

## Deliverable No. 6.3

Identification of the main weakness and strengths of different production system of LTS using sustainability analyses

Project acronym:



Project title:

**New species, processes and products contributing to increased production and improved sustainability in emerging low trophic, and existing low and high trophic aquaculture value chains in the Atlantic**

Grant agreement No: **818173**

Project co-funded by the European Commission within the  
Horizon 2020 Programme

Start date of project: **1st June 2019**

Duration: **54 months**



Due date of deliverable: 10/31/2022 (M41)
Submission date: 30/03/2023 (M46)
File Name: AquaVitae D6.3
Revision number: 01
Document status: Final <sup>1</sup>
Dissemination Level: PU <sup>2</sup>

<sup>1</sup> Document will be a draft until it is approved by the coordinator

<sup>2</sup> PU: Public, PP: Restricted to other programme participants (including the Commission Services), RE: Restricted to a group specified by the consortium (including the Commission Services), CO: Confidential, only for members of the consortium (including the Commission Services)

### Revision Control

<b>Role</b>	<b>Name</b>	<b>Organisation</b>	<b>Date</b>	<b>File suffix<sup>3</sup></b>
Task leader	Wagner Valenti	UNESP	01.01.2023	WV
WP6 leader	Åsa Strand	IVL	04.01.2023	ÅS
Task leader	Wagner Valenti	UNESP	10.02.2023	WW
WP6 leader	Åsa Strand	IVL	12.02.2023	ÅS
Task leader	Wagner Valenti	UNESP	28.02.2023	WW
WP6 leader	Åsa Strand	IVL	03.03.2023	ÅS
Task leader	Wagner Valenti	UNESP	13.02.2023	WW
WP6 leader	Åsa Strand	IVL	16.03.2023	ÅS
Task leader	Wagner Valenti	UNESP	20.02.2023	WW
WP6 leader	Åsa Strand	IVL	21.03.2023	ÅS
WP6 leader	Åsa Strand	IVL	26.03.2023	ÅS
Project coordination support	Celine Boechat	Nofima	27.03.2023	CBO
Project manager	Valur Gunnlaugsson	Matis	28.03.2023	VG
WP6 leader	Åsa Strand	IVL	29.03.2023	ÅS
Project coordinator	Philip James	Nofima	30.03.23	PJ

---

<sup>3</sup> The initials of the revising individual in capital letters

## Deliverable No. 6.3

# Identification of the main weakness and strengths of different production system of LTS using sustainability analyses

Wagner C. Valenti<sup>1</sup>, Patricia Moraes-Valenti<sup>1</sup>, Tamara Fonseca<sup>1</sup>  
Mayara Fabris<sup>1</sup>, Michelle R. Santos<sup>1</sup>, Dioniso S. Sampaio<sup>2</sup>, Florent  
Gilson<sup>3</sup>, Marcel C. Miraldo<sup>1</sup>, Flavia T. Matos<sup>4</sup>, Dallas L. Flickinger<sup>5</sup>,  
Daniela P. Dantas<sup>1</sup>, Laurindo A. Rodrigues<sup>4</sup> and Åsa Strand<sup>6</sup>

<sup>1</sup> UNESP – São Paulo State University, Aquaculture Center, Jaboticabal, SP, Brazil

<sup>2</sup> UFPA – Federal University of Pará, Institute of Coastal Research (IECOS), Bragança, PA, Brazil

<sup>3</sup> Epicura Algae Farm, Ubatuba, SP, Brazil

<sup>4</sup> EMBRAPA - Brazilian Agricultural Research Corporation, Fishery and Aquaculture, Palmas, TO & Western Agriculture Research Center, Dourados, MS, Brazil.

<sup>5</sup> Lincoln University of Missouri (USA), Jefferson City, MS, USA

<sup>6</sup> IVL Swedish Environmental Research Institute, Kristineberg 566, 451 78, Sweden

29/03/2023

## Executive summary

Sustainability is the management of natural, social, financial, technological, and institutional resources, ensuring the continuous satisfaction of human needs for the present and future generations with resilience, equality and equity. Three dimensions have been conventionally considered: environmental, social and economic. Recently, governance has been introduced as a fourth dimension. Sustainable aquaculture has been defined as the cost-effective production of aquatic organisms, maintaining a harmonious and continuous interaction with the ecosystems and the local communities.

The objective of this deliverable was to provide a holistic analysis of sustainability in which the main weaknesses and strengths of different low trophic species (LTS) aquaculture production systems were identified based on an indicator set defined in Lindblom et al. (2021). As AquaVitae (AV) entails LTS aquaculture around the Atlantic, focusing on six functional organism groups (red/green macroalgae, brown macroalgae, filtering mollusks (bivalves), grazing mollusks (abalone), echinoderms (sea urchin and sea cucumber) and freshwater fish (Tambaqui) farmed in a range of systems, and various combinations of these groups in integrated multitrophic aquaculture (IMTA) systems, a complex setup for sustainability analysis was available.

To obtain data to compute the previously identified indicators, a series of workshops were hosted to explain the data collection process, connect data needs to the indicators, and provide methodological advice, and “Queries and Answers” sessions were arranged. However, this was performed during the Covid-19 pandemic, which had significant negative impacts on the data collection process and resulted in poor data coverage for most indicators and all AV case studies. To compensate for the limited data availability, alternative sources of data were explored, and a cooperation with the Aquaculture Sustainability Research Network in Brazil was established. This cooperation enabled access to data from various production systems already available in a database and thereby allowed the demonstration of the applicability of the indicator set to LTS aquaculture systems, although not on the specific CSs in AV, as well as strengths and weaknesses of the studied systems. Data from the grow-out stage of production was obtained from 34 farms and 48 culture units (longlines, surface-based rafts and net-cages, bottom-based tables and inland ponds) for the environmental, social, and economic dimensions. Since governance data for assessing of governance sustainability can be acquired through semi-quantitative indicators, a questionnaire including a set of 35 questions was therefore developed and distributed broadly in the AV network. The questionnaire was filled in by representatives of 37 aquaculture systems from Canada, USA, Sweden, Norway, Denmark, Faroe Island, France, Spain, South Africa, Namibia, and Brazil.

The analysis of the data available in Brazil showed that the methodology was suitable to analyse the sustainability of LTS aquaculture systems. Most indicators showed some variation, hence pointing to different strengths and weaknesses of the studied systems. Moreover, the results indicated that overall, the culture of extractive species, such as macroalgae and filtering mollusks, was more sustainable than that of fed species, such as fish. The culture of fish in integrated culture (IMTA) was more sustainable than that in monoculture. Generally, marine LTS farming tended to be more sustainable than freshwater culture because of the low use of fresh water. These results corroborate what has been forecasted in scientific literature during recent years. However, the study also demonstrated that the differences in the aggregated sustainable indices are small despite potential large differences between specific indicators, and that details may impact the results significantly.

Analysis of specific sustainability aspects showed that the use of native species, a combination of species with complementary functional characteristics, and good management to decrease natural resource use during the production contributed strongly to the observed sustainability in the analysed cases. Consequently, the concept of monotrophic polyculture shows some promise and should be more exploited. This concept focuses on combining species of the same trophic level (e.g., LTS) that use different niches such as space or food source. The generation of local social and economic development and the contribution of the production to local food security also reflected high sustainability. Moreover, sustainability may be reduced in farms that import and export supplies and products or that use technology incompatible with local population abilities and culture. These aspects should be considered during technology development and the choice of systems in areas where sustainable expansion of LTS aquaculture is on the agenda.

In an all-Atlantic perspective, from the stakeholders' perception (such as farms and policy-makers), governance was found to be perceived as relatively well developed. Geographic region 21 (North America) was the most developed area showing a very-high level of governance sustainability, but no general differences between the other geographical regions (Brazil, Africa and Europe) were observed. However, some common weaknesses in governance did exist in all regions, such as difficulties in obtaining permits, and difficulties to obtaining certification to add value to yield. Generally, the cooperation among stakeholders was efficient and all regions had farmer cooperatives and associations, but arrangements for sharing cost of expensive equipment or services is still poorly developed.

The primary constraint for performing sustainability analysis through the use of indicators as identified in this study was the large amounts of specific data required, and the effort to find essential information revealed a mismatch in data availability compared to data requirements. It was apparent from the Brazilian case that data availability was dependent on long-term, strategic investments in industry-oriented research activities, coordinated through a center formation with a well-developed structure for data collection and data storage in a database developed specifically for the purpose. Implementing a similar structure in Europe may facilitate future analysis and development of existing, and new practices, and may support identification of strengths and weaknesses of LTS aquaculture also in a European context.

