivation of kelp (*A. esculenta*, *S. latissima*) and European flat oysters (*O. edulis*). Within the ASTRAL project, additional species are trialled including the red seaweed dulse (*Palmaria palmata*), king scallops (*P. maximus*) and sea urchins (*E. esculentus*). The layout for IMTA lab Scotland is as shown in Figure 1.

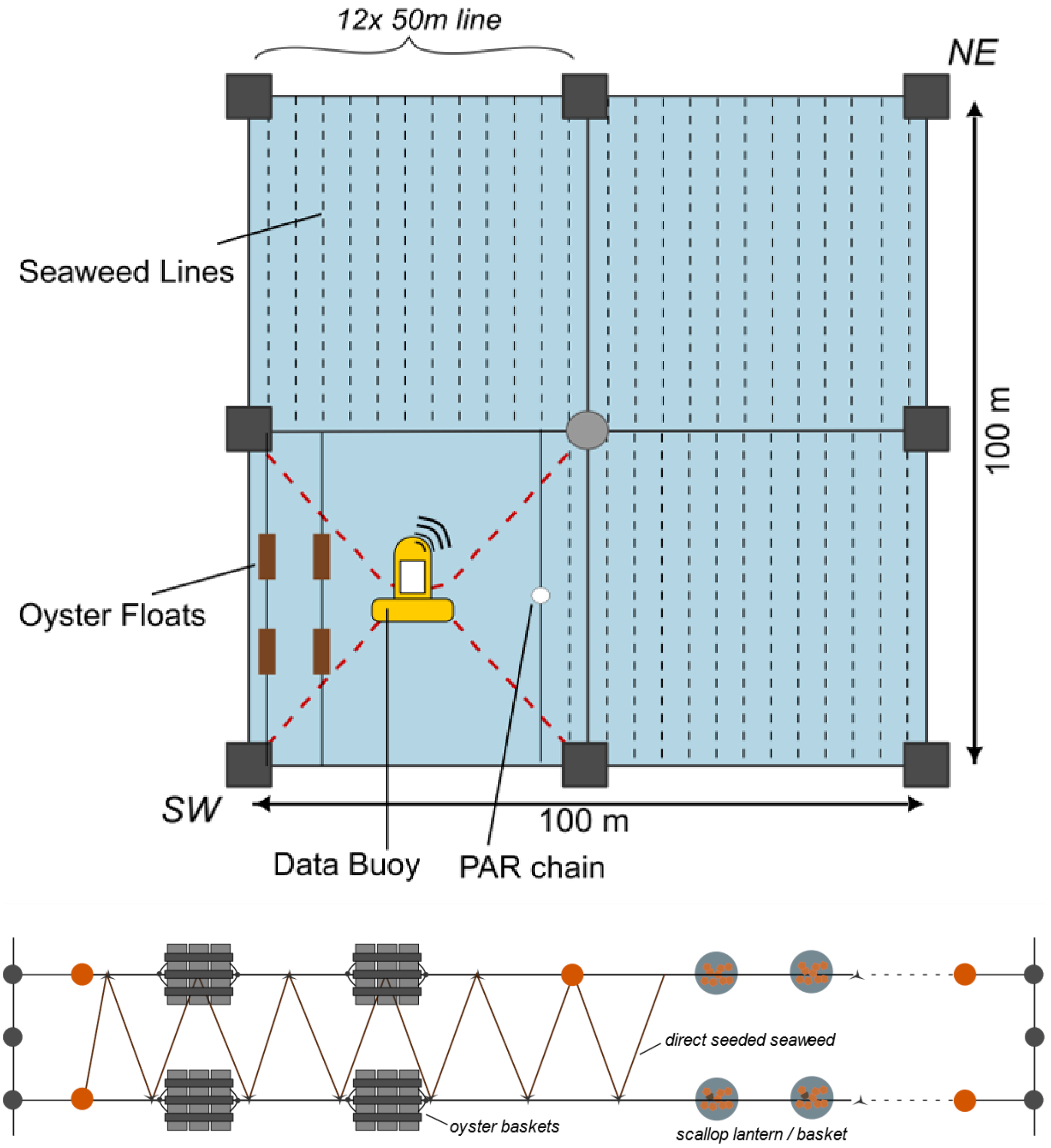


Figure 1 Layout of IMTA system in IMTA lab Scotland.

Top: full site layout, showing seaweed- and shellfish growing lines. Bottom: shellfish cultivation system with floating oyster baskets and hanging nestier trays (for scallop cultivation).

3.1.3 Functional unit

The system's primary function was to yield harvested fresh biomass, allowing for a comparative assessment of environmental impacts between monoculture and the IMTA system. As a result, the study's functional unit was set at 1 kg of harvested fresh weight (FW) biomass. All inputs and outputs were calculated based on the functional unit of 1 kg of seaweed biomass for monoculture (baseline scenario) and 1 kg of biomass of all species from IMTA system.

3.1.4 System Boundaries

The LCA had a cradle-to-farm gate approach encompassing seed transport to site, cultivation at sea until harvesting and transportation from site to shore modelled into one process as cultivation at sea. The study did not include hatchery, preservation, use and disposal stages. Flows and system boundaries of monoculture and IMTA system were established following consultation with the relevant IMTA lab. Two culture models are used in this study, which are seaweed monoculture and the IMTA system consisting of seaweed, king scallops, oysters, and sea urchins.

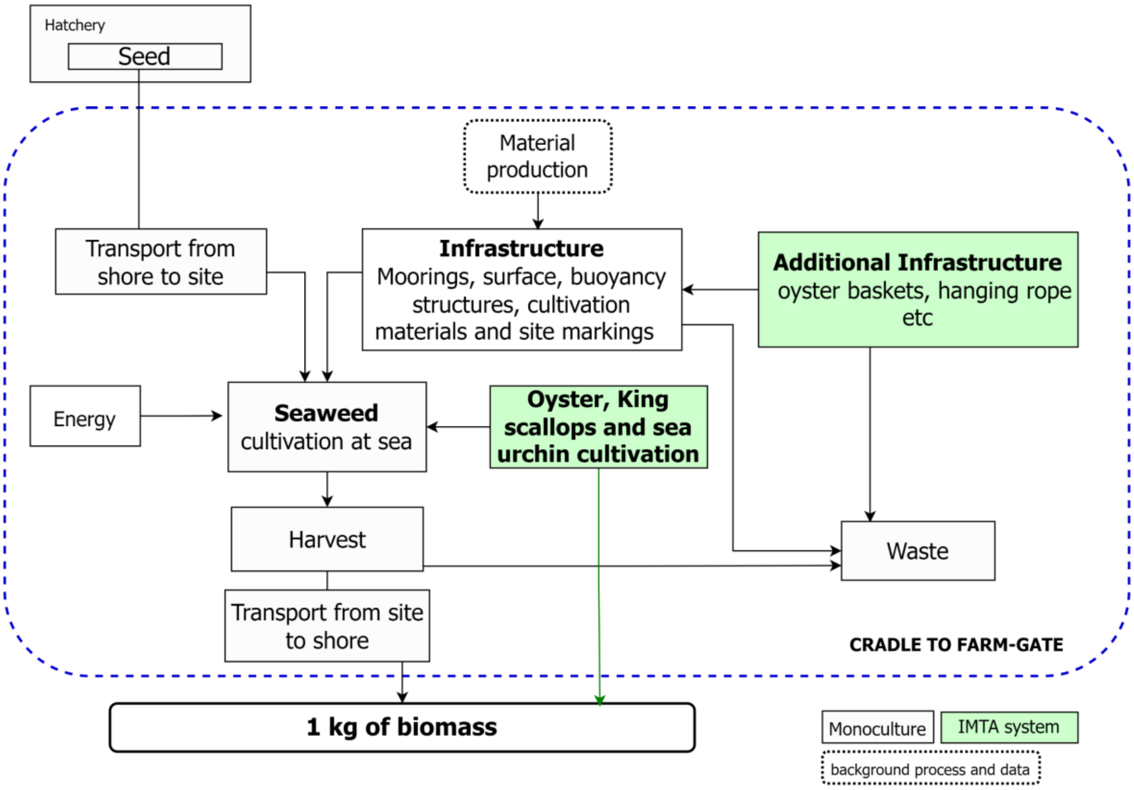


Figure 2 Flow diagram of monoculture and IMTA system at IMTA lab Scotland.

Impacts are calculated per kg of biomass for both the monoculture and the IMTA system. Boxes highlighted in green are process that are added in IMTA system in addition to the monoculture system. Dotted boxes represent background processes for which secondary data were used and solid outline boxes represent the foreground processes for which primary data were collected.

The quantity of seed needed is not included in the system. Transport by boat is included in the assessment during deployment of seed, maintenance, and harvest activities. All infrastructure materials and energy inputs were included to produce the functional unit.

3.1.5 Impact Assessment Choices

The impact assessment method in this study was EF version 3.0 method that includes widely used categories for aquaculture systems. The European Commission developed this method, which is recommended to be used by Product Environmental Footprint Category Rules (PEFCRs). Sixteen impact categories are presented from EF 3.0 methodology as outlined in the Introduction. SimaPro 9.4.0.2 ecoinvent v3.80 (PreConsultants, Amersfoort, The Netherlands) was used for the study.

3.1.6 Data

The data collection for the foreground processes was site specific and was done using an Excel template, workshops with relevant people from IMTA lab Scotland. Data gaps were searched and collected from earlier LCA studies on a similar system (IMPAQT project) and from circularity assessments performed in the same project. Background system data were gathered from databases and from literature. Not all data are detailed or published in the deliverable to protect data for confidentiality or for future publication.

3.1.7 Limitations and Assumptions

Data availability is the key part of Life cycle assessments. Significant amounts of data are needed for an LCA, where absence of reliable data that affect the results and conclusion is common. Due to lack of information and data specifications, many assumptions and simplifications are made. Biomass yield for oyster and king scallops were estimated based on literature (Cook & Kelly, 2007). The production was calculated for one year in a one-hectare farm with maximum biomass yield. The maintenance trips were re-calculated for the necessary trips between research monitoring versus general maintenance and observations.

3.2 Life Cycle Inventory Analysis (LCIA)

Data collected for the monoculture and IMTA system that includes infrastructure, flow diagram (figure 2) and harvesting stage are presented here. Cultivation at sea is the main phase considered in this LCA study that encompasses sea-based infrastructure elements installed, the cultivation of the seeded lines and monitoring, harvesting and transportation of the harvest fresh biomass to shore. Data from this pilot scale research facility is extrapolated to a potential large-scale production system.

IMTA lab Scotland consists of 2 life stages: Cultivation at sea (on-growing stage) and harvest of the biomass. Hatchery stages for spore preparation, seeding for deployment of juvenile seaweed at sea and biomass preservation and storage are not in the scope of this study.

Infrastructure

The site is a one-hectare submerged tensioned grid system holding both permanent and non-permanent infrastructure components. Permanent components include site markings, anchoring systems, grid lines and cushion buoys. Most of these are firmly installed at site and repaired/replaced only when needed and/or when their end of life is reached. Non-permanent components are those required for the on-growing stage of the crops and as such include the deployment structures (e.g. seaweed longlines, shellfish baskets), buoyancy aids (weights and buoys) and ancillary materials. Figure 3 shows a cross-section at the grid corner with anchoring points, submerged grid lines and deployment points for growing structures. In its baseline configuration (=seaweed only) the maximum practiced stocking density is 48x 47m-long seaweed growing lines when spaced four meters apart, and oriented parallel to the shoreline and the predominant current direction. In a commercial IMTA scenario, a shellfish growing line (holding deployment structures such as floating baskets and hanging nestier trays) can be deployed in between the seaweed growing lines. All environmental impacts are calculated to per kg of biomass in fresh weight basis (FU) per year based on life expectancy of the infrastructure.

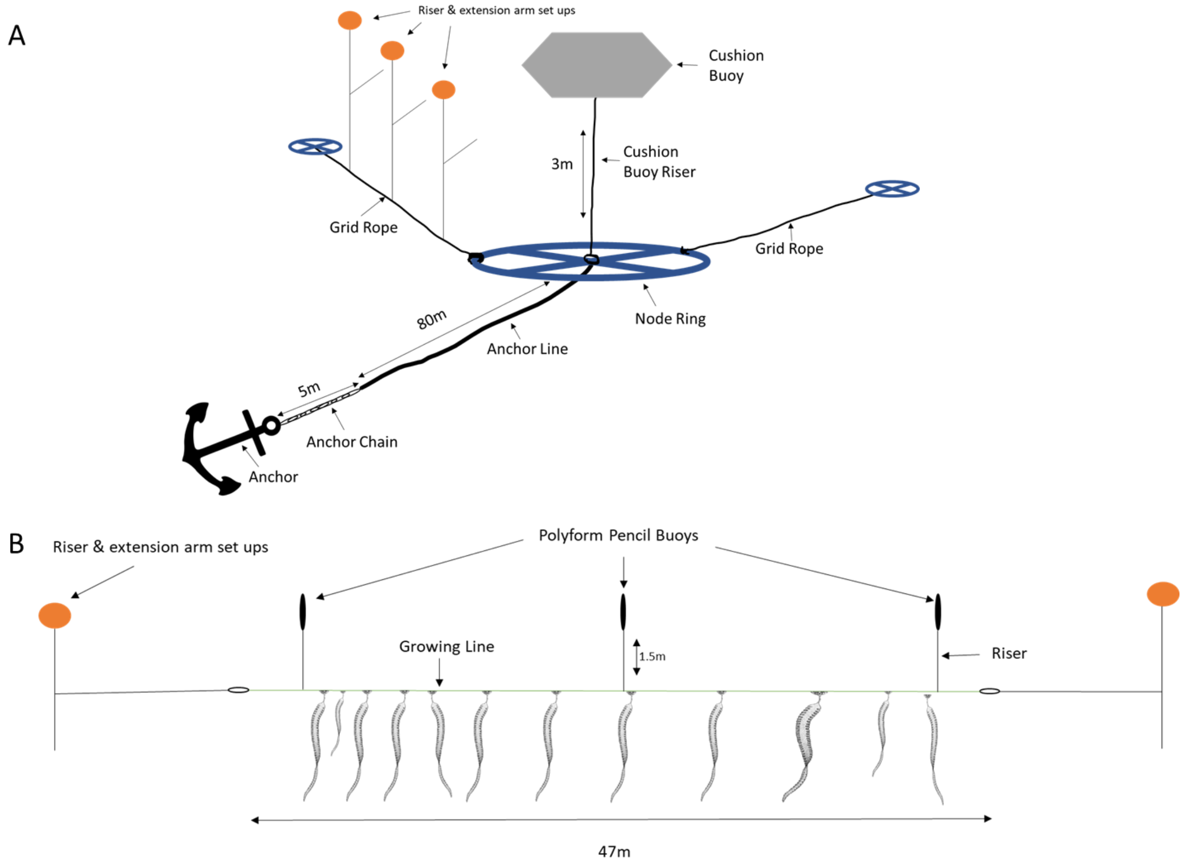


Figure 3 Cultivation infrastructure at IMTA lab Scotland.

A. Tensioned-grid system submerged at 3m water depth with anchoring and buoyancy. B. Typical seaweed growing line maintained at 1.5m water depth by provided pencil buoys and weights.

Deployment of seeded lines

The seeded lines are transported from the shore to the farm site by boat assuming trips starting from SAMS pontoon are approximately 22km return. Based on licence agreement, weekly visual site inspections are conducted accounting for 15 trips using a small boat in addition to 4 trips per annum i.e., cultivation cycle using a large work boat for required maintenance work (e.g. mooring and grid work).

Harvesting

Harvesting is done in a large vessel with the maximum loading capacity of 6 tonnes per trip requiring three days of work and 3 trips to collect 15.8 tonnes of fresh biomass in a monoculture scenario. In a IMTA scenario, added species would be harvested throughout the season whenever harvest size is reached, and thus only one additional trip with a small vessel was added here. Using previous monitoring data, a conservative average of 7 kg/m of fresh biomass was estimated for the seaweed harvest. The loss of biomass on the cultivation line are accounted as trim solid waste in the study.

3.3 Environmental impacts of IMTA lab – Scotland

This section presents the environmental impacts results, first for the total impacts for IMTA, second on the distribution of impacts in IMTA and then comparison of total environmental impacts between monoculture and IMTA system.

Biomass yield:

Seaweed production depends on the inorganic carbon, nitrogen, phosphorus and light. Most limiting nutrients for seaweed growth in seawater are nitrogen and phosphorus depending on the seasonal variation and geographic location. Bioremediation categories refers to the uptake of nutrients from the water until harvest in the IMTA system and carbon that is fixed by photosynthesis is the captured carbon. The uptake and removal of N and P during seaweed harvest are referred as Eutrophication Mitigation potential of seaweeds. Seaweed biomass production was estimated as 7kg/m of longline in fresh weight, 1.1 tons/year per hectare of oysters and approx. 1.6 tons/year per hectare of king scallops. Dissolved inorganic carbon and phosphorus values were calculated from Nederlof et al., 2021 (Nederlof, Verdegem, Smaal, & Jansen, 2022).

Total impacts in IMTA system Scotland

Total environmental impacts were calculated for monoculture and IMTA system for Scotland IMTA lab. Table 2 presents the values of environmental impacts of seaweed cultivation in IMTA system. Figure 4 shows the contribution of cultivation at sea phase, harvesting and infrastructure to the overall impacts. Infrastructure dominates the majority of the impacts except Eutrophication in freshwater and marine category. Cultivation process reduces the eutrophication category impacts due to nutrient uptake (N and P) by the seaweed, oysters, and king scallops in both the Eutrophication freshwater and marine categories. Harvesting show 15% impact on acidification and 18% in eutrophication- terrestrial category.

Table 2 **Environmental impacts of seaweed cultivation in IMTA system**

Impact categories	Unit	Total	Infrastructure	Cultivation	Harvesting
Climate change	kg CO_2 eq	2.86E-01	2.99E-01	-3.76E-02	2.45E-02
Ozone depletion	kg CFC11 eq	3.33E-08	3.03E-08	0.00E+00	3.08E-09
Ionising radiation	kBq U-235 eq	1.28E-02	1.19E-02	0.00E+00	8.46E-04
Photochemical ozone formation	kg NMVOC eq	2.35E-03	2.01E-03	0.00E+00	3.38E-04
Particulate matter	disease inc.	3.16E-08	2.77E-08	0.00E+00	3.91E-09
Human toxicity, non-cancer	CTUh	5.05E-09	4.95E-09	0.00E+00	9.44E-11
Human toxicity, cancer	CTUh	1.59E-09	1.58E-09	0.00E+00	7.76E-12

Acidification	mol H+ eq	3.53E-03	2.98E-03	0.00E+00	5.50E-04
Eutrophication, freshwater	kg P eq	-6.64E-04	9.48E-06	-6.74E-04	6.42E-08
Eutrophication, marine	kg N eq	-1.10E-03	6.52E-04	-1.87E-03	1.20E-04
Eutrophication, terrestrial	mol N eq	8.68E-03	7.07E-03	0.00E+00	1.61E-03
Ecotoxicity, freshwater	CTUe	7.32E+00	7.00E+00	0.00E+00	3.13E-01
Land use	Pt	1.21E+00	1.18E+00	0.00E+00	3.53E-02
Water use	m^3 depriv.	1.11E-01	1.11E-01	0.00E+00	-4.51E-04
Resource use, fossils	MJ	5.06E+00	4.87E+00	0.00E+00	1.94E-01
Resource use, minerals/metals	kg Sb eq	3.97E-06	3.97E-06	0.00E+00	3.54E-09

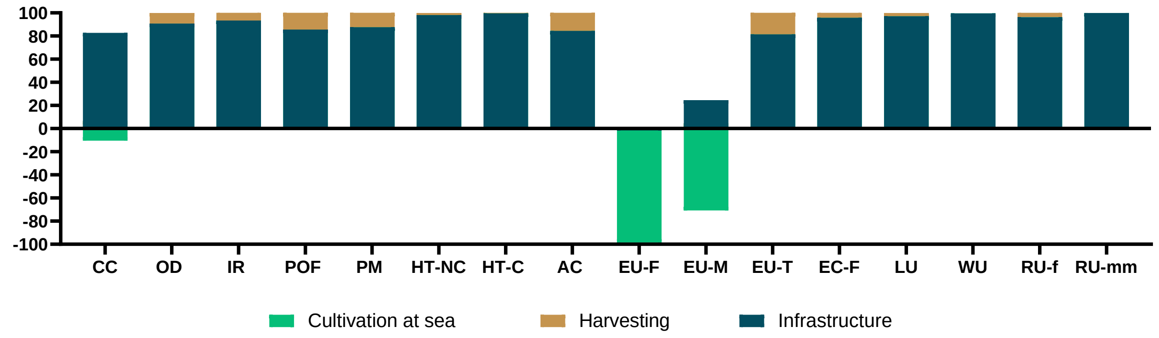


Figure 4 Total impacts per kg of biomass (FW) in IMTA system.

Climate change (CC), Ozone depletion (OD), Ionising radiation (IR), (POF), (PM), (HT-C), Human toxicity -non-cancer (HT-NC), Human toxicity - cancer (HT-C), Acidification (AC), Eutrophication-freshwater (EU-F), Eutrophication-marine (EU-M), Eutrophication-Terrestrial (EU-T), Land use (LU), Water use (WU), Resource use-fossils (RU-f) and Resource use- minerals and metals (RU-mm).

Infrastructure

Figure 5 shows the stack diagram of relative contribution of each infrastructural component for nine of the impact categories related to climate change, acidification, and eutrophication. Transport (seeding and maintenance) of the infrastructure show high environmental impacts in majority of the impact categories except Eutrophication in freshwater and water use categories. This is followed by moorings, chains used in anchors, node rings that are made of galvanised steel that may be due to the emissions of chromium and arsenic during steel production.

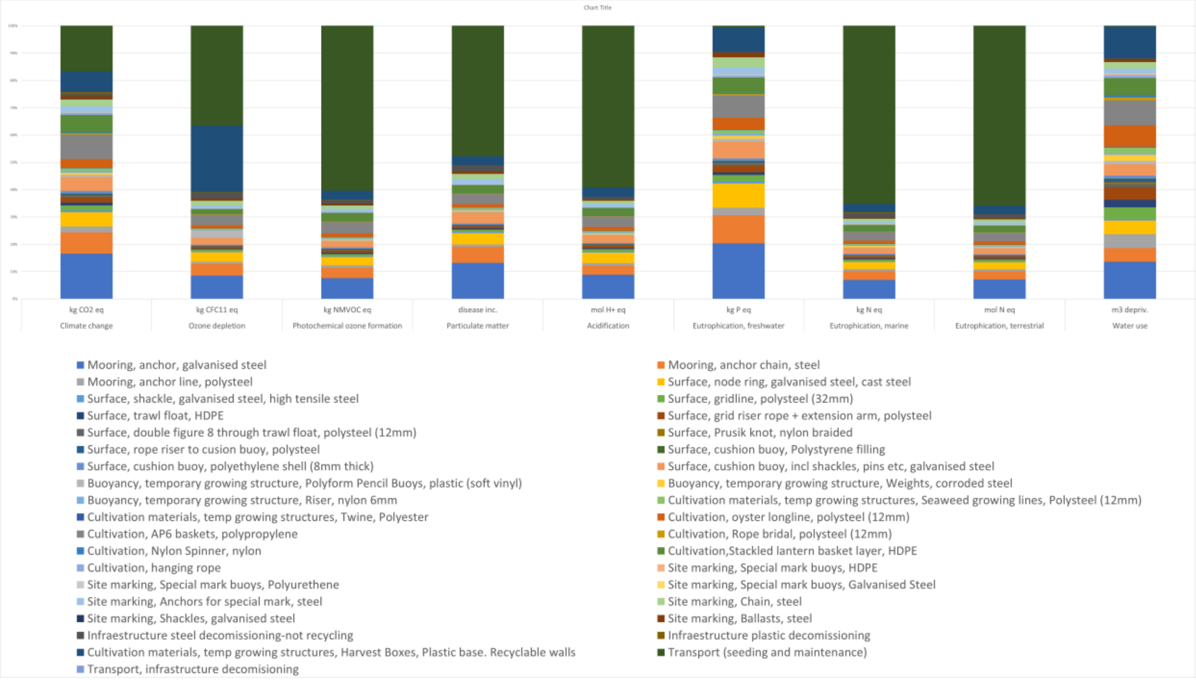


Figure 5 Impacts per kg of fresh weight biomass for the cultivation infrastructure components in IMTA system.

Cultivation material for king scallops for harvesting contribute to an extent in all impact categories, but are notable in ozone depletion (24.4%), climate change (7.56%) and eutrophication (14%) categories. Other infrastructure materials such as buoys, PVC components and gridlines have small contributions overall. Comparing the infrastructure elements performance to monoculture, we observe a higher environmental impact in IMTA system in climate change, ionising radiation, eutrophication-freshwater, ecotoxicity, water use and resource use categories (Figure 6). This is due to the additional infrastructure elements that are added for the additional species. This can be optimised by increasing the biomass yield in IMTA system and finding lower-impact alternatives to infrastructure elements. We must note that the site studied is a research pilot site that may be over-engineered for survivability.

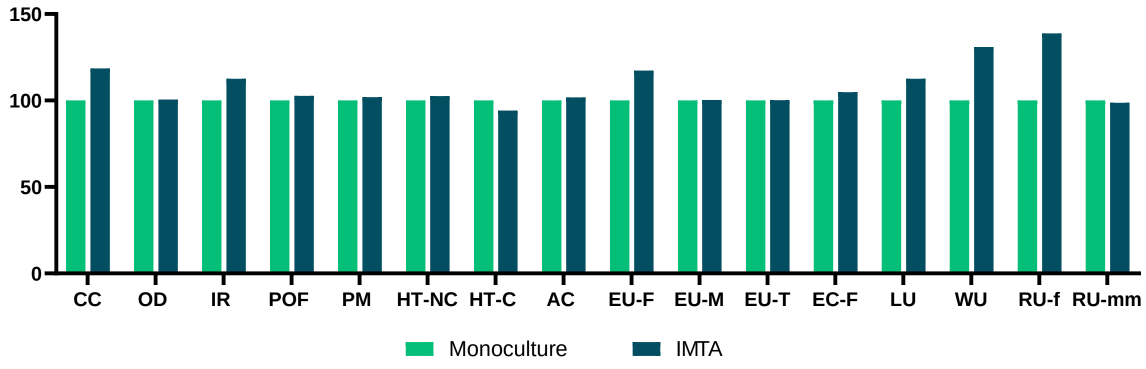


Figure 6 Comparison of environmental impacts of infrastructure per kg of fresh biomass between monoculture and IMTA system.

Climate change (CC), Ozone depletion (OD), Ionising radiation (IR), (POF), (PM), (HT-C), Human toxicity -non-cancer (HT-NC), Human toxicity - cancer (HT-C), Acidification (AC), Eutrophication-freshwater (EU-F), Eutrophication-marine (EU-M), Eutrophication-Terrestrial (EU-T), Land use (LU), Water use (WU), Resource use-fossils (RU-f) and Resource use- minerals and metals (RU-mm).

Harvesting

The harvesting phase, in contrast to the infrastructure, shows lower environmental impacts in all impact categories for IMTA compared to monoculture (Figure 7). The impacts from the harvesting activity are mainly due to the transport from cultivation site to shore and the additional trips for the IMTA species. This phase needs to be optimised and may improve on real data availability in a commercial site compared to data extrapolated from a pilot site.

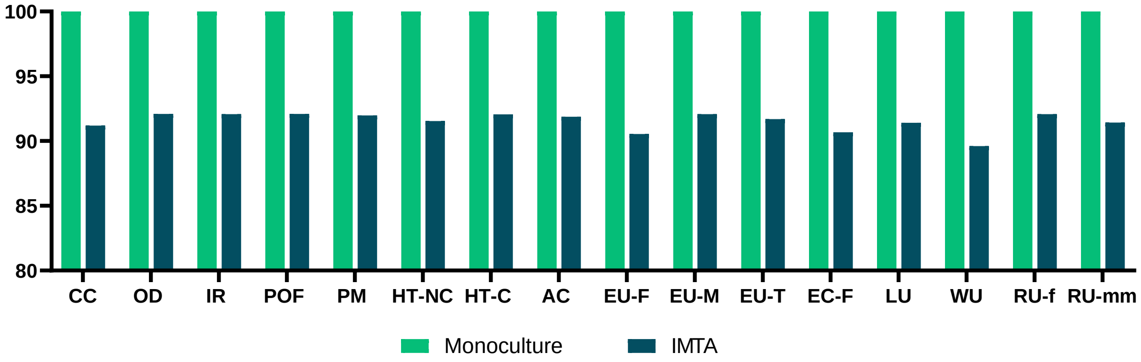


Figure 7 Comparison of environmental impacts at harvesting phase per kg of fresh biomass between monoculture and IMTA system.

Climate change (CC), Ozone depletion (OD), Ionising radiation (IR), (POF), (PM), (HT-C), Human toxicity -non-cancer (HT-NC), Human toxicity - cancer (HT-C), Acidification (AC), Eutrophication-freshwater (EU-F), Eutrophication-marine (EU-M), Eutrophication-Terrestrial (EU-T), Land use (LU), Water use (WU), Resource use-fossils (RU-f) and Resource use- minerals and metals (RU-mm).

Based on the preliminary assessments we can identify using this study to improve the hotspots identified to improve the environmental impacts in the IMTA system.

3.4 Conclusion

IMTA presents the potential to improve the recycling of organic matter and nutrients. This is due to the capacity of algae in an IMTA system to reutilise waste products (nitrogen and phosphorus) from the cultured species. Moreover, the algal biomass can serve as a sustainable, nutrient-rich feed for other cultivated species (Chopin et al., 2001). Nutrient removal potential of seaweeds in open water IMTA systems show higher growth rate, higher N content, similar or even lower based on retention studies. Key aspect of the bioremediation potential of IMTA is the balance between nutrient input and removal. Using tracer methods to distinguish the nutrients taken up from environment and those of fish origin show that seaweeds cultivated in open water IMTA take up N derived from fish feed (Wang et al., 2014). Phosphorus uptake by the seaweeds out-weighs the emissions largely contributing to mitigating eutrophication at the same time providing biomass for other sectors such as aquafeed that make it perform better on the aquatic environment.

Infrastructure elements play a major role in the environmental performance in both monoculture and IMTA system. Here we have corrected for the life expectancy of the infrastructure elements. However, they are highly depending on the exposure and conditions at the site. Selection of materials can a major role such as using an alternative for stainless steel that can degrade faster. If the life expectancy can be improved it could result in less replacements, better maintenance, and lower impacts.