To conclude, this study demonstrated that the desired states and the developed indicator set developed in previous work (Lindblom et al., 2021) were appropriate and suitable to assess LTS aquaculture sustainability during the grow-out phase. Several strengths and weaknesses of different production systems in Brazil, and for governance also for systems around the Atlantic, were identified. In previous work (D6.2, Marinho et al., 2022), it was concluded that ecosystem services (ES) provided by LTS aquaculture may show conflicting impacts (i.e., both services and disservices) even within each analysed organism group. Consequently, methods to assess the net impact on sustainability, e.g. though the use of indicator sets as in this study, is crucial for informed governance decisions. Based on sustainability analysis covering the environmental, economic, societal and governance aspects, financial actors and government policy-makers may define priorities and support the enhancement of sustainable practices in LTS aquaculture. A detailed analysis of specific indicators may also support strategic and targeted enhancement of farm practices and management as this can highlight improvement needs in different aspects of the farm operations. If repeated over time, this analysis may also allow for monitoring of farm development to ensure longevity of the enterprise and enhancement of sustainability.

## Table of contents

Executive summary .....	4
Acronyms Table (Abbreviations).....	8
1. Introduction.....	9
1.1 Synopsis AquaVitae.....	9
1.2 Scope and motivation of T6.2.2 and D6.3.....	9
2. What is sustainability? .....	10
2.1 The concept of sustainability and sustainable aquaculture .....	10
2.2 Conceptual models of sustainability .....	12
2.3 Sustainability frameworks of relevance for aquaculture .....	13
2.3.1 Agenda 2030 .....	14
2.3.2 The Ecosystem approach to aquaculture.....	14
2.3.3 The Strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021 to 2030.....	15
2.3.4 The European Commission (EC) Sustainability Criteria for the Blue Economy .....	15
2.3.5 The FAO Global Conference on Aquaculture Millennium +20 (GCA).....	16
2.3.6 Certifications.....	16
3. Methods.....	17
3.1 Framework and data collection.....	17
<b>3.2 Data Analyses</b> .....	25
3.2.1 Analysis of environmental, social and economic data .....	25
3.2.2 Reference systems for environmental, social, and economic analysis .....	28
3.2.3 Analysis of governance data.....	28
3.2.4 Calculation of the index of sustainability.....	29
4. Results and Discussion.....	30
<b>4.1 Aquaculture systems analyzed</b> .....	30
4.1.1 Data for environmental, social and economic indicators .....	30
4.1.2 Data for governance indicators .....	32
4.2 Environmental, social and economic sustainability of LTS aquaculture .....	34
4.2.1. Environmental sustainability .....	34
4.2.2. Social sustainability .....	45
4.2.3. Economic sustainability .....	52
4.3 Governance.....	59
4.3.1. Subgroups with similar governance .....	59
4.3.2. Governance of LTS aquaculture around the Atlantic .....	66
4.4. Overall sustainability .....	68

5. Synthesis of major findings .....	71
Overall strengths and weaknesses of LTS aquaculture systems.....	72
Strengths and weaknesses illustrated by specific indicators .....	72
Environmental sustainability .....	72
Social sustainability.....	74
Economic sustainability.....	74
Governance sustainability .....	75
The path ahead.....	75
Conclusions.....	76
Acknowledgments.....	77
Data management .....	77
Datasets used.....	77
Environmental, social and economic data .....	77
Governance data.....	77
References.....	78
Appendix 1 – Sustainability aspects and indicators .....	84
Environmental sustainability .....	84
Economic sustainability .....	85
Social sustainability – Social development.....	86
Social sustainability – Policy and Governance.....	88
Appendix 2 – Governance questionnaire .....	94
Appendix 3 – Bar graphs of governance indicators .....	96

## Acronyms Table (Abbreviations)

AD: Assessment Domain

AV: AquaVitae

CS: Case study

D: Deliverable

EC: European Commission

ES: Ecosystem services

EU: European Union

HT: High Trophic

HTS: High Trophic Species

IMTA: Integrated Multitrophic Aquaculture

IPBES: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

IRG: Industry Reference Group

LTS: Low Trophic Species

N: nitrogen

NCP: Nature's Contributions to People

P: Phosphorous

PH: Person-hour

PHY: Person-hour per year

Q&A: Questions and Answers

SDG: Sustainable Development Goals

UN: United Nations

VC: Value Chain

WP: Work Package

# 1. Introduction

## 1.1 Synopsis AquaVitae

AquaVitae (AV) is a research and innovation project funded by the EU's Horizon 2020 program. The project consortium consists of 35 partners from 16 different countries spread across four continents. In addition to Europe, partners are situated in countries bordering the Atlantic Ocean, including Brazil, South Africa, Namibia, as well as in The US and Canada. AV's overall objective is to introduce new and expand existing, low-trophic species (LTS) products and processes to marine aquaculture value chains across the Atlantic. The value chains that AV focuses on include macroalgae, integrated multitrophic aquaculture, echinoderms, underutilized shellfish species and low trophic finfish species. Moreover, AV includes analysis of value chains, market development and profitability, and other biological and socio-economic aspects, including sustainability, environmental monitoring, and risk assessment of LTS. The achievement of sustainable aquaculture requires consideration of the positive and negative impacts of aquaculture on the environment, economy, and society.

## 1.2 Scope and motivation of T6.2.2 and D6.3

Work package (WP) 6 is one of AV's four cross-cutting scientific work packages. Its main objective is to develop recommendations on how to increase LTS aquaculture production with a net positive impact on sustainability in and around the Atlantic Ocean under the principle of circular economy and to understand the possible impact of climate change on aquaculture in this area.

To fulfill its objectives, WP6 is organized into five different tasks: T6.1 Establishing a Challenge-Structuring Framework, T6.2 Perform Sustainability Assessment, T6.3 Conduct Risk Assessment, T6.4 Assess Environmental Monitoring and T6.5 Recommendations for Optimising Sustainable Increase in LTS Production. T6.2.2 builds on the work completed in T6.1 (D6.1, Lindblom et al. 2021) and T6.2.1 (D6.2, Marinho et al., 2022) in which a framework for the activities in WP6 was established, including a set of indicators for assessing LTS aquaculture sustainability performance (D6.1, Lindblom et al. 2021), and a selection of nature's contribution to people (NCPs) were analysed to quantify services and disservices provided by LTS aquaculture (D6.2, Marinho et al., 2022). The picture provided by this work highlighted the complexity of sustainability assessments, with conflicting impacts (i.e., both services and disservices) provided even within each analysed organism group.

Therefore, the aim of T6.2.2 and D6.3 was to provide a more holistic analysis in which the main weaknesses and strengths of different LTS production systems were identified, and the sustainability performance of different systems was assessed using sustainability analysis. This was achieved based on already collected data in T6.2.1 (D6.2, Marinho et al., 2022) and additional data collection for selected LTS value chains, and analysis of the indicators of sustainability selected in T6.1 (D6.1, Lindblom et al., 2021). The results from D6.3 will be integrated into D6.5 (Lindblom et al., in prep.), fact sheets describing environmental effects from and on aquaculture, and into T6.5 (D6.6), recommendations on how to optimise the sustainability of increased LTS aquaculture production, including which positive sustainability aspects to exploit, which negative sustainability aspects to minimise, which risks to consider in relation to these aspects and how to monitor the system for early identification and mitigation of specific risks.

## 2. What is sustainability?

### 2.1 The concept of sustainability and sustainable aquaculture

Sustainability has become a trendy concept and is today used by a range of actors in all types of organizations, such as governments, companies, and in the civil society, from local to global scale. The concept has been developed since the 1970s, when the United Nations created the World Commission on Environment and Development (WCED). From then, it has evolved, resulting in several broad definitions. Nevertheless, the foundation of the concept was derived from the perception that human life and well-being are sustained by the Earth's capacity to provide resources and dilute/recycle wastes. This capacity is, however, limited by biophysical processes, and natural resources are finite. Therefore, the concept of sustainability comprises human societies and the ways they interact with natural systems. This interaction is often intermediated by the economy since production systems transform natural resources into goods and services that sustain human life and well-being (Figure 1). Thus, sustainability involves the combination of three dimensions: environmental, social, and economical, which in turn evolved sequentially on the planet. The environment appeared first, followed by the human society, which in turn was the basis for the economy. Sustainability has been defined in many ways, but there is agreement on some fundamental points, described in the follow paragraphs.