Biomass yield is one of the most influential parameters to improve the environmental impacts in an IMTA system. By increasing the yield, we can reduce the overall impacts per kg of biomass produced in the system. Here we have estimated a yield of 7kg/m of cultivation line compared to the literature where up to 10kg/m of cultivation line is achievable (Oirschot et al., 2017; Seghetta et al., 2017; Thomas et al., 2021; Thomas et al., 2020). The varying seasonal conditions, light regime, sea water temperature, flow rate, disease, storms, technical protocol variations due to research site may provide an uncertainty in a constant yield. We suggest that measures to improve the yield of biomass for seaweed, oyster and king scallops will improve the environmental impact in IMTA system. Recent study in environmental impacts of seaweed protein production for food and feed application, recommends two possible scenarios to produce seaweed protein with better environmental impact than soy protein. The yield was 290- and 170-ton WW per hectare with a protein content of 19.2 and 24.3% of DW when deployed at a depth of 3m and 8m respectively and harvested in August. Both scenarios have a lower GWP and energy demand for seaweed protein in a Norwegian case (Koesling, Kvadsheim, Halfdanarson, Emblemsvåg, & Rebours, 2021). This will be a basis for developing a more environmental protein production from seaweed in a IMTA system in the future.

4 Environmental Assessment of IMTA lab – Ireland (MI)

Growing demand for (fed) aquaculture has motivated the development of IMTA with sustainable technologies and approaches. Cultivation of fed species is associated to the cultivation of extractive species for waste nutrient recycling. This will result in less nutrient release to environment together with biomass production. IMTA lab Ireland is an open system where the nutrient released by the fish are used by other lower trophic species (filter and deposit feeders). Atlantic salmon (*Salmo salar*) production releases approximately 24% phosphorus (as DIP, dissolved inorganic phosphorus) and 39% of the total nitrogen content from the feed (as DIN, dissolved inorganic nitrogen) where NH4+ is excreted due to metabolic activity (Nederlof et al., 2022; Wang et al., 2014). These dissolved nutrients released in the surroundings of the sea pens are diluted in the water due to strong currents. Filter feeders such as mussels and oysters can remove up to 75% of the DIN (Petersen, Holmer, Termansen, & Hasler, 2019). Several studies have reported 70% removal of DIP and 4.4kg of DIP removal per kg of culturing seaweed species (*Saccharina latissima* and *Alaria esculenta*) in proximity of finfish production site (Mao, Yang, Zhou, Ye, & Fang, 2009; Reid et al., 2013).

Bohnes et al., performed a meta-analysis of 65 LCA studies of aquaculture systems focusing on climate change and eutrophication impact categories. LCA has been used to identify the environmental hotspots or components of systems and thereby compare monoculture and IMTA, intensive vs extensive systems (F. Bohnes & Laurent, 2018; F. A. Bohnes, Hauschild, Schlundt, & Laurent, 2019). Here, we focus on the environmental impacts and benefits of moving from salmon monoculture to an open-water IMTA system and the effect of adding new species in the system.

4.1 Goal and Scope

4.1.1 Goal and Scope Definition

The main goal of this LCA study for IMTA lab Ireland was to compare environmental performances of Atlantic salmon (*S. salar*) monoculture to an open-water IMTA system where seaweeds, urchin and oysters are co-cultured.

4.1.2 Site and Process Description

Lehanagh Pool Research site is a coastal aquaculture site located 0.25 km from the shore in Bertraghboy Bay, on the West coast of Ireland. This is a fully experimental, non-commercial cultivation site operated by the Marine Institute. Infrastructure on site consists of a traditional 6 x 50m circumference pen grid for fish culture that corresponds to a quarter of a commercial pen. To the southeast of the pen grid, there is an attached Low Trophic Grid (LTG) consisting of a submerged rectangular grid with capacity for ca.780m suspended longlines. Species were chosen based on market demand, or where an interest in culturing has been expressed to validate future potential production. Figure 8 shows the IMTA lab Ireland site layout. The species are categorized as: fed and extractive species. Fed Fish species: Atlantic salmon is the species in this system that is fed. This excretes faeces and metabolites that can be utilised by the extractive species as nutrients and for energy. Salmon can retain 38% nitrogen, 30% phosphorus and 30% carbon from feed (Wang et al., 2014). Extractive species: Seaweed species (*A. esculenta* and *S. latissima*) absorb dissolved minerals and carbon (DIN, DIP and DIC), native oyster (*Ostrea edulis*) that consumes particulate organic matter (POM) suspended in the water column and sea urchin (*Paracenrotus lividus*) that are fed with the seaweeds form the site.

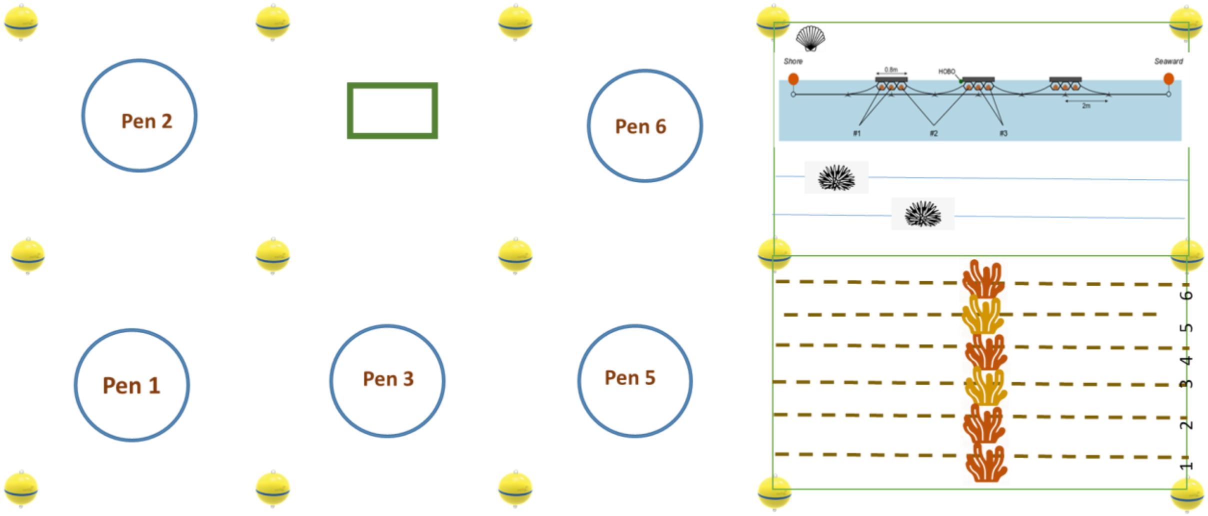


Figure 8 Site layout of IMTA lab Ireland.

4.1.3 Functional Unit

The system's primary function was to yield harvested fresh biomass, allowing for a comparative assessment of environmental impacts between monoculture and the IMTA system. As a result, the study's functional unit was set at 1 kg of harvested fresh weight (FW) biomass. All inputs and outputs were calculated based on the functional unit of 1 kg of biomass.

4.1.4 System Boundaries

The LCA had a cradle-to-farm gate approach encompassing seed transport to site, cultivation at sea until harvesting and transportation from site to shore modelled into one process as cultivation at sea. Chemical production, energy production, feed production and transport to the site, equipment and infrastructure production are included. The study did not include hatchery, post-harvest processing, use and disposal stages. Flows and system boundaries of monoculture and IMTA system were established following consultation with the relevant IMTA lab. Two culture models are used in this study, which are salmon monoculture and the IMTA system consisting of salmon, seaweeds, native oyster, and sea urchin. Figure 9 shows the processes within the boundaries of monoculture and IMTA system. The green highlighted boxes in the figure represent the additional processes for IMTA system compared to the monoculture.

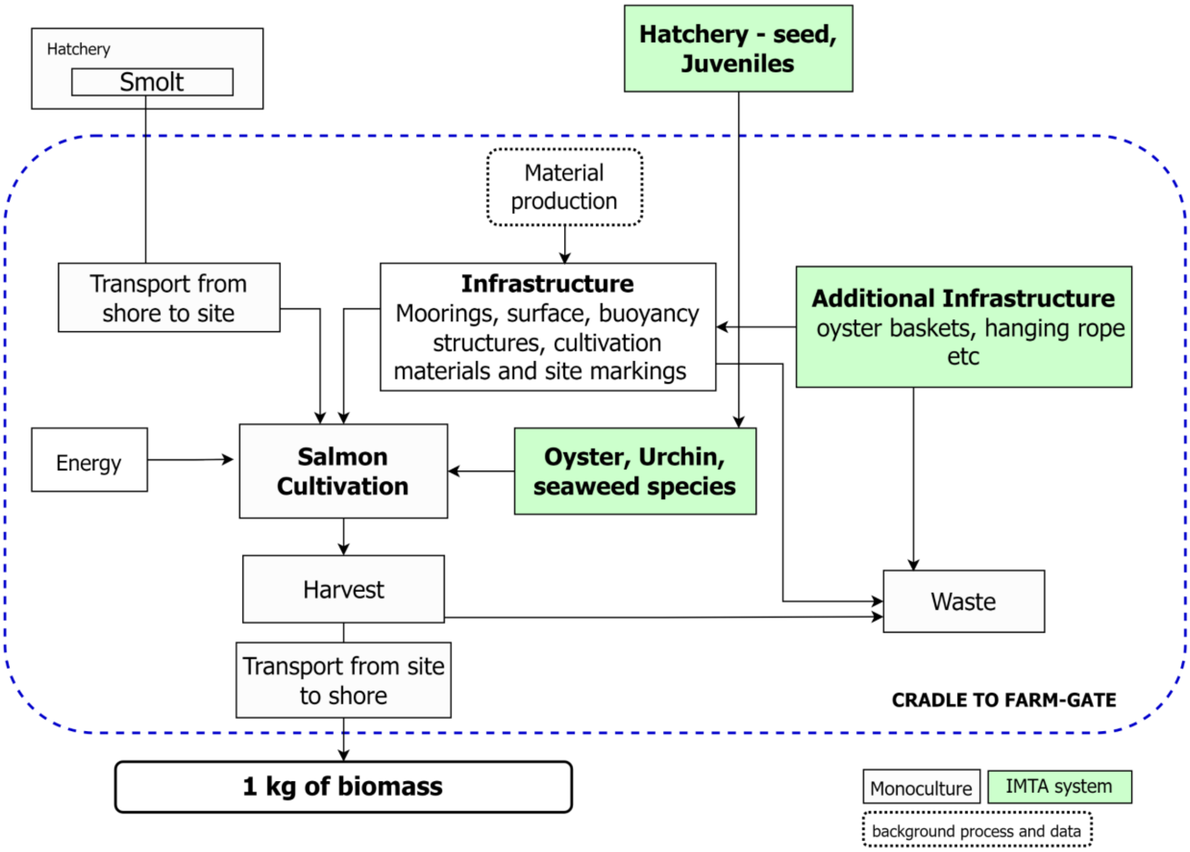


Figure 9 Flow diagram of monoculture and IMTA system at IMTA lab Ireland.

Boxes highlighted in green are process that are added in IMTA system in addition to the monoculture system. Dotted boxes represent background processes for which secondary data were used and solid outline boxes represent the foreground processes for which primary data were collected.

4.1.5 Impact Assessment Choices

The impact assessment method used in this study was EF version 3.0 method that includes widely used categories for aquaculture systems. European Commission developed this method and is the one that is recommended to be used by Product Environmental Footprint Category Rules (PEFCRs). Sixteen impact categories are presented from EF 3.0 methodology as outlined in the introduction section.

4.1.6 Data

The data collection for the foreground processes was site specific and was done using a excel template, workshops with relevant people from IMTA lab Ireland. Data gaps were searched and collected from earlier LCA studies on a similar system (such as IMPAQT project) and from circularity assessments performed in the same project. Background system data were gathered from databases and from relevant literature. Not all data are detailed or published in the deliverable as to protect data for confidentiality or for future publication.

4.1.7 Limitations and Assumptions

Life cycle inventories (LCI) data for salmon monoculture were obtained from the data provided from previous studies and literature (Wang et al., 2020). Due to lack of information and data specifications, many assumptions and simplifications are made. Data on site infrastructure and equipment, energy consumption were obtained from the IMTA lab where the fuel and electricity were estimated. Annual production data were obtained from literature for that farm size and data on seaweed production were assumed from the IMTA lab Scotland. Biomass yield for salmon was assumed to be the same for the monoculture and IMTA systems and based on the number of cycles for a production period of 3 years. Emissions for this IMTA lab were calculated from the Product Environment Footprint Category Rule (PEFCR) Marine model (https://www.marinefishpefcr.eu/supporting-studies). Biomass yield for oyster and urchin were estimated based on literature (Cook & Kelly, 2007). The maintenance trips were re-calculated for the necessary trips between research monitoring versus general maintenance and observations.

4.2 Life Cycle Inventory Analysis

The LCI of both the system monoculture and IMTA were developed, and their processes were modelled using SimaPro 9.4.0.2 software and its databases (Pre Consultants, Amersfort, Netherlands). Ecoinvent databases v3.80 was used for all background data. The LCA results for the baseline scenario and IMTA and comparison between baseline monoculture and IMTA systems will be presented here: the reference flow, flow diagram (figure 4.2), and interpretation of the LCI. Due to data confidentiality, the amount, and exact details of the different parts in the process will not be provided.

Description of the monoculture and IMTA system:

The salmon monoculture system is an open system, where smolts were transferred to the grow-out farm with an average mass of 80-100 grams in the cultivation phase. In the IMTA system, we considered a production cycle of 3 years that consists of 2 cycles of salmon, 4 cycles of seaweeds *(A. esculenta and S. latissima*), 1 cycle of oysters and 2 cycles of urchins. We assumed 70g of wet weight of oysters and 80 g for urchin based on (Cook & Kelly, 2007) and data obtained from the IMTA lab. The seaweeds were grown on 300m longline and were 7kg/m based on comparative data with Scotland. The feed conversion ratio (FCR), the quantity of feed (kg dw) needed per kg of animal weight gain (kg WW), was estimated as 1.2 in both systems.

Infrastructure and Transport:

Figure 4.1 shows the layout of the site for which the infrastructure data was collected. Infrastructure elements in the monoculture system and additional infrastructure required for the integration of additional species in the IMTA system were collected. Petrol was the main source of energy for the boat trips for transporting smolt, juveniles of urchin, oyster, and seaweed seed strings to cultivation site from shore, during maintenance and for harvesting of the biomass.

4.3 Environmental impacts of IMTA lab – Ireland

This section presents the environmental impacts results, first for the total impacts for IMTA, second on the distribution of impacts in IMTA and then comparison of total environmental impacts between monoculture and IMTA system.

Total impacts in IMTA system Ireland:

Contribution analysis shows infrastructure in the IMTA system as the main contributor to most of the impact categories of both monoculture and IMTA system. Figure 10 shows the contribution analysis in IMTA system for cultivation at sea, harvesting and infrastructure and Table 3 provides the values for each stage studied for the impact categories.