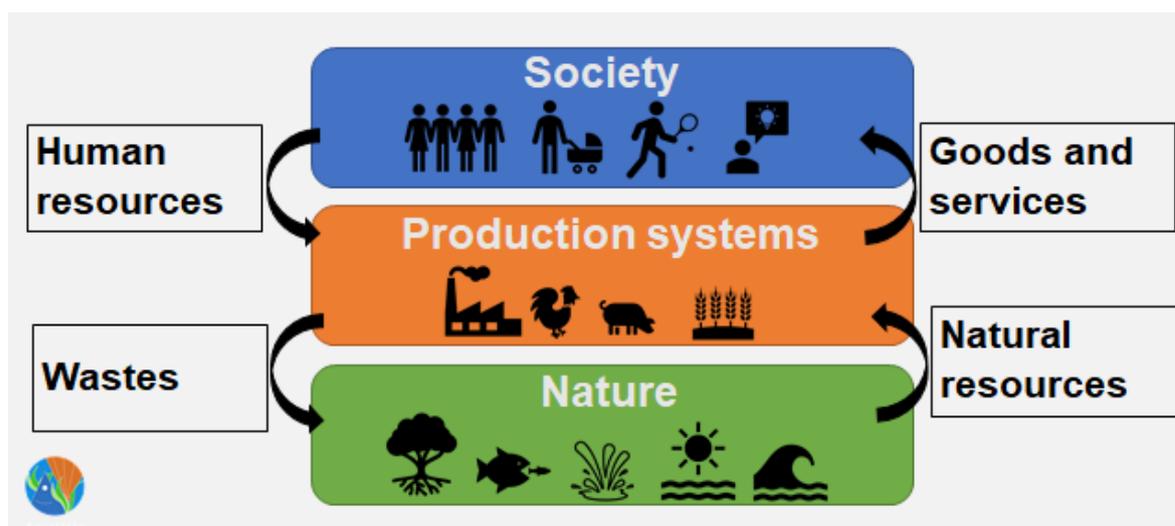


Figure 1. Nature and human society generally interact via production systems to transform natural resources and improve the well-being.

During the Conference of the WCED in 1987, the concept of “meeting the present needs without compromising the ability of the future generations to meet their own needs (Brundtland, 1987)” was introduced. This definition highlights two essential aspects of sustainability: equality and perennity, inferring that the well-being provided by our production systems must be shared equally among all people living in the world, and that this distribution of services should also be sustained over generations. To achieve this, humanity needs to stay within the safe operating limit of the planetary boundaries (Steffen et al., 2015), and consequently a transition towards the use of renewable resources and circularity is required. A resource is non-renewable when its withdrawal rate is higher than its natural recovery rate. The most common example of a non-renewable resource is fossil fuel, which was naturally produced and stored over billions of years, a timescale for repositioning that turns

its use inevitably unsustainable. That rationale also applies to other mineral resources (Svedrup et al., 2013) and even biosphere resources such as biodiversity (IPBES, 2019; WWF, 2020), with for example, fish stocks that are overfished (FAO 2020). In a sustainable society, nature is not steadily subject to physical degradations, increasing concentrations of substances extracted from the Earth's crust or produced by society, and people are not subject to conditions that undermine their capacity to meet their needs (Johnston et al., 2007).

According to the Stockholm Resilience Center (2022), resilience is “the capacity of a system, be it an individual, a forest, a city, or an economy, to deal with change and continue to develop”. In other words, it is the capacity of a system to maintain a steady state under external disturbance. A resilient system maintains dynamic stability and can self-reorganize to adapt to stress and persist in time. Humans and nature can react to shocks and disturbances with renewal and innovative thinking or process. To exemplify, financial crisis and climate change act as shocks and disturbances that, in turn, spur renewal and innovative internal reorganization to maintain the steady state. A sustainable system should consequently be resilient to be perennial and meet the needs of the present and future generations.

Production systems generally affect third parties outside the system negatively or positively. These effects are called externalities. Therefore, the efforts to improve sustainability should reduce the negative externalities and, if possible, generate positive ones. Positive externalities have been associated with ecosystem services (ES), which are the benefits to people derived directly and indirectly from the functioning of the ecosystems (Millennium Ecosystem Assessment, 2005). They include climate regulation, water supply, nutrient cycling, pollination, food and raw materials provision, genetic resources, and recreational and cultural benefits that derive from nature. Since establishing the ES concept in 1997 (Costanza et al., 1997), the research community has invested significant effort into mapping, quantifying, and valuing ES. Money-wise or not, society recognizes the natural systems' central role in sustaining human life and well-being (Costanza et al., 2017). Recently the concept of ES has also been expanded to include negative externalities in the concept of “nature's contributions to people” (NCPs, Díaz et al., 2018, see D6.2, Marinho et al., 2022 for discussion). In addition to natural systems, several anthropogenic systems (such as aquaculture) benefit people by providing the same services as the natural systems. Consequently, such systems deliver positive externalities that increase sustainability. Therefore, designing and managing social-economic systems that enhance human well-being while improving ES increases sustainability.

All in all, based on the combination of the above-discussed aspects, we can define sustainability as the management of natural, social, financial, technological, and institutional resources, ensuring the continuous satisfaction of human needs for the present and future generations with resilience, equality and equity. Sustainable development creates conditions that lead to a combination of human welfare and a balance of natural resources, and consequently does not allow growth to exceed the planet's carrying capacity. In other words, it creates a perennial steady state with harmonic interaction among nature, society, and economy. Sustainable aquaculture has been defined as; “the cost-effective production of aquatic organisms, maintaining a harmonious and continuous interaction with the ecosystems and the local communities” (Valenti et al., 2018). The aquaculture farm should be productive and profitable, generate and distribute benefits with equity, and optimize the use of capital and natural resources, conserving the surrounding ecosystems (including biodiversity, biogeochemical cycles, and trophic structure) and the planetary boundaries.

## 2.2 Conceptual models of sustainability

The three dimensions of sustainability, i. e., environmental, social, and economic, are generally accepted as a base for the concept of sustainability. Nevertheless, the understanding of how the dimensions are interconnected diverges between different actors, from some seeing the three dimensions as distinct perspectives to others having a systemic approach (Purvis et al., 2019). Accordingly, the sustainability dimensions have been represented in different ways, for example, by three pillars, intersecting spheres and hierarchical-dependent spheres (Figure 2). The first model illustrates that the three dimensions bear sustainability sovereignly, disregarding their synergy. The second model denotes that the dimensions are independent and have the same level of importance, but a balance between them is essential to achieve sustainability. The third model represents a systemic perspective, in which one dimension is sustained by the other in a hierarchical configuration based on the sequential theory described in section 2.1 (Biely et al., 2018, Purvis et al., 2019). In this last model, the environmental dimension is independent and sustains the social and economic dimensions. Likewise, the social dimension depends on the environment but not on the economic dimension, and this last one depends on the other two. These divergent points of view result in different directions to managing the three dimensions to reach sustainability. In the first model, actions toward sustainability may be done in each pillar independently. In the second one, actions in one dimension should consider the effects and interaction with the others; development should be simultaneously in the three pillars to retain equilibrium. In the third one, the environment is clearly the more important dimension, followed by social and economic; thus, actions to increase sustainability in the environmental dimension are more important. Nevertheless, the three models consider that sustainability is based on the three dimensions. All models will be considered in this deliverable

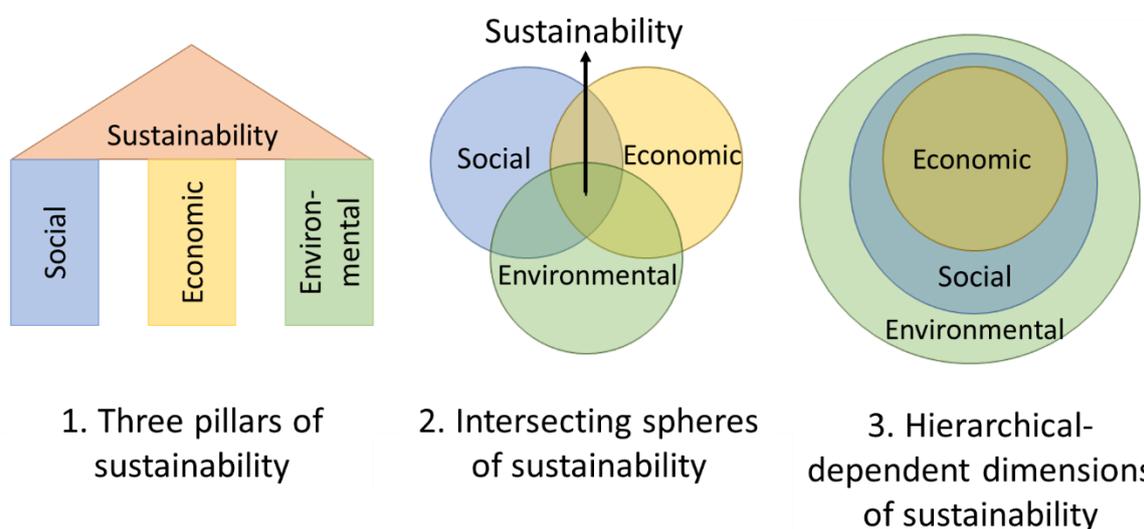


Figure 2. Graphical representation of major conceptual models for sustainability, showing the relationship between the dimensions environmental, social and economic (based on Purvis et al., 2019).

Moreover, governance has recently been included as a fourth dimension of sustainability (e.g., Fezzardi et al., 2013; Osmundsen et al., 2020). However, it does not appear in the primary official documents, such as Agenda 21 (UN, 1992) and Agenda 2030 (UN, 2015). Governance means the assemblage of laws, rules, regulations, and government practices agreed upon and followed by all sector stakeholders. Although governance is certainly not a natural dimension of sustainability, strong

governance, suitable policies, and strong institutions are essential for any sector, including aquaculture, to attain sustainability. Consequently, in the framework developed within WP6, LTS aquaculture sustainability included four dimensions: environmental, social, economic and governance, which were related to the sustainable development goals of Agenda 2030 (Figure 3, D6.1, Lindblom et al., 2021).

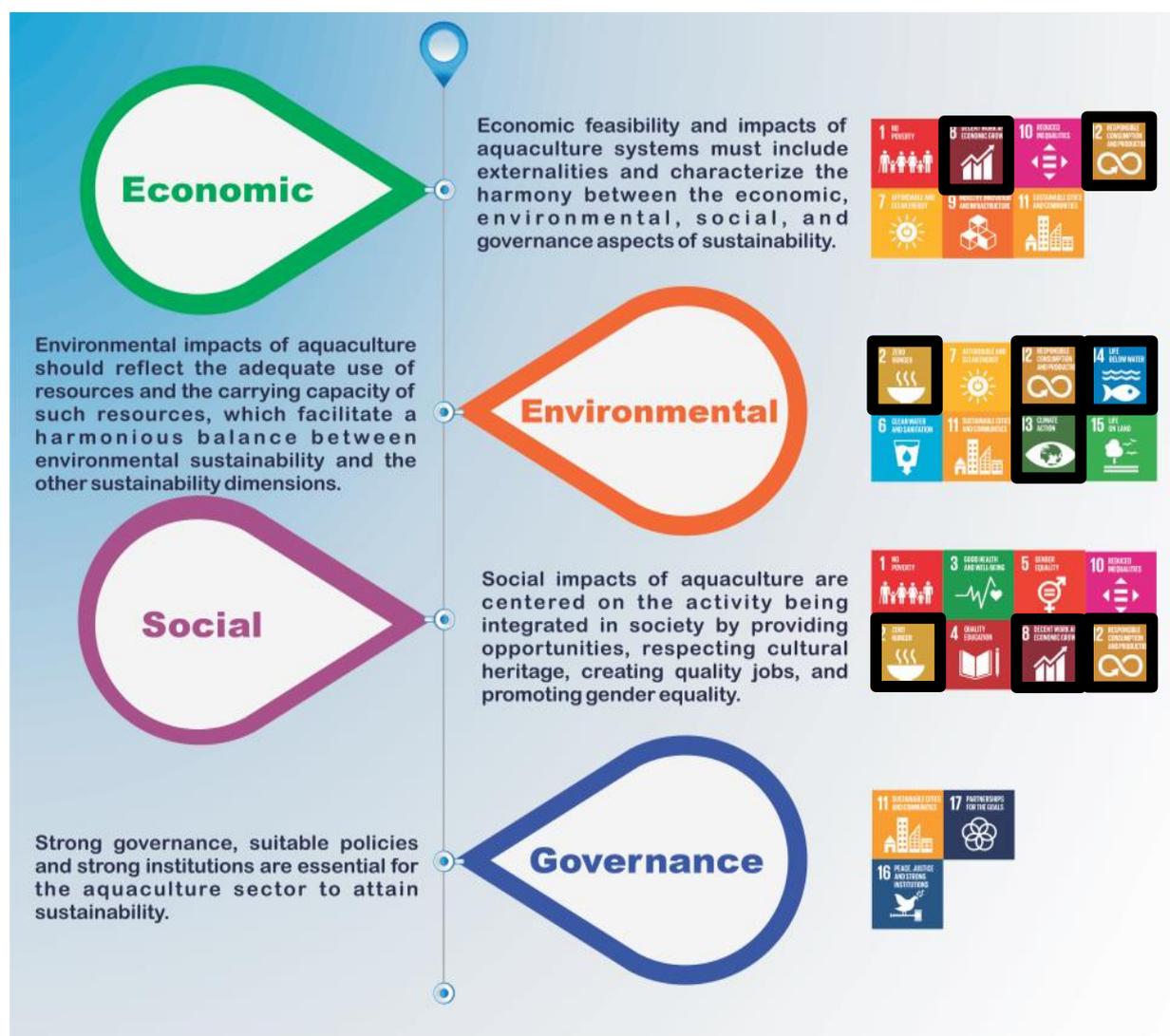


Figure 3. The four dimensions of sustainability of LTS was associated with the sustainable development goals (SDGs) of Agenda 2030 in the work of WP6 (D6.1, Lindblom et al., 2021).

### 2.3 Sustainability frameworks of relevance for aquaculture

A framework is a model designed to clarify a complex topic, organize it in a conceptual structure, provide a clear methodology for its application, and define the relationships between its components (Kobryn, 2000). Addressing sustainability is a complicated task due to its complex, multidisciplinary, and broad nature, and as the models for sustainability differ (see section 2.2). Therefore, frameworks are helpful in guiding organizations to put sustainability into practice (Chofreh and Goni, 2017) by supporting decision-makers during the processes of integrating the sustainability concept into decision-making. The major frameworks used in the sustainable assessment of aquaculture are described below. Some of these frameworks are only guiding documents, providing a general description of the principles of, or connection to, sustainability, whereas others provide support and

methodology to monitor and assess the current sustainability, the effect of actions and progress toward sustainability.

### 2.3.1 Agenda 2030

The Agenda 2030 for the Sustainable Development is a framework for guiding the government actions of the United Nations (UN) members toward sustainability (UN, 2022). It was supported by all countries within UN in 2015 and remained the most important guide for sustainable development. At its core are the 17 Sustainable Development Goals (SDGs), and each has several targets to be achieved, totaling 169 targets that can be described by indicators to be monitored to evaluate progress. The framework covers the three dimensions of sustainability (Economic, Social and Environmental), with specific goals for economic prosperity, people's social development, and the planet's health. In addition, some plans are proposed to ensure the governance necessary to attain sustainability. Agenda 2030 match conceptual model 2 of sustainability (see section 2.2). The concepts presented in the SDGs have been built upon decades of work in different countries supported by the UN. This framework has been refined and strengthened over time (Figure 4). The SDGs are widely applied and have a global perspective, but the resolution and connection to specific sectors are sometimes coarse or difficult to discern.

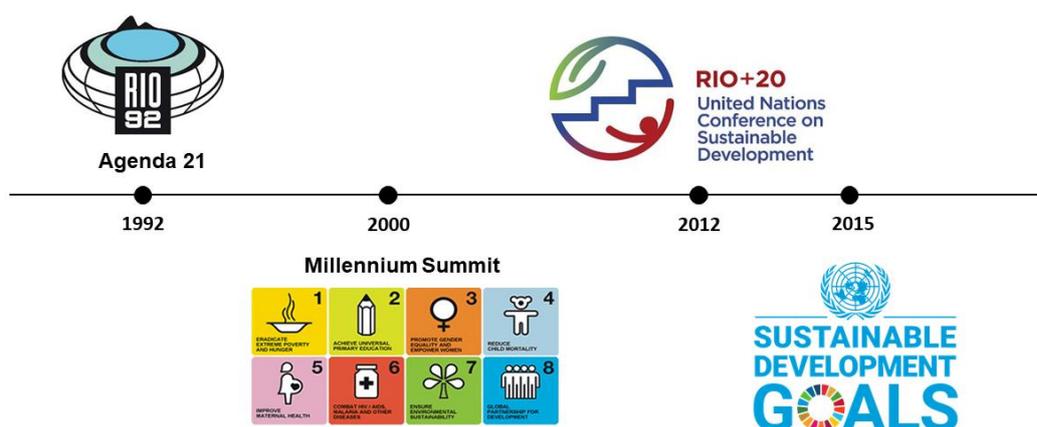


Figure 4. Timeline of the recent United Nations conferences that generated the Agenda 2030 for the Sustainable Development (United Nations, 2022).