Table 3 Environmental impacts of seaweed cultivation in IMTA system

Impact category	Unit	Total	Infrastructure	Cultivation	Harvesting
Climate change	kg CO_2 eq	1.02E+00	1.03E+00	-3.17E-02	1.49E-02
Ozone depletion	kg CFC11 eq	5.01E-08	3.11E-08	1.81E-08	9.10E-10
Ionising radiation	kBq U-235 eq	2.78E-02	2.26E-02	4.88E-03	2.58E-04
Photochemical ozone formation	kg NMVOC eq	5.16E-03	3.08E-03	1.98E-03	9.91E-05
Particulate matter	disease inc.	8.75E-08	6.45E-08	2.16E-08	1.30E-09
Human toxicity, non-cancer	CTUh	1.64E-08	1.60E-08	4.08E-10	6.91E-11
Human toxicity, cancer	CTUh	5.75E-09	5.70E-09	4.46E-11	2.93E-12
Acidification	mol H+ eq	7.80E-03	4.72E-03	2.88E-03	2.02E-04
Eutrophication, freshwater	kg P eq	3.75E-05	3.74E-05	9.58E-08	6.00E-08
Eutrophication, marine	kg N eq	4.53E-02	1.11E-03	4.42E-02	3.67E-05
Eutrophication, terrestrial	mol N eq	1.75E-02	9.19E-03	7.63E-03	6.94E-04
Ecotoxicity, freshwater	CTUe	2.09E+01	2.01E+01	5.90E-01	2.56E-01
Land use	Pt	3.17E+00	3.01E+00	1.38E-01	1.98E-02
Water use	m^3 depriv.	6.51E-01	6.51E-01	5.45E-04	-4.44E-04
Resource use, fossils	MJ	1.65E+01	1.53E+01	1.12E+00	5.97E-02
Resource use, minerals&metals	kg Sb eq	8.81E-06	8.79E-06	1.41E-08	2.58E-09

For all impact categories except eutrophication-marine category, infrastructure plays a major role similar to the results observed in monoculture (data not shown). Harvesting phase that includes the transport of the biomass has a marginal impact in eutrophication terrestrial category due to fossil energy extraction for boat fuel. Cultivation at sea has a significant contribution in eutrophication - marine category followed by EU-terrestrial, acidification, particulate and ozone depletion.

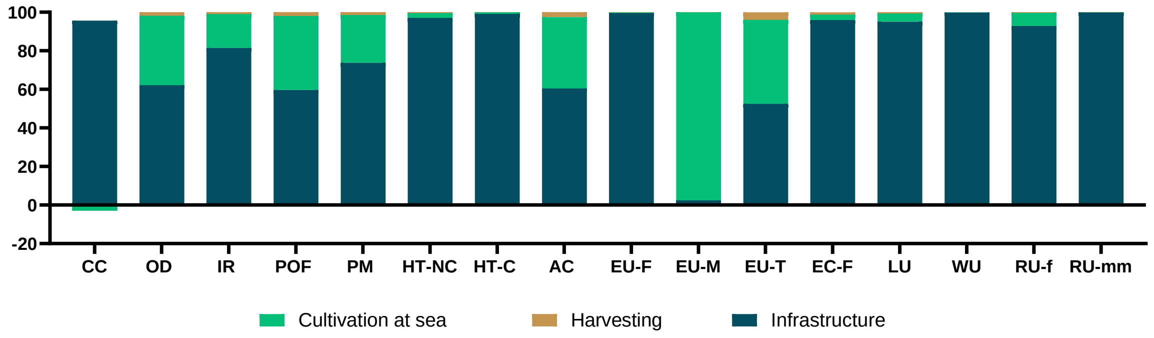


Figure 10 Total impacts per kg of biomass (FW) in IMTA system, Ireland.

Climate change (CC), Ozone depletion (OD), Ionising radiation (IR), photochemical ozone formation (POF), Particulate matter (PM), Human toxicity -non-cancer (HT-NC), Human toxicity - cancer (HT-C), Acidification (AC), Eutrophication-freshwater (EU-F), Eutrophication-marine (EU-M), Eutrophication-Terrestrial (EU-T), Land use (LU), Water use (WU), Resource use- fossils (RU-f) and Resource use- minerals and metals (RU-mm).

Infrastructure:

Figure 11 shows the stack diagram of relative contribution of each infrastructural component for nine out of the sixteen impact categories in the EF method, related to climate change, acidification, and eutrophication. A significant contribution of cages made of polypropylene pipes like monoculture condition as observed in the increase in environmental impact in IMTA system for particulate matter category. The difference in infrastructure between the two systems was mainly seen in seeding lines and baskets that were added in the IMTA system. Otherwise, infrastructure elements made from galvanised steel (many of the shackles and anchors) need attention in both systems.

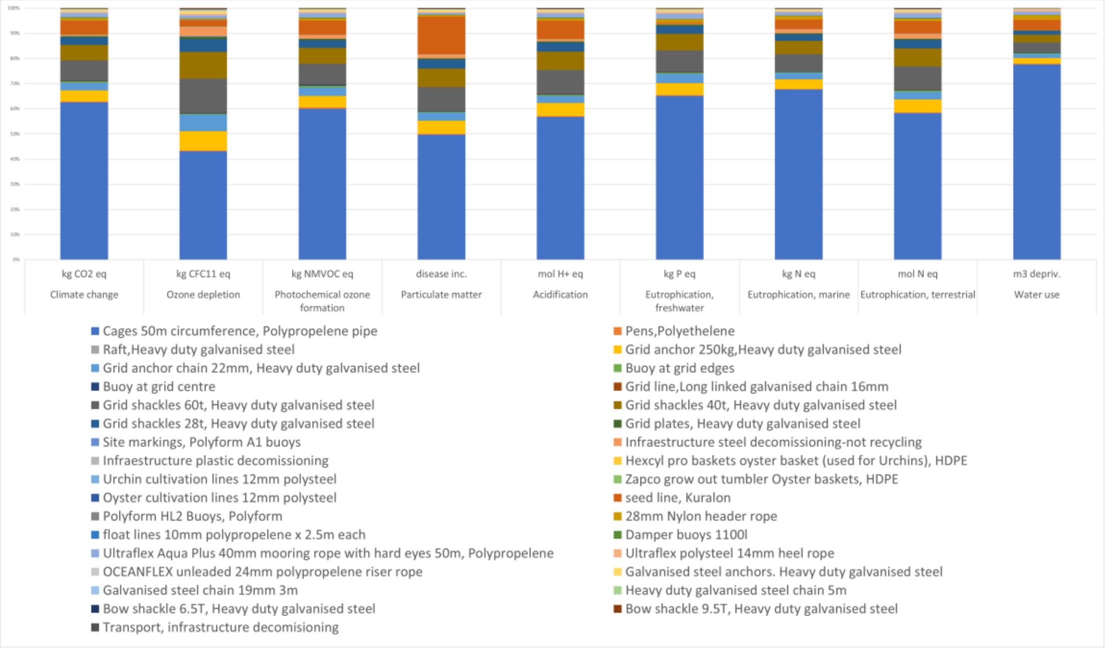


Figure 11 Impacts per kg of fresh weight biomass for the cultivation infrastructure components in IMTA system.

Comparison of total impacts between monoculture and IMTA system:

Comparison was made for the functional unit per kg of biomass in fresh weight produced in both monoculture and IMTA system (Figure 12). Our focus on Climate change and Eutrophication- marine categories shows that IMTA performs 6.56% and 27.48% better than the monoculture system. We can observe the nutrient recycling effect of introducing seaweed, urchin, and oyster in the surrounding of a salmon grow-out farm based on the eutrophication marine category and a slight decrease in climate change category.

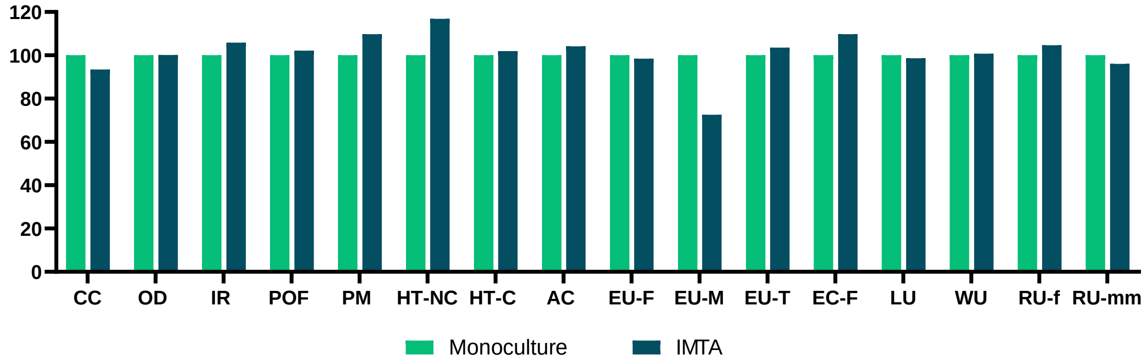


Figure 12 Total environmental impacts per kg of fresh weight biomass for IMTA system compared to monoculture.

Climate change (CC), Ozone depletion (OD), Ionising radiation (IR), photochemical ozone formation (POF), Particulate matter (PM), Human toxicity -non-cancer (HT-NC), Human toxicity - cancer (HT-C), Acidification (AC), Eutrophication-freshwater (EU-F), Eutrophication-marine (EU-M), Eutrophication-Terrestrial (EU-T), Land use (LU), Water use (WU), Resource use- fossils (RU-f) and Resource use- minerals and metals (RU-mm).

When comparing the harvesting phase, IMTA had major impact on all categories. Harvesting phase considers transport for harvesting, deadfish treatment (incineration). Impacts are higher for IMTA conditions due to the treatment of the biofouling generation related to the algae production. However, cultivation stage clearly shows reduction in both Climate Change and Eutrophication-marine category for IMTA system compared to monoculture (Figure 13).

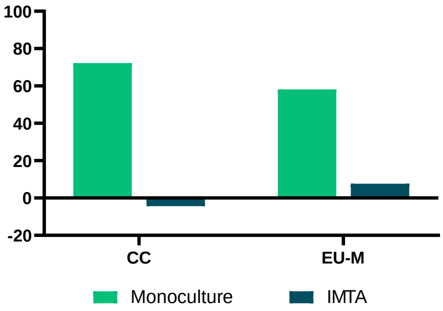


Figure 13 Total environmental impacts per kg of fresh weight biomass for IMTA system compared to monoculture harvesting stage.

Climate change (CC) and Eutrophication-marine (EU-M).

4.4 Conclusion

We assess the environmental performances of salmon monoculture and seaweed, urchin, oyster – salmon IMTA system. The assessment presents possibilities to improve environmental performances of IMTA systems while benefiting from the multiple product generation, nutrient recycling, and better waste management.

Bioremediation performance of IMTA species needs assessment based on the net solid uptake rate and efficiency by these low trophic species. Determination of biomass culture ratio as mentioned by Reid et al., 2018 will maximise the waste and nutrient extraction efficiency from the fed species, salmon at a commercial scale (Reid et al., 2013). This is reflected in the results where harvesting has very high impacts in all major impact categories. The low productivity of low trophic species is due to unbalanced scales of fed species. The additional 4t biomass produced in IMTA system compared to 100t of fed species production in monoculture, cannot improve the environmental performance of IMTA system as shown in literature (Beltran, Guinée, Schenck, & Huizen, 2014; F. Bohnes & Laurent, 2018; Chary et al., 2020). IMTA will stand out as a better aquaculture system considering the reduction in overall feed needed per unit of biomass production, and waste extraction from fed species by low trophic species that reduces eutrophication potential leading to bioremediation.

Increasing the production of the low trophic species can be considered to improve the environmental performance with caution due to scaling effects that can increase energy demand. Improving the rearing system infrastructure for the low trophic species can increase the culture surface area and ultimately the area for bioremediation.

5 Environmental Assessment of IMTA lab – South Africa

Sea urchins have high commercial interest due to the high market value of their gonads that are consumed worldwide as a seafood delicacy. For sustainable development of sea urchin aquaculture (echinoculture), feed and/or feeding regimes that promotes somatic and gonadal growth, and produce gonads with the desired colouration, texture, firmness, and taste are needed. Using wild seaweeds as urchin feed can have negative environmental impacts, and there is limited availability due to seasonal and geographical variations, and low protein content in wild seaweeds (Cook & Kelly, 2007). Currently formulated feeds are used that promote growth and gonad productivity (M.D. Cyrus, Bolton, Scholtz, & Macey, 2015). Some of these feeds contain significant amounts of dried seaweed. Large scale commercial production of urchins cannot be economically and technically feasible using only wild seaweeds as feed. Farming seaweeds in IMTA systems with sea urchins would be a move towards a more sustainable practice where the excretions from one organism are utilised by the other cultured organism from a different trophic level.

The tropical and sub-tropical sea urchin *Tripneustes gratilla* is a commercially valuable species for its rapid growth rate of 9-12 months to marketable size and high market value (Dworjanyn, 2012; Shpigel, Shauli, Odintsov, Ashkenazi, & Ben-Ezra, 2018). Recent studies have been performed to study the effect of fresh seaweed and formulated diet supplemented with dried seaweed on the growth and gonad quality of *T. gratilla* (Mark D Cyrus, Bolton, De Wet, & Macey, 2013; Mark D. Cyrus, Bolton, & Macey, 2015; Onomu, Vine, Cyrus, Macey, & Bolton, 2020; Shpigel et al., 2018). Shpigel et al. (2018) reported the use of IMTA-produced seaweed as a good biofilter and sea urchin feed for better somatic and gonadal growth (Shpigel et al., 2018). Similarly, gonad enhancement studies showed that the use of fresh and formulated diet supplemented with seaweed can enhance gonad growth and produce gonads that are commercially acceptable under farm conditions in South Africa (Mark D Cyrus et al., 2013; Mark D. Cyrus et al., 2015; M.D. Cyrus et al., 2015; Onomu et al., 2020)

In ASTRAL, IMTA lab South Africa aimed to optimise culture technology to produce a new high value species, the sea urchin *T. gratilla*, in IMTA systems with *Ulva lacinulata*. By integrating *Ulva* in a commercial sea urchin farm, the lab can bioremediate water, thereby enabling partial recirculation, while at the same time producing valuable biomass to be used as sea urchin feed on site.

5.1 Goal and Scope

This is the first phase of an LCA study to provide a clear statement on the purpose of the study. Scope definition is comprised of the system boundaries, functional unit, methodology for impact assessment and impact categories used in this study. Here inputs included in the study and those that are excluded or out of scope of this study are summarised.

5.1.1 Goal and scope

The goal of this study was to compare environmental performances of the sea urchin (*T. gratilla*) cultured in monoculture and compared to urchins cultured in a partially recirculating IMTA system with seaweed (*U. lacinulata*). The IMTA system (urchin-Ulva) is partially modelled on commercially successful abalone-Ulva IMTA systems in South Africa.

5.1.2 Site and Process Description

A pilot commercial scale sea urchin and Ulva production facility has been designed and constructed at the Buffeljags abalone farm (a subsidiary of Viking Aquaculture) in the Western Cape Province. Sea urchin and Ulva growth trials were conducted in this system, which is a partially recirculating aquaculture system of sea urchin tanks integrated with two seaweed (Ulva) paddle-raceways (Figure 14). The system allows testing of several important functionality aspects to do with sea urchin/Ulva integration, including: 1) Cycling of nutrients (N – including ammonium and nitrate, P, calcium, etc.) in both the sea urchin and Ulva tanks; 2) nutritional content and growth rate of Ulva under different conditions (recirculation rate, temperatures, nutrient loading, stocking density; 3) optimal harvesting rates of Ulva. This IMTA system is a land-based partially recirculating system where the water was pumped first into the sea urchin system and the sea urchin effluent water flows to the seaweed raceway. For IMTA, there is 50% recirculation between urchin raceways and the Ulva paddle-ponds on the farm, meaning 50% less seawater needs to be supplied to the system when running the IMTA.