### 2.3.2 The Ecosystem approach to aquaculture

The “Ecosystem Approach to Aquaculture” (EAA, Soto et al., 2008) is an FAO initiative, with the support of a multidisciplinary and multinational group of experts, to design a guide to improve the management and enhance the social and economic benefits of the aquaculture sector, following the ecosystem-based management concept. This framework is aligned with conceptual model 3 of sustainability. The EAA is a strategy for integrating the activity into the broader ecosystem to promote sustainable development, equity and resilience of interlinked social and ecological systems (Costa-Pierce, 2022). The document was launched in 2008 and stated three main principles to ensure the contribution of aquaculture to sustainable development (Soto et al., 2008):

- Aquaculture should be developed in the context of ecosystem functions and services with no degradation of these beyond their resilience capacity

- Aquaculture should improve human well-being and equity for all relevant stakeholders
- Aquaculture should be developed in the context of (and integrated to) other relevant sectors

The application of EAA should comprise the farm, the watershed, and the global (market-trade) scales. Over ten years later, the EAA has successfully raised the debate on the importance of aquaculture's participatory and holistic management, leading the sector toward greater sustainability (Brugère et al., 2018).

### ***2.3.3 The Strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021 to 2030***

The “Strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021 to 2030” (EC, 2021a) is a framework launched by the European Commission. The aim is to develop the sector in a way it contributes to the European Green Deal<sup>4</sup> and the Farm to Fork Strategy<sup>5</sup>. This guideline has a strong environmental focus, thus, matches conceptual model 3 of sustainability better. It will help the sector become more resilient and competitive by improving its climate and environmental performance. Moreover, it recognizes aquaculture's unique role in contributing to food security with a low carbon footprint. The general objectives of the guidelines are:

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

### ***2.3.4 The European Commission (EC) Sustainability Criteria for the Blue Economy***

The “European Commission (EC) Sustainability Criteria for the Blue Economy” (EU, 2021b) provides criteria and indicators to assess marine activities, including aquaculture (Figure 5). A circular economy approach is emphasized by promoting integrated multitrophic aquaculture (IMTA), and thus, it can be better associated with conceptual model 3 of sustainability. The document indicates the use of four broad frameworks to guide and assess the marine economic sector's reorganization to reach sustainably. One was developed for aquaculture: “Sustainability Indicators for Aquaculture” (Valenti et al., 2018). This is based on sustainability's economic, social, and environmental dimensions divided into criteria reflecting major sustainability features. A set of indicators to measure each criterion was developed. Economic features included are the efficiency in using financial resources, the economic feasibility, the capacity to absorb negative externality costs, the capacity for resilience, and the capacity to generate capital for reinvestment. Social criteria considered the capacity to create benefits for local communities, including jobs and food security, equitable income distribution, equal opportunities, and inclusion of vulnerable populations. Environmental features include the use of natural resources, the efficiency of using resources, the release of pollutants and unused by-products,

---

<sup>4</sup>[https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal\\_en](https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en)

<sup>5</sup> <https://www.europarl.europa.eu/committees/en/farm-to-fork-strategy/product-details/20201029CDT04383>

and the risk of damaging genetic diversity and biodiversity. The document also recommended including governance in the framework to assess the blue economy.



Figure 5. Documents showing frameworks to support actions to move aquaculture towards sustainability.

### 2.3.5 The FAO Global Conference on Aquaculture Millennium +20 (GCA)

The “FAO Global Conference on Aquaculture Millennium +20” (GCA) encompasses a comprehensive debate about building more sustainable aquaculture systems. Some priorities to accelerate sustainable aquaculture development were:

- integrate aquaculture with the natural environment and other economic sectors to enhance resilience
- improve the efficiency of using natural resources, reduce carbon footprint, and generate ES
- promote opportunities for women, indigenous and young people.

As a result of the GCA, two important documents were launched: “The Shanghai Declaration” (FAO, 2022a) and the “Perspectives on aquaculture’s contribution to the SDGs for improved human and planetary health” (Troell et al., 2023). They highlight the characteristics of aquaculture to contribute to matching the SDGs from Agenda 2030 and give directions for this. This guiding framework is better associated with conceptual model 2 of sustainability.

### 2.3.6 Certifications

Certifications are market-based strategies adopted by companies to communicate the mechanisms of compliance with sustainability standards to their audience (Bush et al., 2013). This can increase consumers’ trust in the company’s practices, enhance product traceability, open market niches and provide premium prices for the certificated products. Product certifications are frequently used to define sustainable processes based on conceptual model 1 of sustainability and often describe different aspects in terms of indicators that can be monitored over time. However, the frameworks used by certificatory companies often do not contemplate the essential concepts of sustainability and thus cannot be used as a framework to assess sustainability. Generally, the certification processes are based on setting standards for ecological and social performances defined by consumer preferences. The procedures are audited to ensure the standards, and the products are signed by labels (Bush et

al., 2013). The certification process is carried out by an external institution, such as private enterprises, non-governmental organizations (NGOs), or public institutions (Parkes et al., 2010).

A discussion of the indicators used in certifications for aquaculture was done in D6.1. The most known certifier institutions in aquaculture are the Aquaculture Stewardship Council (ASC Certification), Marine Stewardship Council (MSC), and Global Aquaculture Advocate (BAP Certification). Both have developed indicators to assess the compliance of production systems with legislation, rules, and regulations defined in response to the consumers' desires. Thus, they can be criticized for not matching most of the sustainability principles. Although certifications may be an excellent first step towards more sustainable aquaculture systems, the frameworks should comprise the major sustainability topics measured using scientific-based methods rather than consumer concerns.

### 3. Methods

Assessing the performance of production systems, such as aquaculture, is a necessary step to reach the objective of sustainability. By evaluating the interactions of an aquaculture farm with the environment and society, it is possible to identify weaknesses and strengths, as well as overall performance compared to other systems, which may provide insights on how to improve the systems towards sustainability. This is often an iterative process. To date, some tools have been developed to evaluate sustainability. The choice of the most suitable method is case-dependent and should consider the objectives of the analysis, the boundaries of the systems, and the data available. For analysis of system performance in AV, indicators were selected as the preferred method. For justification of this choice, please refer to D6.1 (Lindblom et al. 2021).

#### 3.1 Framework and data collection

The sustainability of farming LTS depends on the organism's functional group, characteristics of the surrounding environment, farm design and operation, productivity, social condition and demographic composition of the workforce, value chain, selling price, and exploited market, among other factors. In the context of AV, the project entails LTS aquaculture around the Atlantic, focusing on six functional organism groups: red/green macroalgae, brown macroalgae, filtering mollusks (bivalves), grazing mollusks (abalone), echinoderms (sea urchin and sea cucumber), freshwater fish (from rivers that drain to the Atlantic – Tambaqui or Cachama), and various combinations of these groups in integrated multitrophic aquaculture (IMTA) systems (plus the inclusion of marine fish and crustaceans in IMTA systems). These species are farmed in different production systems, creating a complex setup for sustainability analysis. Therefore, the boundaries for the present study were defined by two frameworks:

- the AV “Assessment Domain” (T6.1; Strand et al., 2022), a matrix describing the system boundaries based on the combination of different explanatory elements such as organism group, production mode (monoculture or polyculture), geographical area, production phase (hatchery, nursery, or grow-out), and production location (land-based, near-shore, and off-shore).
- D6.1, in which the desired state for LTS aquaculture in each sustainability dimension (environmental, social, economic, and governance) was described and connected to a set of sustainability aspects through the use of quantitative indicators (see appendix 1), including

already established and new indicators (see D6.1, Lindblom et al. 2021). The framework was focused on the grow-out phase only, and most of the indicators included were universal and suitable for assessing all LTS systems, including open seabased systems and land based systems, and extractive species as well as fed aquaculture. The freshwater fish group was a vital addition to the analysis as low trophic fish represent the most important group of organisms produced by aquaculture worldwide (see FAO, 2022b for data).

Based on this setup, the work in T6.2.2 commenced with data collection for sustainability analysis. Target groups approached for the data collection were AV CS and WP leaders, AV full industry partners and IRG partners, and all organism groups were included in the first attempt to collect data.

The data collection was initially focused on environmental indicators as this is one of the most data demanding domains in the sustainability matrix. The aim was to complement the data already collected during the work with the quantification of ES (D6.2, Marinho et al., 2022). A series of workshops were hosted to explain the data collection process, connect data needs to the indicators, and provide methodological advice, and “Queries and Answers” sessions were arranged. However, this was performed during the Covid-19 pandemic, which had significant negative impacts on the data collection process as summarised below:

- Limited interaction with the AV stakeholder partners despite activation of online solutions slowed down the data collection process;
- The restrictions imposed on physical meetings impaired effective interaction among the partners. Online activities were performed but were found to be insufficient;
- AV industry partners had to reorganize and prioritize their activities, often with reduced staff, and consequently could not put as much effort into the data collection as anticipated;
- The covid-19 pandemic delayed the work in CSs and impacted data collection negatively; hence the expected data were unavailable or delivered very late.

Additionally, a mismatch in expectations in terms of data collection requirements and availability of already existing data was noted between WP6 and CS leaders. In some cases, it had not been clear during the framework development process (D6.1, Lindblom et al., 2021) what data was actually needed to calculate some of the indicators, and, in some cases, data was not available in high enough resolution or lacked reference data points and could therefore not be used. This was particularly obvious for open sea-based systems. Moreover, as the indicator set was developed during the course of the project, all data requirements could not be anticipated during the AV application process, and consequently, budget was not allocated to collect the data needed for some of the indicators in the CSs. In summary, the data required to compute many of the selected environmental indicators could not be obtained despite strenuous efforts by both the AV partners and other stakeholders. Some environmental data were obtained from stakeholders to develop D6.2 (Marino et al., 2021). Although these data are sound, divergences in the methodology used collect that data from that was required to compute the sustainability analyses were observed. Adaptations of the D6.2 data to the sustainability analysis would require access to the primary data and a deeper exploration of the methods used to develop the data, which was not feasible in the current work.

To reduce the risk of stakeholder fatigue, the data needed for the socio-economic and governance indicators was discussed with WP5, 7 and 8 to see if synergy effects in data collection processes could

be achieved. It was decided to coordinate data collection with WP7, with a focus on data needed for social and economic indicators. This resulted in further delays due to a mismatch in the timing of the deliverables between WP6 and 7, yet this was a necessary step to reduce pressure on the stakeholders. As for the environmental indicators, data collection was challenging, and only fragmented data was obtained in the process.

The set of indicators to describe governance (available in D6.1, Lindblom et al. 2021) was primarily qualitative. This stems from the lack of quantitative indicators in the literature, which can be explained by the nature of governance information. Based on the experiences related to data collection of environmental, social and economic data, a new approach for collection of governance data was developed. The previous 55 governance indicators were grouped based on similarity and redundancy into a set of 35 questions that included the data necessary to assess all governance desired states (see appendix 2) assessed by a new set of semi-qualitative governance indicators. To increase the data resolution and avoid dichotomic variables (e.g., yes or no), an ordinal semi-quantitative scale from 1 to 5 was established for each question. The questions were structured in a questionnaire addressed to aquaculture stakeholders. In addition to scoring each question between 1-5, the respondents also had the opportunity to provide open answers. The survey was based on a nonprobability purposive design combined with a snowball sample design (Sheppard, 2021). This approach posed greater demands on replication yet offered the advantage of the data collection questionnaire being quick and easy to fill. The indicator set was evaluated internally before being sent out as a questionnaire (Afolalu, S.A., Ikumapayi, O.M., Ogedengbe, T.S., Kazeem, R.A., Ogundipe, A.T. 2022. Waste pollution, wastewater and effluent treatment methods – An overview. *Materials Today: Proceedings*, 62, Part 6:3282-3288.

- Ajibade, F.O. Adelodun, B. Lasisi, K.H. Fadare, O.O. Ajibade, T.F. Nwogwu, N.A. Sulaymon, I.D. Ugya, A.Y. Wang, H.C. Wang, A. 2021. Environmental pollution and their socioeconomic impacts, in: Kumar, A. Singh, V.K. Singh, P. Mishra, V.K. (Eds.), *Microbe Mediated Remediation of Environmental Contaminants*. Woodhead Publishing. pp. 321 -354.
- Alonso, A.A, Álvarez-Salgado, X.A, Antelo, L.T. 2021. Assessing the impact of bivalve aquaculture on the carbon circular economy. *Journal of Cleaner Production* 279. e12387.
- Álvarez-Salgado, X.A., Fernández-Reiriz, M.J., Fuentes-Santos, I., Antelo, L.T., Alonso, A.A., Labarta, U. 2022. CO<sub>2</sub> budget of cultured mussels metabolism in the highly productive Northwest Iberian upwelling system. 2022. *Science of the Total Environment* 849, e157867.
- Asai, H., Yamamoto, Y., Takeuchi, T., Ito, T., Sato, T., & Okazaki, S. 2009. Economic value of oyster aquaculture in Japan. *Aquaculture*, 295: 27-33.
- Barreto, M.O.; Planellas, S.R.; Yang, Y., Phillips, C. Descovich, K. 2022. Emerging indicators of fish welfare in aquaculture. *Rev. Aquac.*, 14:343-361.
- Bennett, N.J., Villasante, S. Espinosa-Romero, M.J., Lopes, P.F.M., Selim, S.A., Allison E. H. 2022. Social sustainability and equity in the blue economy. *One Earth* 5:964-968.
- Biely, K., Maes, D., Passel, S. V., 2018. The idea of weak sustainability is illegitimate. *Environment, Development and Sustainability*, 20: 223:232.
- Boyd CE, Tucker C, McNevin A., Bostick, K., Clay, J., 2007. Indicators of resource use efficiency and environmental performance in fish and crustacean aquaculture. *Rev Fish Sci* 15:327–360.
- Boyd, C.E., Wood, C.W., Chaney, P.L., Queiroz, J.F., 2010. Role of aquaculture pond sediments in sequestration of annual global carbon emissions. *Environ. Pollut.* 158, 2537e2540.
- Brugere, C., J. Aguilar-Manjarrez, M. Beveridge, and D. Soto. 2018. The ecosystem approach to aquaculture 10 years on — a critical review and consideration of its future role in blue growth. *Reviews in Aquaculture*, 11.
- Brundtland, G. H. 1987. *Our Common Future: The World Commission on Environment and Development*. Oxford: Oxford University Press.