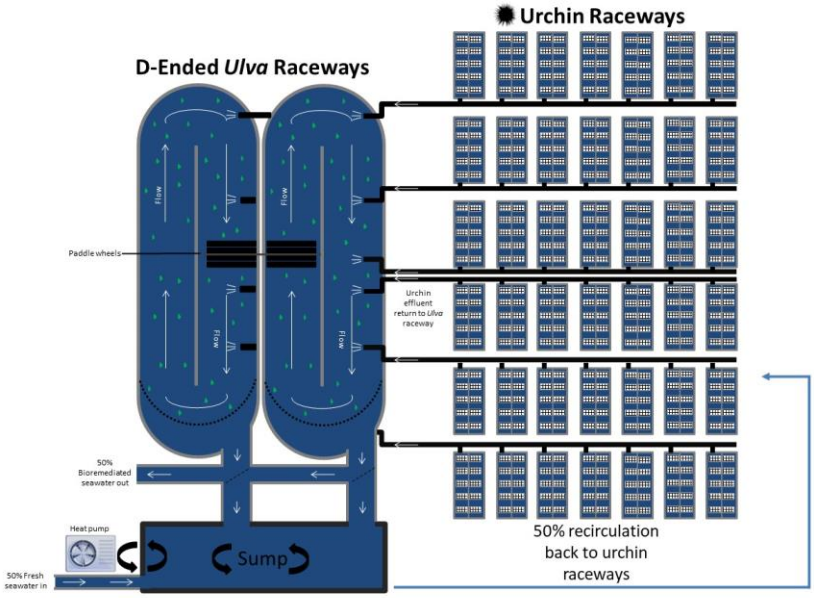


Figure 14 Schematic representation of the IMTA system modelled for the LCA study for IMTA lab South Africa.

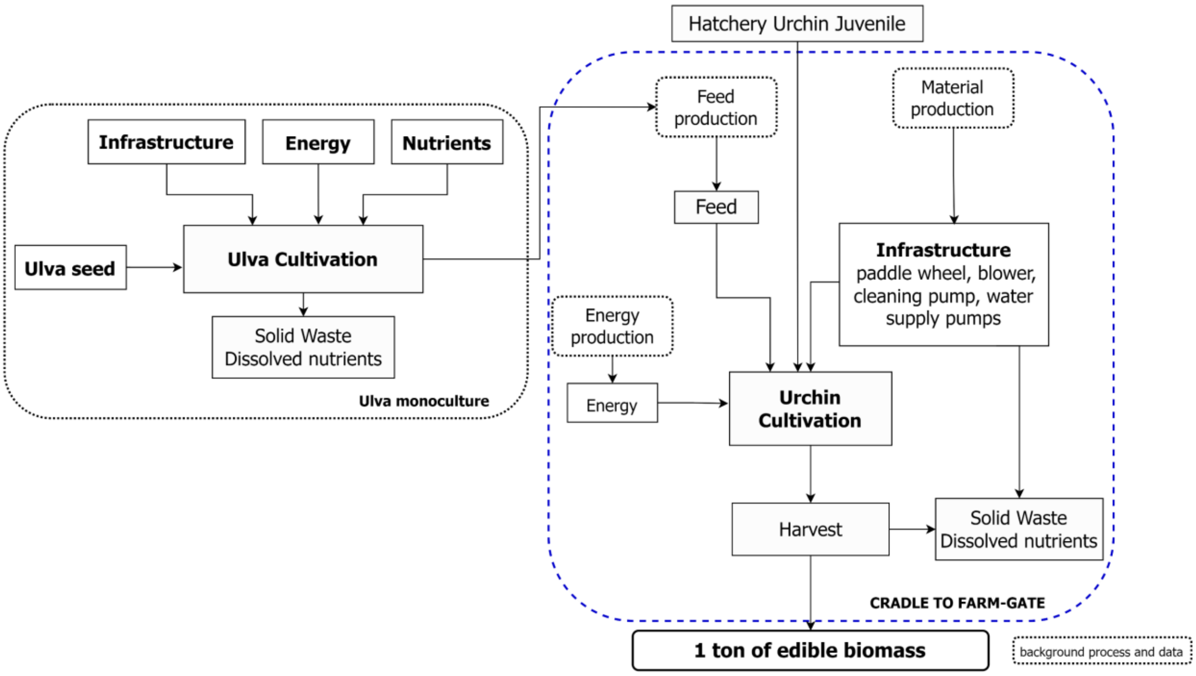
5.1.3 Functional unit

The functional unit for this study is expressed per tonne of edible biomass (urchin gonad, fresh weight basis).

5.1.4 System Boundaries

System boundaries define the processes included in the LCA. The LCA was performed from the cradle to farm gate. In monoculture, feed production for urchin, feed transport to site, energy production, infrastructure and farm operations/maintenance were included. Ulva that is processes as feed in a formulated feed is assumed to be produced in an *Ulva* monoculture system consisting of the two raceways as shown in figure 15 A. In the IMTA system, *Ulva* cultivation system is integrated within the urchin system where the Ulva produced is used as fresh feed or is the source of the formulated feed. Figure 15 shows the process flow chart for monoculture and IMTA system (highlighted in green boxes). In contrast to the monoculture system, IMTA-cultivated *Ulva* was used as a feed for urchin in the first four months of their production cycle. Information about the use of commercial feed and *Ulva* as direct feed from site, infrastructure is discussed under section 5.2.

A.



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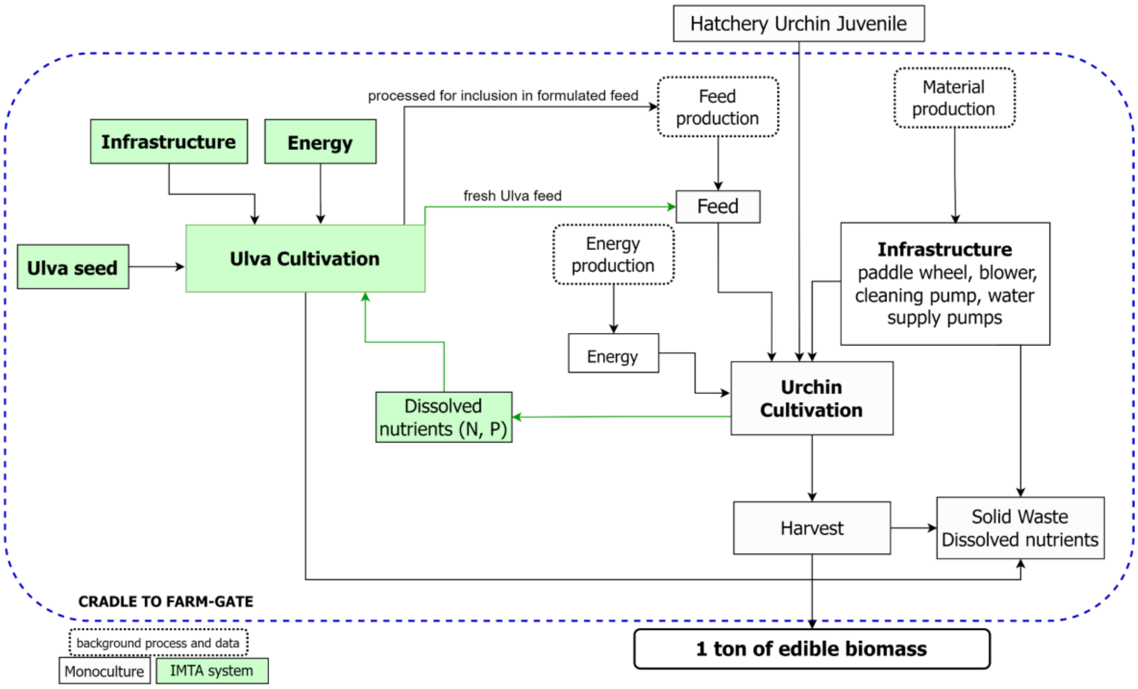

Figure 15 Flow diagram of (A) monoculture and (B) IMTA system at IMTA lab South Africa.

Boxes highlighted in green are process that are added in IMTA system in addition to the monoculture system. Dotted boxes represent background processes for which secondary data were used and solid outline boxes represent the foreground processes for which primary data were collected. Green arrow indicates the nutrient uptake in the IMTA system by Ulva from the urchin system and the processing of cultivated Ulva as fresh feed or processed formulated feed for the urchins.

5.1.5 Impact Assessment Choices

The impact assessment method used in this study was EF version 3.0 method that includes widely used categories for aquaculture systems. European Commission developed this method and is the one that is recommended to be used by Product Environmental Footprint Category Rules (PEFCRs). Sixteen impact categories are presented from EF 3.0 methodology as outlined in the introduction section.

5.1.6 Data

The data collection for the foreground processes was site specific and was done using an excel template, and workshops with relevant people from IMTA lab South Africa. Data gaps were searched and collected from earlier LCA studies on a similar system (such as Abalone-Ulva system at IMTA lab South Africa) (Mark D Cyrus et al., 2013; Mark D. Cyrus et al., 2015; M.D. Cyrus et al., 2015) and from circularity assessments performed in the same project. Background system data were gathered from databases and from relevant literature. Not all data are detailed or published in the deliverable as to protect data for confidentiality or for future publication.

5.1.7 Limitations and Assumptions

Urchin monoculture and Urchin-*Ulva* IMTA system is modelled by the IMTA lab South Africa based on the experimental system constructed at Buffeljags and from preliminary smaller scale trials based at the Marine Research Aquarium in Sea Point (email and personal communications). This will serve as the actual design to implement a commercial system. The IMTA lab estimated that two *Ulva* raceways are required to provide sufficient *Ulva* for direct feeding or processing it as urchin dry/formulated feed in an integrated system. Whereas in a monoculture system, we have assumed that *Ulva* is fertilised and used in formulated feed as described in the literature (Nobre, Robertson-Andersson, Neori, & Sankar, 2010; Robertson-Andersson et al., 2008). Due to data limitation on phosphates and carbon in the system, dissolved nitrogen is modelled as fertiliser for the monoculture and as bioremediation in the IMTA system. All *Ulva* produced is used as urchin feed in the IMTA system. Mass allocation of energy consumption in the integrated system.

5.2 Life Cycle Inventory Analysis

Biomass

Annual whole urchin harvest is estimated at 38.64 tons assuming 23.29% gonad somatic index (GSI) yielding approximately 0.75 tons FW gonad. In the IMTA system, where *Ulva* is produced for urchin feed, two *Ulva* raceways are predicted to yield 8.64 tons DW *Ulva* per annum.

Feed

In monoculture, urchins will only be fed with commercial pellets (formulated feed) during the 7-month grow-out phase. We estimated 2.57 ton of feed DW based on feeding urchin 1.5% of their mass four times a week. A separate process for *Ulva* monoculture production is considered to provide for 20% of *Ulva* for the formulated feed. In IMTA, urchins in the production cycle from zero to four months (during the somatic growth phase) are only fed with *Ulva* at 6% of their body mass daily three times a week. Then, pellets (supplemented with 20% dried Ulva) are fed for the last three months of the grow-out phase. Therefore, for the IMTA system, 0.9975 tons of commercial pellets and a total of 0.735 tons of *Ulva* is required. Table 4 shows the feed ingredient and proximate composition of feed used for the feed production phase in this LCA study. Seymour et al. (2013) reported FCRs from 0.8 - 8.0, and these values depended on the species of seaweed fed to the urchins (Seymour, Paul, Dworjanyn, & de Nys, 2013). Similarly, Cárcamo (2015) reported FCR’s of 0.68 ± 0.09 for *Loxechinus albus* fed *Ulva* (Cárcamo, 2015). Similar FCR is reported from site based on trials at the Marine Research Aquarium in Sea Point, where urchins were fed pellets at 1.83% body weight per day and for 5 days a week. This FCR is in line with what has been reported in the literature for other urchin species fed pellets.

Table 4 Feed ingredient (g/kg) and proximate composition of the feed

Ingredients (g/kg) (Mark D Cyrus et al., 2013; Mark D. Cyrus et al., 2015)	
Maize (extruded)	256.6
Wheat bran	256.6
Ulva	200
Fish meal	122.3
Soybean	122.3
Di-calcium phosphate	14.7
De-oiled lecithin	11
Vitamin and mineral premix	8.8
Oil-fish	7.7
Total	1,000
Proximate composition	
Protein (g/kg)	256.9
Fat (g/kg)	23.1
Moisture (g/kg)	96.1
Ash (g/kg)	138.9
Gross energy (MJ/kg)	15.49
Fibre (g/kg)	47.5
Carbohydrate (g/kg)	437.5

Infrastructure

The urchin cultivation system consisted of 42 raceway units where 20 baskets per urchin raceway made of uPVC were used under a greenhouse tunnel construction. Two *Ulva* paddle ponds are accounted in the system that are required to produce sufficient *Ulva* for processing as feed to urchins in the IMTA system. When running an IMTA with 50% recirculation following bioremediation with *Ulva*, the volume of fresh seawater required is 50% less.

Electricity

Table 5 shows the list of equipment accounting for electricity usage for monoculture and IMTA systems. Total KW per day for each system was calculated based on the maximum energy consumption of the equipment. In the monoculture case, urchin raceways and *Ulva* raceways used for feed processing are included. Compared to the monoculture, the IMTA system used 53% less energy.

Table 5 List of equipment accounting for electrical consumption in monoculture and IMTA system.

Monoculture	**IMTA**
Main water supply pumps	Main water supply pumps
Paddle Wheel	Recirc pump (Cluster)
Blower (Cluster)	Blower (Cluster)
Cleaning Pump	Cleaning Pump

	Foam Fractionator
	Paddle Wheel

5.3 Environmental impacts of IMTA lab – South Africa

Life cycle impact assessment was based on the EF 3.0 methodology. This section presents the environmental impacts results, in monoculture and the IMTA system, contribution of feed, infrastructure, electricity and other processes in the system, and then comparison of total environmental impacts between monoculture and IMTA system.

Total impacts in IMTA system South Africa:

Both in monoculture and IMTA system, contributions of the urchin cultivation phase dominated almost more than 95% of all the impact categories followed by the harvesting phase (Figure 16). Infrastructure had an impact of approximately 2% in the water use (Table 6).

Table 6 Total environmental impacts of the urchin monoculture system.

Impact category	Unit	Total impacts	Cultivation	Harvesting	Infrastructure
Climate change	kg CO2 eq	1.27E+05	1.25E+05	7.96E+02	1.23E+03
Ozone depletion	kg CFC11 eq	1.89E-02	1.87E-02	1.19E-04	2.26E-05
Ionising radiation	kBq U-235 eq	3.90E+03	3.85E+03	3.54E+01	1.51E+01
Photochemical ozone formation	kg NMVOC eq	3.74E+02	3.65E+02	6.23E+00	3.19E+00
Particulate matter	disease inc.	5.85E-03	5.65E-03	9.36E-05	9.82E-05
Human toxicity, non-cancer	CTUh	6.38E-04	6.10E-04	1.07E-05	1.72E-05
Human toxicity, cancer	CTUh	3.66E-05	3.44E-05	3.51E-07	1.90E-06
Acidification	mol H+ eq	7.74E+02	7.63E+02	5.92E+00	5.77E+00
Eutrophication, freshwater	kg P eq	1.02E+00	9.78E-01	2.29E-02	1.46E-02
Eutrophication, marine	kg N eq	1.33E+02	1.29E+02	1.97E+00	1.44E+00
Eutrophication, terrestrial	mol N eq	1.32E+03	1.29E+03	2.18E+01	9.28E+00
Ecotoxicity, freshwater	CTUe	9.21E+05	8.89E+05	1.72E+04	1.51E+04
Land use	Pt	4.39E+05	4.27E+05	1.05E+04	1.48E+03
Water use	m3 depriv.	1.88E+04	1.77E+04	9.08E+01	1.05E+03
Resource use, fossils	MJ	1.66E+06	1.63E+06	1.09E+04	1.77E+04
Resource use, minerals and metals	kg Sb eq	1.61E-01	1.55E-01	3.59E-03	2.99E-03

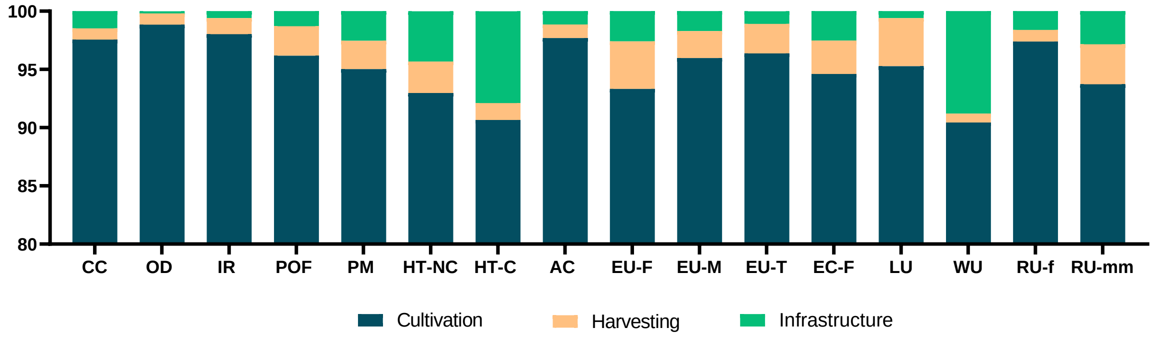

Figure 16 Total environmental impacts of IMTA system per kg of fresh weight edible biomass.