- Brusseu, M.L., 2019. Sustainable development and other solutions to pollution and global change. In: Environmental and pollution science (pp. 585-603). Academic Press.
- Bush, S. R., Belton, B., Hall, D., Vandergeest, P., Murray, F. J., Ponte, S., Oosterveer, P., Islam, M. S., Mol, A.P.J., Hatanaka, M., Kruijssen, F., Ha, T. T. T., Little, D. C., Kusumawati, R., 2013. Certify Sustainable Aquaculture? *Science*, 341(6150): 1067-1068.
- Chen, G., Bai, J., Bi, C., Wang, Y., Cui, B. 2023. Global greenhouse gas emissions from aquaculture: a bibliometric analysis. *Agriculture, Ecosystems and Environment* 348, e108405.
- Chofreh, A. G., Goni, F. A., 2017. Review of Frameworks for Sustainability Implementation. *Sustainable Development*, 25(3): 180-188.
- Chopin, T. (2013a). Integrated multi-trophic aquaculture. Ancient, adaptable concept focuses on ecological integration. *Global Aquaculture Advocate*, 16(2), 16–19.
- Costanza, R., De Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., Farber, S., Grasso, M., 2017. Twenty years of ecosystem services: How far have we come and how far do we still need to go? *Ecosystem Services* 28: 1–16.
- Costanza, R., Folke, C., 1997. Valuing Ecosystem Services with Efficiency, Fairness, and Sustainability as Goals. *Nature's Services: Societal Dependence on Natural Ecosystems*. G. C. Daily. Washington D.C., Island Press: 49–69.
- Costa-Pierce, B. A., 2021. The Principles and Practices of Ecological Aquaculture and the Ecosystem Approach to Aquaculture. *World Aquaculture Magazine*, 52:25-31.
- CTDEEP (2021) Cost of Equalized Nitrogen Credit for Buyers 2021. Available at <[https://portal.ct.gov/-/media/DEEP/water/nitrogen\\_credit\\_advisory\\_board/Cost-of-Equalized-Nitrogen-Credits-for-Buyers-2021.pdf](https://portal.ct.gov/-/media/DEEP/water/nitrogen_credit_advisory_board/Cost-of-Equalized-Nitrogen-Credits-for-Buyers-2021.pdf)>. Accessed in December 2022.
- David, F.S.; Proença, D.C.; Flickinger, D.L.; Bueno, G.W.; Valenti, W.C. 2021. Carbon budget in integrated aquaculture systems with Nile tilapia (*Oreochromis niloticus*) and Amazon river prawn (*Macrobrachium amazonicum*). *Aquaculture Research*, 52:5155–5167.
- David, F.S.; Proença, D.C.; Flickinger, D.L.; Bueno, G.W.; Valenti, W.C. 2021. Carbon budget in integrated aquaculture systems with Nile tilapia (*Oreochromis niloticus*) and Amazon river prawn (*Macrobrachium amazonicum*). *Aquaculture Research*, 52:5155–5167.
- Díaz, S., Pascual, U., Stenseke, M., Martín-López, B., Watson, R. T., Molnár, Z., et al. 2018. Assessing nature's contributions to people. *Science* 359, 270–272.
- EAS, 2005. Defining indicators for sustainable aquaculture development in Europe, CONSENSUS – A multi-stakeholder platform for sustainable aquaculture in Europe. Workshop report, Oostende, Belgium, November 21–23, 2005.
- Ecological Footprint Network, 2022. How the footprint works. Available at: (<https://www.footprintnetwork.org/our-work/ecological-footprint/>, accessed on April 9th, 2022).
- Engle C. R. 2019. *Aquaculture businesses: a practical guide to economics and marketing*. 5m Publishing, Sheffield.
- Engle, C. R. & van Senten, J. 2022. Resilience of Communities and Sustainable Aquaculture: Governance and Regulatory Effects. *Fishes* 7, e268. <https://doi.org/10.3390/fishes7050268>
- Engle, C. R. , van Senten, J. Fornshell, G. 2019. Regulatory costs on U.S. salmonid farms. *J. World Aquacult Soc.* 2019, 1–28.
- Engle, C.R., 2010. *Aquaculture Economics and Financing: Management and Analyses*. Wiley-Blackwell, Oxford.
- EU (European Commission), 2021a. Strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021 to 2030. Communication COM/2021/236 final.
- EU (European Commission), 2021b. Sustainability criteria for the blue economy. European Climate, Infrastructure and Environment Executive Agency (CINEA). B-1049 Brussels.
- Fabris, M. 2023. Correlação jurídica entre os objetivos de desenvolvimento sustentável (ODS) e os indicadores de sustentabilidade para avaliação dos sistemas de aquicultura no Brasil. Universidade Estadual Paulista (UNESP), Centro de Aquicultura, Jaboticabal, Brazil. (Master Thesis). 83 p.

- FAO 2022a. Shanghai Declaration. Global Conference on Aquaculture: Aquaculture for Food and sustainable development. 22-25 September 2021, Shanghai, China.
- FAO 2022b The State of World Fisheries and Aquaculture 2022. Rome, FAO, Towards blue transformation.
- FAO, 1999. Indicators for sustainable development of marine capture fisheries. FAO Technical Guidelines for Responsible Fisheries. No. 8. FaO, Rome. pp. 68.
- FAO. 2017. The 2030 Agenda and the Sustainable Development Goals: The challenge for aquaculture development and management, by John Hambrey. FAO Fisheries and Aquaculture Circular No. 1141, Rome, Italy.
- FAO. 2020. The State of World Fisheries and Aquaculture 2020. Sustainability in action. Rome. Pp. 224
- Fernandes, J. B. 2013. Análise da sustentabilidade econômica e social na produção extensiva de ostras em uma região subtropical. Universidade Estadual Paulista, Jaboticabal. 78p. (Master Thesis).
- Fezzardi, D., Massa, F., Àvila-Zaragoza, P., Rad, F., Yücel-Gier, G., Deniz, H., Hadj Ali Salem, M., Hamza, H.A., Ben Salem, S., 2013. Indicators for sustainable aquaculture in Mediterranean and Black Sea countries. Guide for the use of indicators to monitor sustainable development of aquaculture. Studies and Reviews. General Fisheries Commission for the Mediterranean. No 93. Rome, FAO. pp. 60.
- Fialho, N.S.; Valenti, W.C.; David, F.S.; Godoy, E.M.; Proença, D.C.; Roubach, R.; Bueno, G.W. 2021. Environmental sustainability of Nile tilapia net-cage culture in a neotropical region. *Ecological Indicators*, 129, e108008.
- Fierro-Sanudo, J.F., Oca, G.A.R.M, Paez-Osuna, F.P. 2020 Co-culture of shrimp with commercially important plants: a review. *Reviews in Aquaculture* (2020) 12, 2411–2428.
- Flickinger, D.L., Costa, G.A., Dantas, D.P., Moraes-Valenti, P., Valenti, W., 2019. The budget nitrogen in the grow-out of the Amazon river prawn (*Macrobrachium amazonicum* Heller) and tambaqui (*Colossoma macropomum* Cuvier) farmed in monoculture and integrated multitrophic aquaculture systems. *Aquaculture Research*, 50:3444–3461.
- Flickinger, D.L., Costa, G.A., Dantas, D.P., Proença, D.C.; David, F.S.; Durborow, R.M.; Moraes-Valenti, P., Valenti, W.C. 2020. The Budget of carbon in the farming of the Amazon river prawn and tambaqui fish in earthen pond monoculture and integrated multitrophic systems. *Aquaculture Reports*, 17, e100340, p.1-14.
- Flickinger, D.L., Costa, G.A., Dantas, D.P., Proença, D.C.; David, F.S.; Durborow, R.M.; Moraes-Valenti, P., Valenti, W.C. 2020. The Budget of carbon in the farming of the Amazon river prawn and tambaqui fish in earthen pond monoculture and integrated multitrophic systems. *Aquaculture Reports*, 17, e100340, p.1-14.
- FOESA, 2010. Defining sustainability indicators for Mediterranean Aquaculture. Spanish Aquaculture Observatory Foundation (FOESA), Madrid, Spain.
- Franchini, A. C., Costa, G. A., Pereira, S. A., Valenti, W. C., & Moraes-Valenti, P. 2020. Improving production and diet assimilation in fish-prawn integrated aquaculture, using iliophagus species. *Aquaculture*, 521, 735048.
- Frankignoulle, M. & Canon, C. 1994. Marine calcification as a source of carbon dioxide: Positive feedback of increasing atmospheric CO<sub>2</sub>. *Limnol. Oceanogr.*, 39(2), 1994, 458-462.
- Giannetti, B. F., Almeida, C. M. V. B., Bonilla, S. H., 2010. Comparing Emergy accounting with well-known sustainability metrics: The case of Southern Cone Common Market, Mercosur. *Energy Policy*, 38: 3518–3526.
- Gulbrandsen, L., Husa, V., & Nordrum, S. 2012. Economic valuation of seaweed aquaculture in Norway. *Aquaculture Economics & Management*, 16: 116-132.
- Henry-Silva, G.G., da Silva Cacho, J.C., Moura, R.S.T., Flickinger, D.L., Valenti, W.C., 2022. Economic, social, and environmental assessment of farming Nile tilapia in net-cages in a reservoir in hot semi-arid region during an extended drought event. *Environ Sci Pollut Res*.