Climate change (CC), Ozone depletion (OD), Ionising radiation (IR), photochemical ozone formation (POF), Particulate matter (PM), Human toxicity -non-cancer (HT-NC), Human toxicity - cancer (HT-C), Acidification (AC), Eutrophication-freshwater (EU-F), Eutrophication-marine (EU-M), Eutrophication-Terrestrial (EU-T), Land use (LU), Water use (WU), Resource use- fossils (RU-f) and Resource use- minerals and metals (RU-mm).

Contribution analysis of feed, fresh *Ulva* as feed and electricity in the cultivation phase

Figure 17 shows the contribution analysis of IMTA system for feed, Ulva as direct feed and electricity in the cultivation phase. Electricity contributes 95% of the impact in the Climate change category. Electricity usage contributes more than 90% to several impact categories in the cultivation phase. Feed has highest impacts, 79%, 16% and 9% in the Eutrophication – freshwater, marine and terrestrial respectively which is due to the nutrient rich effluents from the ingredient processing stage.

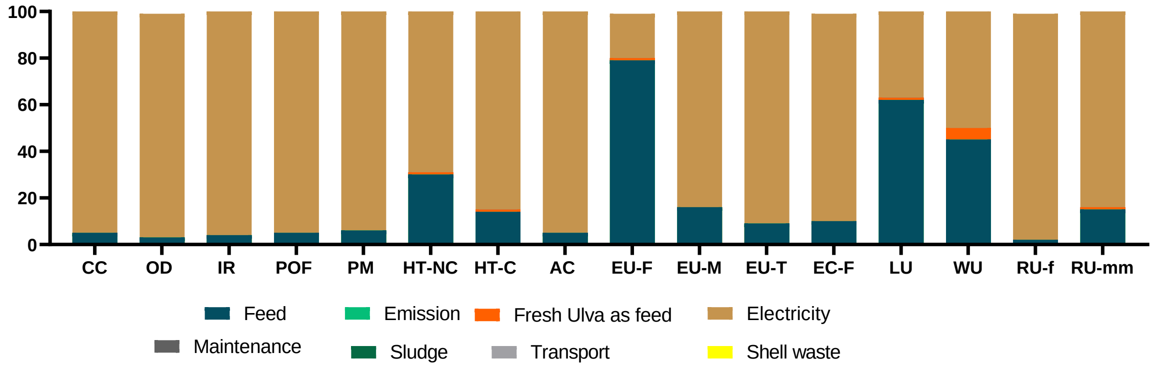

Figure 17 Stack diagram showing contribution of feed, fresh Ulva as feed and electricity to the environmental impacts per kg of fresh weight edible biomass for IMTA system for the cultivation phase.

Climate change (CC), Ozone depletion (OD), Ionising radiation (IR), photochemical ozone formation (POF), Particulate matter (PM), Human toxicity -non-cancer (HT-NC), Human toxicity - cancer (HT-C), Acidification (AC), Eutrophication-freshwater (EU-F), Eutrophication-marine (EU-M), Eutrophication-Terrestrial (EU-T), Land use (LU), Water use (WU), Resource use- fossils (RU-f) and Resource use- minerals and metals (RU-mm).

In the monoculture, formulated feed is supplemented with 20% Ulva from a monoculture of Ulva system. In the IMTA system, Ulva that is co-cultured with the urchin is used as the source of feed. The total formulated feed used in the IMTA system is less because of using the fresh Ulva as direct feed from the farm. Analysing the feed ingredients , shows that Ulva co-cultured for urchin feed in the IMTA system has minor impact on the climate change and eutrophication impact categories. IMTA system performs 2-7% better than the monoculture system in the climate change, acidification, and eutrophication categories (Table 7).

Table 7 Environmental impacts of Ulva feed in monoculture and IMTA for climate change, acidification and eutrophication impact categories

Impact category	Unit	Ulva Feed mono	Ulva Feed IMTA	Percentage difference
Climate change	kg CO2 eq	3.11E+00	3.02E+00	3.04%
Acidification	mol H+ eq	1.82E-02	1.70E-02	7.06%
Eutrophication, freshwater	kg P eq	3.19E-04	3.11E-04	2.55%
Eutrophication, marine	kg N eq	9.74E-03	9.58E-03	1.65%
Eutrophication, terrestrial	mol N eq	5.65E-02	5.46E-02	3.22%

Ulva feed supplemented in the formulated feed for urchin in the monoculture scenario is sourced from Ulva monoculture set up compared to Ulva in the IMTA scenario is sourced from the Ulva cultivated in co-culture with urchin.

Comparison of total impacts between monoculture and IMTA system:

The environmental assessments comparing monoculture and IMTA systems clearly indicate that the IMTA system exhibits better environmental performances across all impact categories examined, as illustrated in Figure 18. This improved performance in IMTA can be attributed to several key advantages. The IMTA system incorporates a recirculation system that significantly enhances the recycling of organic matter and nutrients. *Ulva*, plays a pivotal role in this system by acting as a biofilter, efficiently harnessing, and utilizing waste nutrients, primarily nitrogen (N, mostly as ammonia) and phosphorus (P), originating from the sea urchin production system. Simultaneously, *Ulva* biomass replaces the need for formulated feed and is employed as a direct feed source for sea urchins on-site. This is also reflected in the eutrophication impact categories in the IMTA system where *Ulva* effectively assimilates approximately 84% of the dissolved nitrogen that is released by the sea urchins. This not only curtails the ecological impact but also promotes a more sustainable aquaculture environment. Beyond its ecological benefits, the IMTA system reduces electricity consumption, which further enhances its overall efficiency and sustainability.

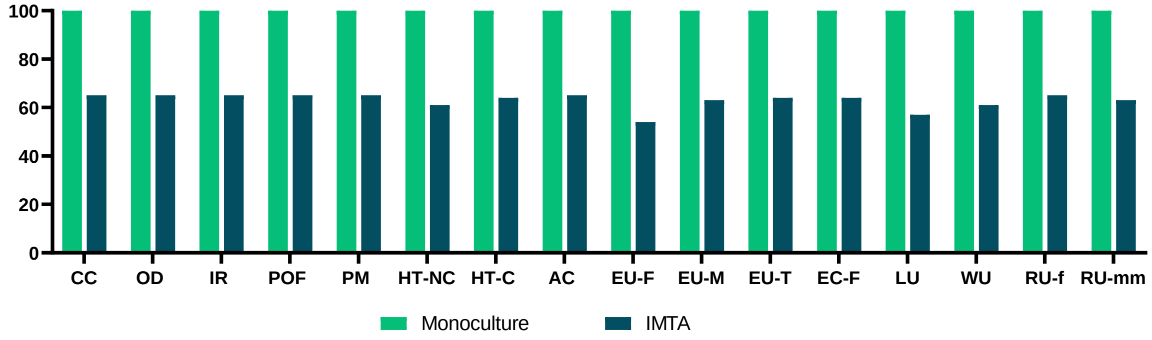

Figure 18 Comparison of environmental impacts per kg of fresh weight edible biomass for IMTA system and monoculture for the cultivation phase.

Climate change (CC), Ozone depletion (OD), Ionising radiation (IR), photochemical ozone formation (POF), Particulate matter (PM), Human toxicity -non-cancer (HT-NC), Human toxicity - cancer (HT-C), Acidification (AC), Eutrophication-freshwater (EU-F), Eutrophication-marine (EU-M), Eutrophication-Terrestrial (EU-T), Land use (LU), Water use (WU), Resource use- fossils (RU-f) and Resource use- minerals and metals (RU-mm).

5.4 Conclusion

The IMTA lab South Africa developed an experimental scale IMTA system where the *Ulva* system was integrated with the sea urchin production system to improve biofiltration capacity, feed production and increase water recirculation efficiency. To comprehensively assess the environmental impact of transitioning from a sea urchin monoculture to the IMTA system, an LCA study was conducted.

The results of this study demonstrated that the IMTA system consistently outperformed the sea urchin monoculture in all the impact categories examined. Notably, the major contributors to the environmental footprint were found to be feed production, electricity consumption, and the processing of Ulva for use as sea urchin feed. Previously, researchers have shown the feasibility of IMTA systems with fish, sea urchins and Ulva at semi-commercial scale based on their experience from IMTA culture with fish, abalone, and seaweed (Shpigel et al., 2018). However, a significant challenge in the context of sea urchin aquaculture is the need to use formulated feeds to optimize gonadal growth and produce sea urchin gonads of the desired size and coloration. Studies have indicated that formulated feed is only required at the end of the production cycle (last ca. 2-months) to enhance the size of the gonad. When fresh seaweed (*Ulva*) is available, it can be used for most of the production cycle and the somatic growth of urchin fed fresh *Ulva* is identical to that of urchins fed a formulated feed (Mark D Cyrus et al., 2013; Mark D. Cyrus et al., 2015; M.D. Cyrus et al., 2015).

In the South African context, extensive research has been conducted to advance the technology for aquaculture of *T. gratilla* for commercial purposes. The incorporation of a formulated feed with a 20% supplementation of *Ulva* (*U. lacinulata*) has shown significant improvements in FCR, tissue composition, and gonadal growth as well as quality (Onomu et al., 2020). In the current study, the environmental impact of using feed supplemented with 20% *Ulva* was examined in both sea urchin monoculture and the IMTA system. The findings revealed that the choice of feed type had a substantial impact on the environmental performance of the system, particularly in terms of energy consumption, resource utilization, land use, and climate change (F. Bohnes & Laurent, 2018; F. A. Bohnes et al., 2019; Ghamkhar et al., 2021). However, the incorporation of Ulva from the IMTA system's site mitigated the overall environmental impact by reducing the reliance on formulated feed that minimizes the systems' environmental footprint. In conclusion, 38.45% reduction in Climate change and 49%, 47%, and 37% reduction in Eutrophication-freshwater, marine and terrestrial categories was achieved.

6 Environmental Assessment of IMTA lab – Brazil

Shrimp farming is a growing industry as an alternative food source to meet the global demand for seafood products (Food & Agriculture Organization of the United, 2021). Legislative restrictions on traditional pond system due to environmental pollution in the coastal seawater and biosafety reasons. Alternative technologies such as recirculating aquaculture systems (RAS) and biofloc technology (BFT) are rising. BFT is an aquaculture approach microbial growth is promoted to control organic material and nitrogen compounds (ammonia, nitrate and nitrite) in the culture water. This improves the water quality, waste treatment and disease prevention in intensive aquaculture systems.

In a BFT system, uneaten feed, and faeces rich in nutrients are converted to edible bioflocs through microbial processes. These biofloc particles enable microbial nitrification of ammonia to nitrate stabilising the water quality and are become the feed for cultured species such as shrimp and tilapia. Commercial feed is supplied on a regular basis to feed the main cultivation organism, and external carbon is supplied to promote the bioflocs formation, under strong aeration and organic fertilization. Uneaten feed and faeces from shrimp farming are associated with environmental impacts such as eutrophication, acidification, and greenhouse gas emissions (Noguera-Muñoz et al., 2021). Environmental assessments such as LCA tool is used to evaluate and manage the environmental impacts to promote a more sustainable aquaculture practice. Sun et al.~~,~~ (2023) performed a consequential LCA study to compare intensive shrimp farming technologies (RAS, BFT and higher-place ponds-HPP). The researchers showed that RAS and BFT had significantly lower environmental impact than HPP system. In a cradle to farm-gate approach, cultivation phase was the highest contributor and feed, energy were key factors contributing to the environmental impacts (Sun et al., 2023). Currently, BFT is employed as a monoculture system for warm water shrimp or tilapia farming. Combining aquaculture species in a IMTA system, where nutrient not used by one species is used by another species, reuse the wastewater will be the future strategy for improving environmental performances of such super-intensive aquaculture system. In IMTA lab Brazil, shrimp in BFT system is combined with tilapia and extractive species such as seaweeds with commercial value to improve water quality, reducing the dependency on commercial feed, increase growth performance and health of the cultivated species. Nederlof et al. (2021) reported the conceptual four-species marine IMTA system that combines fish-seaweed-bivalve -deposit feeder) to achieve maximum nutrient retention (Nederlof et al., 2022).

6.1 Goal and Scope

This goal and scope definition is the first step of an LCA that provides a clear statement of the purpose of the study. Scope defines the functional unit, system boundaries, the impact assessment methodology, impact categories, and allocation used in this study.

6.1.1 Goal and scope

The goal of this study was to assess and compare environmental impacts of super-intensive recirculation IMTA and conventional shrimp monoculture system in Brazil. The monoculture species is the Pacific white shrimp (*Litopenaeus vannamei)* and the IMTA species are shrimp (*L. vannamei*), tilapia (*Oreochromis niloticus*), and Seaweed *(Ulva lactuca).*

6.1.2 Site and Process Description

IMTA lab Brazil is located at Rio Grande do Sul State – South earn Brazil. The Marine Aquaculture Center is located 300 meters away from the shoreline and has 9 experimental shrimp ponds (600 m^2 each), 3 greenhouses for research with shrimp production in bioflocs, 1 pilot commercial size greenhouse for shrimp production (2 tanks with 237 m^2 each) and 1 multi-trophic greenhouse (6 systems with 3 tanks each).

One-hectare conventional earthen ponds was set as the baseline monoculture scenario. In IMTA system, as shown in figure 19 is an independent system consisting of three compartments: i) 20 m^3 raceway for shrimp and biofloc community, ii) 4 m^3 circular tank for tilapia and iii) 4 m^3 circular tank for seaweed inside a greenhouse. Water from the shrimp raceway is pumped to the tilapia tank for removal of suspended particles. Water is then directed from the tilapia tank into the seaweed tank for biofiltering inorganic nutrients before flowing back to the shrimp raceway. Solids in the shrimp effluent is utilised by the biofloc community to convert toxic ammonia to nitrate.

6.1.3 Functional unit

The functional unit was 1 kg of biomass (in fresh weight). This study is based on experimental results from IMTA lab Brazil research site.

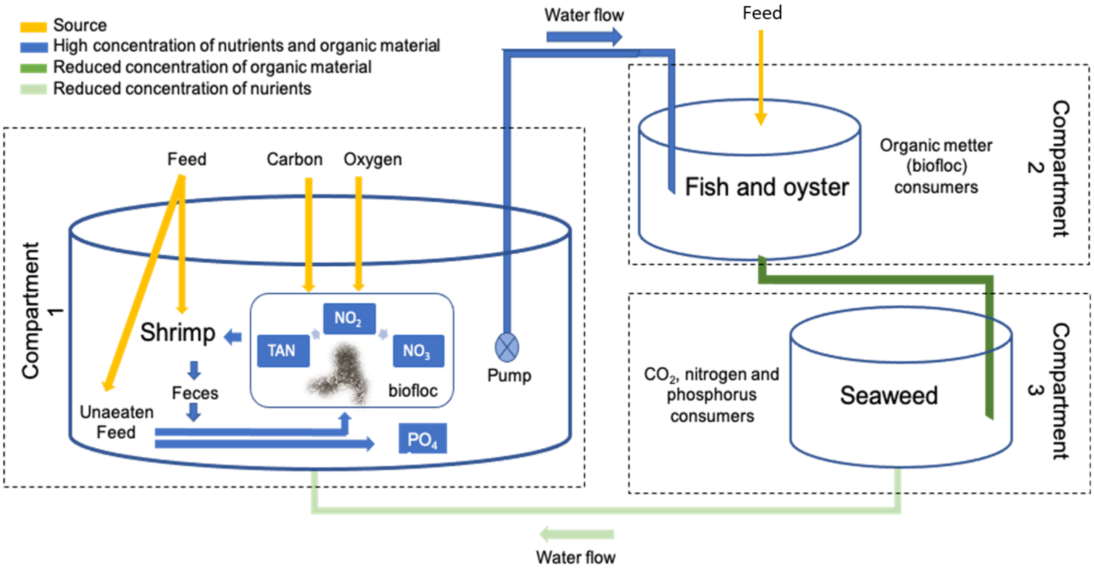

Figure 19 Schematic representation of IMTA system combined with BFT of IMTA lab Brazil.

The IMTA system consists of three compartments i) BFT consisting of shrimp and biofloc, ii) Fish tank with tilapia and iii) Seaweed tank consisting of U.lactuca.

6.1.4 System Boundaries

The system boundaries used in this study was “cradle to farm-gate” approach that consisted of shrimp feed or fish feed transport to site, cultivation and harvesting as show in Figure 20. The inputs considered for the cultivation stage were feed, stocking animals, equipment, infrastructure (ponds and buildings), transport, electricity, and water. Emissions to the soil, water and air from the experimental systems were included. This study does not include hatchery activity, as they are located at different premises.

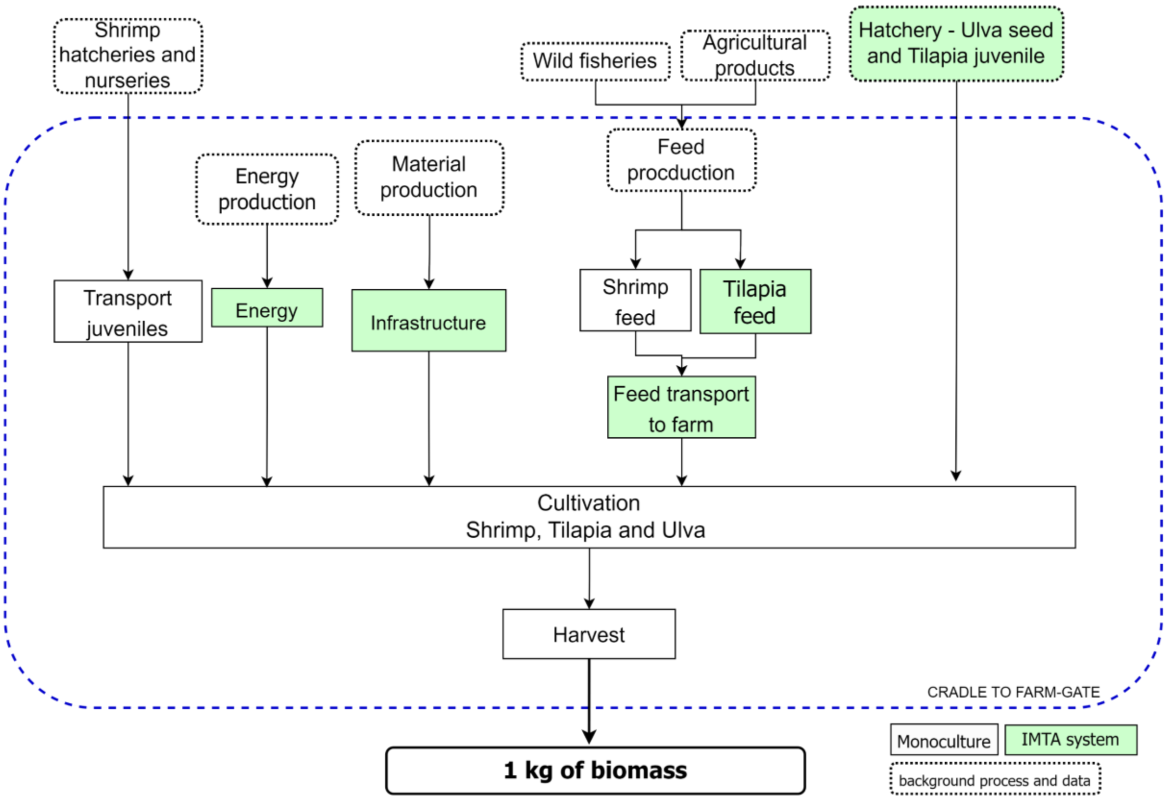

Figure 20 Flow diagram of monoculture and IMTA system at IMTA lab Brazil.

Boxes highlighted in green are process that are added in IMTA system in addition to the monoculture system. Dotted boxes represent background processes for which secondary data were used and solid outline boxes represent the foreground processes for which primary data were collected. Green arrow indicates the nutrient uptake in the IMTA system by Ulva from the urchin system and the processing of cultivated Ulva as feed for the urchins.

6.1.5 Impact Assessment Choices

The impact assessment method used in this study was EF version 3.0 method that includes widely used categories for aquaculture systems. European Commission developed this method and is the one that is recommended to be used by Product Environmental Footprint Category Rules (PEFCRs). Sixteen impact categories are presented from EF 3.0 methodology as outlined in the introduction section (SimaPro database manual – Methods library © 2022 PRé Sustainability B.V.).

6.1.6 Data

The study used primary and secondary data. Foreground data was site specific and collected for IMTA lab Brazil. Data on shrimp and tilapia feed were adapted from literature and re-calculated for the feed used in the lab (Medeiros, Aubin, & Camargo, 2017). Background data were collected from the

Ecoinvent database v3.8 for Brazilian context. See inventory section 6.2 for more details for each processes included.

6.1.7 Limitations and Assumptions

Data for conventional shrimp farming was collected from one-hectare and re-calculated to a cultivation area that will be comparable to the IMTA system. For IMTA scenario, one system of the six-replicate system is modelled. Total production cycle was set to one year period where in monoculture 3 cycle of shrimp is harvested and in IMTA 3 cycles of shrimp, 2 cycles of tilapia and 12 cycles of *Ulva* (harvested every month). Due to data limitation, oysters and halophytes were excluded from the system.

6.2 Life Cycle Inventory Analysis

Process flow and materials are accounted in the inventory data analysis phase. Data collection was done using excel templates and workshops with the IMTA lab. Inputs and outputs are shown in Figure 6.2. Data about the biomass yield, feed amounts, water consumption, electricity consumption and land area occupied were obtained from the IMTA lab. All electricity considered during the experiment was for aeration, water arrived by gravity unless otherwise stated as pumped. N and P from water was considered for mass balance. Feed P and crude protein contents were based on package labels. Background data related to equipment, infrastructure materials, electricity, fuel, and transport were obtained from the ecoinvent V3.8 database. Transport (including air freight and diesel truck) for shrimp larvae, tilapia juveniles, shrimp feed and tilapia feed from the feed manufacturers are included and the distances were estimated using Google maps.

Infrastructure

The IMTA consisted of shrimp tank, tilapia tank and seaweed tank in the size ratio of 4:1:1 were made of high-density polyethylene. Biofloc were in the shrimp tank that was aerated and recirculated by blower (0.66HP) and water pumping (submersal pump). To circulate water from the shrimp tank to the tilapia tank were used a submersal pump (0.25HP) during 24 hours per day and 7 days a week. After the tanks were filled, no water renewal is necessary during the production cycle and the level is maintained adding tap water due to evaporation in the greenhouse. The cultivation systems in the farm are rigid and considered as long-term infrastructure with lifetime of at least 5 years (PVC pipes and tubes, water pumps and blower) up to 15-20years (depot, machine house, tanks).

The conventional system consists of an excavated pond (1 hectare) that receives water directly from the ocean. A pump is used to fill the pond and renew the water, between 3 and 5% of the volume per day. Water pump runs 6 hours/day for 180 days in a year (3 cycles of shrimp production per year). Aeration is carried out by paddle-wheel which is activated at night.

Feed

Commercially available shrimp and tilapia feed were used. Lab provided that 9.37 kg of feed (DW) was required to produce 6.25 kg of shrimp (FW) per cycle in a monoculture case corresponding to an FCR of 1.5. For the IMTA, 93.6 kg and 112.8 kg of shrimp and tilapia feed was required to gain 72 and 240 kg of biomass, indicating an FCR of 1.3 and 0.470 respectively per cycle. Due to confidentiality for commercial feed, composition was calculated based on the label information and adapted from Medeiros et al.~~,~~ (2017) as shown in Table 8 (Medeiros et al., 2017). Background data was collected from Ecoinvent database v3.80.

Table 8 Feed composition of Shrimp and Tilapia. Ingredient and composition values are based on the feed label.

Shrimp Feed		from label used at FURG		
Ingredients*	**Quantity (%)**	**Composition (%)**	**Min.**	**Max.**
Soybean meal	33	Moisture	-	10
Wheat bran	18	crude protein	35	-
Maize starch	15	lipids	7.5	-
Fish meal	9	Fibre	-	5
Rice bran	8	Phosphorus	1.3	-
Calcium carbonate	5	Ash		13
Soy lecithin	4			
Meat meal	3			
Viscera meal	3			
Fish oil	1			
Premix (vitamin and minerals)	1			

Tilapia Feed		**from label used at FURG**		
Ingredients	**Quantity (%)**	**Composition (%)**	**Min.**	**Max.**
Soybean meal	28	Moisture	-	10
Wheat bran	5	crude protein	40	-
Viscera meal	23	lipids	10	-
Fish meal	16	fiber	-	4
Fish oil	3	Phosphorus	1.45	-
Maize starch	11	Ash		14
Sunflower meal	13			
Premix (vitamins and minerals)	1			

Ingredient and composition values are based on the feed label. The relative quantity of each feed ingredient was adapted from Medeiros et al., 2017 to achieve the label composition.

Cultivation

Stocking density in the monoculture system was 25 ind/m^2 and 300 individuals/m^2 in the IMTA system. Biofloc in the shrimp tank is composed of bacteria, flagellates, ciliates, nematodes, microalgae and other microorganisms that transform uneaten feed and faeces in microbial biomass under aeration and organic fertilization. Biofloc aid in the conversion of toxic ammonia to nitrate, improving the water quality at the same time providing microbial nutrients that improve the overall productivity of the system. For each 1 mg of ammonia in the water, 15 mg of carbon (molasses) to keep the relation C:N = 15:1. During cultivation in the monoculture, dolomit lime was used to adjust pH whereas calcium hydroxide is used in the IMTA system. Due to conventional system for the monoculture scenario, sinking of phytoplankton results in high carbon content in the soil. This is included as the total organic carbon emitted in the soil for the monoculture scenario. Sludge was modelled as solid waste at the end of the production cycle corresponding to 2kg in the monoculture and 25 kg in the IMTA system.

6.3 Environmental impacts of IMTA lab Brazil

Biomass

In the monoculture, yield of shrimp is 0.25g/m^2 whereas the super-intensive IMTA system yields 4.5 kg/m^3 of shrimp, 60 kg/m^3 of tilapia and 1.28 kg/m^3 of *Ulva*. Therefore, the total biomass produced in a production year in the monoculture is 18.75 kg (FW) and in the IMTA the productivity is 216 kg (FW) of shrimp, 480 kg (FW) of tilapia and 61.44 kg (FW) of *Ulva*. Compared to the monoculture scenario with the FCR of 1.5, the IMTA system FCR was 1.3 indicating lower feed consumption because of the biofloc as a feed source in the shrimp tank in addition to the commercial feed. The lower amount of feed required will result in lower material and energy needed for feed production and transportation thus improving the IMTA system.

Infrastructure

For all impact categories IMTA has better environmental performance in all categories, especially in climate change and eutrophication categories except human toxicity (cancer and non-cancer), resource use (minerals and metals) and ecotoxicity (freshwater) categories (Figure 21). Further analysis is needed to interpret the relevance of the categories in which IMTA had the highest impacts, especially ecotoxicity (freshwater).

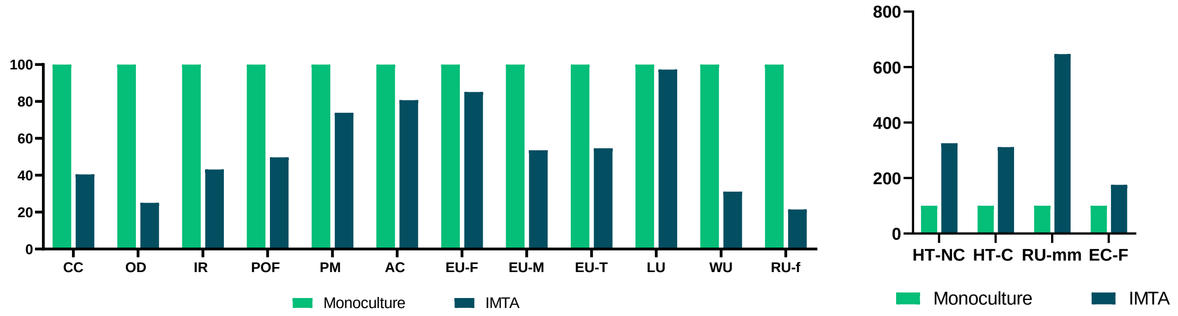

Figure 21 Comparison of environmental impacts per kg of fresh weight biomass of infrastructure for IMTA system and monoculture.

Climate change (CC), Ozone depletion (OD), Ionising radiation (IR), photochemical ozone formation (POF), Particulate matter (PM), Human toxicity -non-cancer (HT-NC), Human toxicity - cancer (HT-C), Acidification (AC), Eutrophication-freshwater (EU-F), Eutrophication-marine (EU-M), Eutrophication-Terrestrial (EU-T), Land use (LU), Water use (WU), Resource use- fossils (RU-f) and Resource use- minerals and metals (RU-mm).

Cultivation

Cultivation phase for the monoculture requires the provision of shrimp feed, lime, fertilisers, transport, electricity and filtered seawater. In addition to the monoculture, IMTA included tilapia feed, freshwater and molasses. Contribution analysis for the IMTA system in the cultivation stage shows the effect of feed and electricity playing a major role in all the impact categories. Electricity contributed 50% of the impact in the Climate change category followed by the shrimp and tilapia feed that contributed 21% and 23% respectively. Electricity used for aeration to maintain the dissolved oxygen concentration in water was the hotspot for the shrimp cultivation stage. In the eutrophication categories, a general trend with feed having the highest impact followed by electricity and transport (Figure 22 B). Medeiros et al. (2017) reported similar results when they compared monoculture of native Brazilian fish and shrimp species and polyculture systems in the freshwater ponds. They showed that the cultivation stage as the main contributor to the eutrophication, land occupation and water dependence categories. Within cultivation, feed had highest impacts in acidification and net primary production use in all the systems studied (Medeiros et al., 2017).

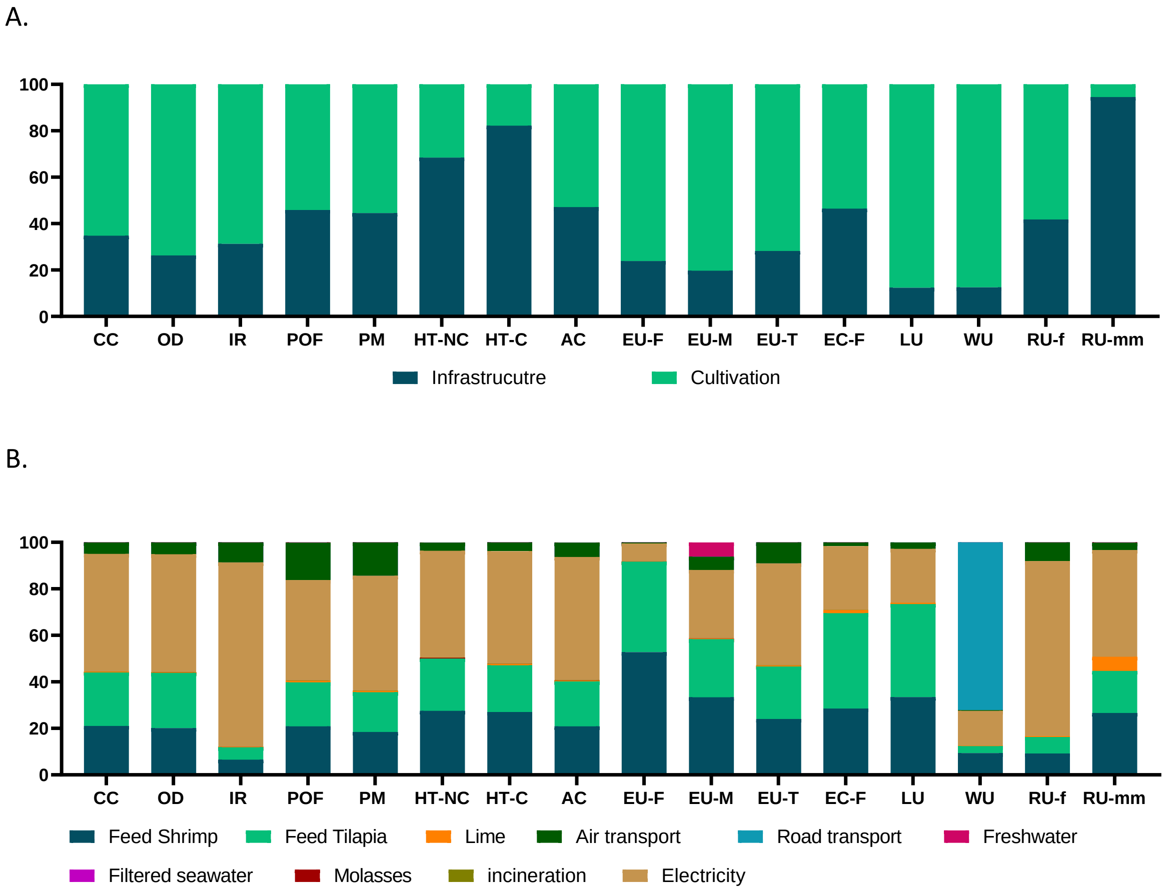

Figure 22 A. Total environmental impacts in the IMTA system and B. contribution analysis of the IMTA system expressed per kg of fresh weight biomass.

Climate change (CC), Ozone depletion (OD), Ionising radiation (IR), photochemical ozone formation (POF), Particulate matter (PM), Human toxicity -non-cancer (HT-NC), Human toxicity - cancer (HT-C), Acidification (AC), Eutrophication-freshwater (EU-F), Eutrophication-marine (EU-M), Eutrophication-Terrestrial (EU-T), Land use (LU), Water use (WU), Resource use- fossils (RU-f) and Resource use- minerals and metals (RU-mm).

Comparing the two systems, IMTA has lower impacts showing a better environmental profile in all categories than monoculture (Figure 23). Higher impacts of IMTA in resource use – freshwater and Ionising radiation categories needs further investigation.

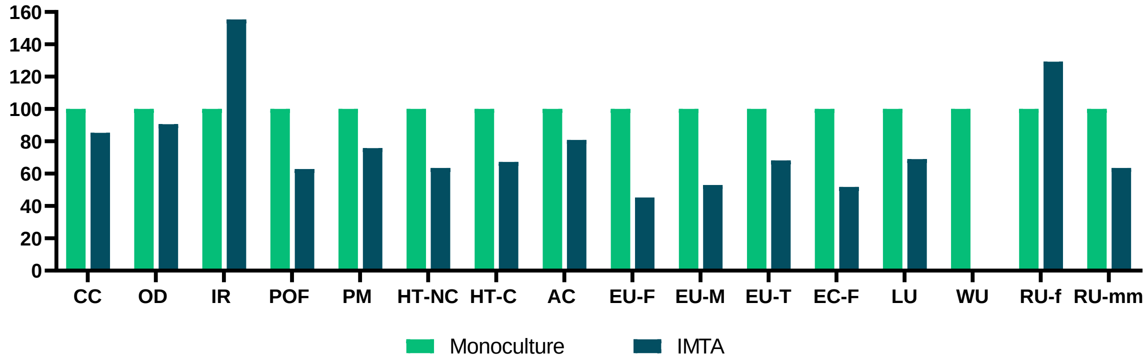

Figure 23 Comparison of environmental impacts per kg of fresh weight biomass for IMTA system and monoculture in the cultivation phase.

Climate change (CC), Ozone depletion (OD), Ionising radiation (IR), photochemical ozone formation (POF), Particulate matter (PM), Human toxicity -non-cancer (HT-NC), Human toxicity - cancer (HT-C), Acidification (AC), Eutrophication-freshwater (EU-F), Eutrophication-marine (EU-M), Eutrophication-Terrestrial (EU-T), Land use (LU), Water use (WU), Resource use- fossils (RU-f) and Resource use- minerals and metals (RU-mm).

Comparison of total impacts between monoculture and IMTA system:

Environmental assessment of total impacts and comparing between the monoculture and the IMTA systems shows that the IMTA system outperforms the monoculture system in most of the impact categories, especially in the climate change and eutrophication categories (Figure 24). The higher impacts of IMTA on human toxicity (cancer and non-cancer) and resource use (minerals and metals) is because of infrastructure elements that needs to be addressed in the future. The results are mainly influenced by the productivity, feed, and FCR. However, increasing productivity in the intensive system can also result in higher impacts (Cao, Diana, Keoleian, & Lai, 2011; Dekamin et al., 2015).

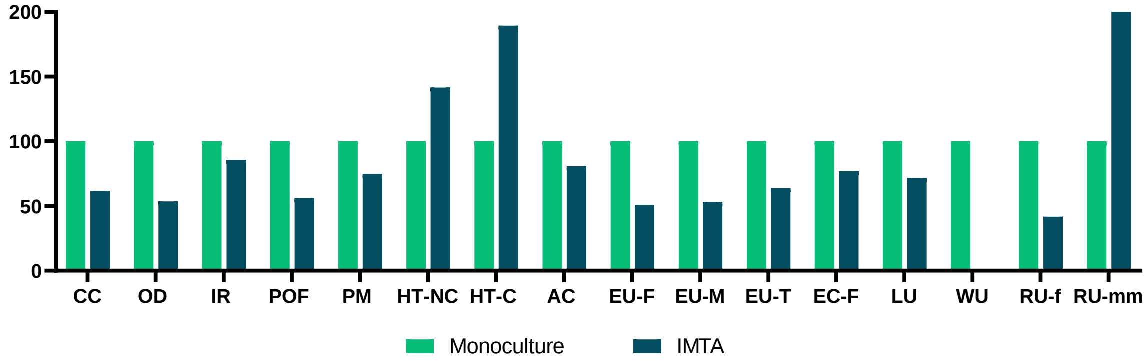

Figure 24 Comparison of total environmental impacts per kg of fresh weight biomass for IMTA system and monoculture system.

Climate change (CC), Ozone depletion (OD), Ionising radiation (IR), photochemical ozone formation (POF), Particulate matter (PM), Human toxicity -non-cancer (HT-NC), Human toxicity - cancer (HT-C), Acidification (AC), Eutrophication-freshwater (EU-F), Eutrophication-marine (EU-M), Eutrophication-Terrestrial (EU-T), Land use (LU), Water use (WU), Resource use- fossils (RU-f) and Resource use- minerals and metals (RU-mm).

In this IMTA lab, the rearing technology, using BFT in IMTA and combing tilapia and seaweed for better solid and nutrient recycling indicate 38% and 36 - 49% reduction in climate change and eutrophication categories resulting in better environmental profile of IMTA system. Improving the FCR by using BFT and other species also explains the improvement in the environmental performance of IMTA.

6.4 Conclusions

IMTA lab Brazil has adapted the concept of BFT and IMTA to a self-contained indoor culture for efficient nutrient recycling, and as an alternative to intensive culture systems that require expensive filtration systems to remove wastes from the culture environment. Here, the system for simultaneous culturing of the Pacific white shrimp (*L. vannamei*), tilapia (*Oreochromis niloticus*), and macroalgae (*Ulva lactuca*) is established.

The LCA helped to determine that the IMTA system with shrimp, tilapia and seaweed has lower environmental impacts per kg of biomass produced. This study identified the main contributors as feed, and electricity during the cultivation phase. Cao et al. (2011) reported that cultivation stage contributed between 96.4% and 99.6% of the cradle-to-farm-gate impacts mainly due to feed production, electricity use, and farm-level effluents (Cao et al., 2011). The categories in which the IMTA had higher impacts needed further elucidation. The extrapolation of the data from the experimental facility to a commercial farm tends to overestimate the impacts of infrastructure. Some impacts of infrastructure elements may be higher at this scale compared to a commercial farm. Al Eissa et al.~~,~~ (2016) recommend using renewable energy and controlling water quality using heterotrophic bacteria to reduce nutrient discharge will be the future to reduce environmental impacts from intensive shrimp farming (Al Eissa, Chen, Brown, & Huang, 2022). In line with the literature, this LCA study presents that environmental performance and profile of IMTA system that combines BFT is better than the non-BFT monoculture system.

7 Discussion and Conclusions

In this report we present the results from the LCA study where the environmental performance of the various monoculture and IMTA systems were assessed and compared. An IMTA system is expected to reduce the nutrient emissions released by the main cultivated species (monoculture species in this study). The LCA results from each IMTA labs (Scotland, Ireland, South Africa and Brazil) are presented. Each phase of the LCA study is provided, including aims and scope for the studies comprising system boundaries, functional unit, results, and interpretation. Overall, the results on the environmental performance of the IMTA systems compared to monoculture show the importance of moving towards the IMTA system to achieve sustainable aquaculture practices. In IMTA labs (Scotland and Ireland) the environmental hotspots in the IMTA system were identified that could be addressed to move the system towards better environmental profiles. In some systems, like the IMTA lab Scotland and IMTA lab Ireland, IMTA systems has higher environmental impacts compared to the monoculture systems. Cultivation phase in Scotland had -10%, -98%, and -70% in the Climate change and Eutrophication categories (freshwater, marine and terrestrial respectively). In rest of the IMTA labs, cultivation phase dominated the impacts such as 97% in Eutrophication -marine in Ireland, above 90% in South Africa and 65% in Brazil. This was followed by infrastructure and harvesting phases. Infrastructure has the major impact on all categories in Scotland and Ireland. Material selection holds substantial influence in this context, particularly when considering alternatives to stainless steel that have a faster degradation rate. By enhancing the longevity of materials, we can reduce the frequency of replacements, improve maintenance practices, and ultimately lessen environmental impacts.

This LCA study has revealed key processes that contribute to higher environmental impacts such as feed production, infrastructure, and energy. The impact of feed production in aquaculture is a well-known critical parameter in LCA assessments (F. A. Bohnes et al., 2019; Ghamkhar & Hicks, 2020). Intensity level and FCR have clear impacts due to energy, infrastructure, and feed processes in many of the impact categories. There is a requirement to reduce the impacts of feed by improving the feed utilisation of the whole system through production of a secondary species that used excess nutrients could increase the total system production and improve efficiency (Neori et al., 2004). IMTA lab South Africa have successfully integrated the cultivation of Ulva in the effluents of urchin system. This resulted in utilising the cultivated Ulva as direct feed in the early stages of urchin growth and processed in the formulated feed for later growth period. This reduced the overall requirement of the formulated feed and the impact on Eutrophication category by 36 -46%. Thus, IMTA systems can provide a way to increase environmental sustainability due to bioremediation and improved resource utilisation. Having multiple species using the same amount of feed could also reduce the energy and fuel use that can improve the climate change categories. New technological developments and use of more environmentally sustainable materials can reduce the impact of infrastructure elements (Ayer, Martin, Dwyer, Gace, & Laurin, 2016; Ghamkhar et al., 2021).

Emissions and uptake of major nutrients (nitrogen and phosphorus) were a key focus in this study due to their links with eutrophication. The nutrient emission in the IMTA system was calculated as the difference between net nutrient emissions from fish growth and the net nutrient uptake by the IMTA extractive species. The overall nutrient released to the environment in the IMTA systems is less compared to the monoculture system. Increasing nutrient retention and utilisation that minimises nutrient losses and maximises resource use efficiency results in circularity and aids in closing the nutrient loop (Nederlof et al., 2022). The overall reduction in the Eutrophication -marine category were

27.48%, 47%, and 47% in Ireland, South Africa, and Brazil in the IMTA system compared to the monoculture system, indicates the efficient nutrient retention and utilisation in all the IMTA labs.

Finally, common guidelines for LCA studies for aquaculture are necessary to compare the aquaculture studies. For example, a functional unit that reflects the actual function of the aquaculture system is recommended by many LCA practitioners to allow comparison of studies ((F. A. Bohnes et al., 2019; Chary et al., 2020). Marine Fish PEF recommends the use of 1 kg consumed edible fish as functional unit for LCA studies in aquaculture. In this present study, as protein was not the main output when farming seaweeds, harvested biomass was considered as the function unit. This limitation of the LCA when combining different trophic species farmed for different purpose in one production system influences the LCA study output. Guidelines for harmonising FU for non-fish species included in a study (such as seaweeds) into the PEF study for marine aquaculture are needed. Further, LCA studies in the future should broaden the assessment the system boundaries beyond the farm gate and include further along the value chain.

The European bioeconomy strategy places significant emphasis on fostering the sustainable development of coastal regions. This goal is to be achieved through the efficient utilization of marine resources and the cultivation of marine biomass within the same ecosystem. The adoption of an IMTA system will play a pivotal role in this effort, delivering substantial benefits in terms of mitigating environmental impacts. This transition to an IMTA system is anticipated to yield short-term net impact reductions, primarily attributable to its comprehensive approach that considers the entire life cycle from production inception to farm gate. One of the key mechanisms contributing to this reduction is the controlled flow of nutrients from higher trophic species to lower ones, as underscored by nutrient indicators in the Eutrophication categories. The findings of this study underscore the substantial value of transitioning towards sustainable IMTA systems within the context of a circular bioeconomy. This approach not only enhances the utilization of marine resources but also contributes to the broader goal of fostering sustainability in coastal regions.

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