- Henry-Silva, G.G.; da Silva Cacho, J.C.; Moura, R.S.T.; Flickinger, D.L.; Valenti, W.C.. 2022. Economic, social, and environmental assessment of farming Nile tilapia in net-cages in a reservoir in hot semi-arid region during an extended drought event. *Environ Sci Pollut Res*.
- IPBES. 2019. Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. S. Díaz, et al. (eds.). IPBES secretariat, Bonn, Germany. 56 pages.
- IPCC, 2021. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R., Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press.
- IPCC. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R., Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press. 2021.
- Johnston, P., Everard, M., Santillo, D., & Robèrt, K. H. (2007). Reclaiming the definition of sustainability. *Environmental science and pollution research international*, 14(1), 60-66.
- Kobryn, C., 2000. Modeling components and frameworks with UML. *Communications of the ACM* 43: 31–38.
- Kosten, S., Almeida, R.M., Barbosa, I.,.....et al. 2020. Better assessments of greenhouse gas emissions from global fish ponds needed to adequately evaluate aquaculture footprint. *Science of the Total Environment*, 748, e141247.
- Krause G., Le Vay L., Buck B.H., Costa-Pierce B.A., Dewhurst T., Heasman K.G., Nevejan N., Nielsen P., Nielsen K.N., Park K., Schupp M.F., Thomas J.-B., Troell M., Webb J., Wrangle A.-L., Ziegler F., Strand Å. 2022. Prospects of Low Trophic Marine Aquaculture Contributing to Food Security in a Net Zero-Carbon World. *Frontiers in Sustainable Food Systems*, 6, pp10.
- Lindblom et al. 2021. Recommendation of indicators to be used in sustainability analysis of new and underutilized low-trophic species in aquaculture. (D6.1)
- Lindblom et al. 2023. Fact sheets describing environmental effects from and on aquaculture. AquaVitae Deliverable 6.5. Grant agreement No: 818173. (D6.5).
- Lindblom, E., Bengtsson, L., Rydstedt, A., Strand, Å., Strandberg, J. 2022. Assessment of environmental risks exerted upon, and by, low-trophic aquaculture in the Atlantic Region. (D6.4)
- Lothmann, R. & Sewilam, H. 2023 Potential of innovative marine aquaculture techniques to close nutrient cycles. *Reviews in Aquaculture*. First published on line: 28 December 2022.
- Marine Harvest. 2017. *Salmon farming industry handbook 2017*. Retrieved from
- Marinho, G. S., Álvarez-Salgado, A., Fuentes-Santos, I., Burgués, I., Sousa-Pinto, I., Strand, Å. 2022. Quantification of Ecosystem Services. AquaVitae Deliverable 6.2. 12/04/2022. Grant agreement No: 818173. (D6.2).
- Martinell, D.P., Vergara-Solana, F.J., Almendarez-Hernandez, L.C., Araneda-Padilla, M.E. 2020. Econometric models applied to aquaculture as tools for sustainable production. *Reviews in Aquaculture* (2020) 12, 1344–1359.
- Millennium Ecosystem Assessment (MEA)., 2005. *Ecosystems and Human Well-Being: Synthesis*. Island Press.
- Molinos-Senante M, Hernández-Sancho F, Sala-Garrido R, Garrido-Baserba M (2011) Economic feasibility study for phosphorus recovery processes. *Ambio* 40: 408– 416.
- Moraga, G., Huysveld, S., Mathieux, F., Blengini, G. A., Alaerts, L., Van Acker, K., ... Dewulf, J. (2019). Circular economy indicators: What do they measure? *Resources, Conservation & Recycling*, 146, 452–461.
- Morro, B., Davidson, K., Adams, T.P., et al. 2022. Offshore aquaculture of finfish: Big expectations at sea. *Rev Aquac.*, 14: 791– 815.

- Moura, R.S.T., Valenti, W.C., Henry-Silva, G.G., 2016. Sustainability of Nile tilapia netcage culture in a reservoir in a semi-arid region. *Ecol. Ind.* 66, 574–582.
- Nathanson, J. A. 2023. Pollution. *Encyclopedia Britannica*.  
<https://www.britannica.com/science/pollution-environment>. (Accessed 24 February 2023).
- Odum, H.T. (Ed.) 1996. *Environmental Accounting: Emergy and Environmental Decision Making*, 1st ed.; John Wiley & Sons: New York, NY, USA.
- Osmundsen, T.C., Amundsen, V.S., Alexander, K.A., Asche, F., Bailey, J., Finstad, B., Olsen, M.S., Hernández, K., Salgado, H. 2020. The operationalisation of sustainability: Sustainable aquaculture production as defined by certification schemes. *Global Environmental Change*, 60: e102025.
- Parkes, G., Young, J. A., Walmsley, S. F., Abel, R., Harman, J., Horvat, P., Lem, A., MacFarlane, A., Mens, M., Nolan, C., 2010. Behind the Signs—A Global Review of Fish Sustainability Information Schemes. *Reviews in Fisheries Science*, 18(4): 344-356.
- Pedrazzani, A.S., Tavares, C.P.S., Quintiliano, M., Cozer, N., Ostrensky, A. 2022. New indices for the diagnosis of fish welfare and their application to the grass carp (*Ctenopharyngodon idella*) reared in earthen ponds. *Aquaculture Research*. 53(17):5825-5845.
- Pereira, S.A., Kimpara, JM., Valenti, W.C. 2021. Sustainability of the seaweed *Hypnea pseudomusciformis* farming in the tropical Southwestern Atlantic. *Ecological Indicators*, 121, e107101. p. 1-9.
- Pereira, S.A.; Kimpara, JM.; Valenti, W.C. 2020. A bioeconomic analysis of the potential of seaweed *Hypnea pseudomusciformis* farming to different targeted markets. *Aquaculture Economics & Management*, 24(4): 507-525.
- Pigou, A.C., 2005. *The Economics of Welfare: Volume I*. Cosimo, New York, London.
- Purvis, B, Mao, Y., Robinson, D. 2019. Three pillars of sustainability: in search of conceptual origins. *Sustainability Science* 14:681-695.
- R Core Team (2021). *A language and environment for statistical computing*. R Foundation for Statistical Computing. Vienna. <https://www.R-project.org/>.
- Rees, B., Campbell, L., & Williamson, P. 2002. The economic value of mussel aquaculture in New Zealand. *Aquaculture Economics & Management*, 6: 225-239.
- Rees, W., Wackernagel, M., 1996. *Our Ecological Footprint: Reducing Human Impact on the Earth*. New Society Publishers, Gabriola Island, BC. New Society Publishers.
- Schepers, J., van Wijnen, H., & van den Burg, E. 2010. Economic value of mussel aquaculture in the Netherlands. *Aquaculture Economics & Management*, 14: 303-316.
- Sheppard, V. 2021. *Research Methods for the Social Sciences: An Introduction*. Vancouver/Vitoria. BC Campus, 415p.
- Silva, T. H., Joana Mesquita-Guimarães, J., Henriques, B., Silva, F.S., Fredel, M.C. 2019. The Potential Use of Oyster Shell Waste in New Value-Added By-Product. *Resources* 2019, 8(1), 13;
- Soares, C.E. & Henry-Silva, G.G. 2019. Emission and absorption of greenhouse gases generated from marine shrimp production (*Litopenaeus vannamei*) in high salinity. *Journal of Cleaner Production* 218, 367-376.
- Sokal, R. R., & Rohlf, F. J. 1995. *Biometry: The principles and practice of statistics in biological research*, 3rd ed. W.H. Freeman, New York. 887p.
- Soto D, Aguilar-Manjarrez J, Hishamunda N, eds. (2008) *Building an ecosystem approach to aquaculture*. FAO/Universitat de les Illes Balears Expert Workshop. 7–11 May 2007, Palma de Mallorca, Spain. FAO Fisheries and Aquaculture Proceedings. No. 14. FAO, Rome.
- Steffen et al. 2015. Planetary Boundaries: Guiding human development on a changing planet. *Science* Vol. 347 no. 6223
- Stockholm Resilience Center, 2022. What is resilience? Available at:  
<https://www.stockholmresilience.org/research/research-news/2015-02-19-what-is-resilience.html>, assessed on March 15th, 2022.
- Strand Å, Rydstedt A, Lindblom E, 2022. Mapping existing and emerging LTS aquaculture in the Atlantic Region, AquaVitae, Tromsø, 18 pp.

- Sverdrup, H., Koca, D., & Ragnarsdottir, K. V. 2013. Peak Metals, Minerals, Energy, Wealth, Food and Population: Urgent Policy Considerations for a Sustainable Society. *Journal of Environmental Science and Engineering B2*, (2013), 189-222.
- Troell, M., B. Costa-Pierce, S. Stead, R.S. Cottrell, C. Brugere, A. Farmery, D. Little, Å. Strand, D. Soto, R. Pullin, M. Beveridge, K. Salie, R. Yossa, P. Moraes-Valenti, J. Blanchard, J. Dresdner, P. James, E. Allison, C. Devaney and U. Barg. 2023. Perspectives on aquaculture's contribution to the SDGs for improved human and planetary health. Background paper for FAO Shanghai Symposium - "Aquaculture and the SDGs". Paper published during the Global Conference on Aquaculture Millennium +20.
- UN (United Nations), 1992. Agenda 21. In: United Nations Sustainable Development, United Nations Conference on Environment & Development. United Nations, New York.
- UN (United Nations), 2007. Indicators of Sustainable Development: Guidelines and Methodologies, 3rd ed. United Nations, New York.
- UN (United Nations), 2015. Transforming Our World: The 2030 Agenda for Sustainable Development. United Nations, Department of Economic and Social Affairs.
- UN (United Nations), 2022. Sustainable Development Goals. Available at: <https://sdgs.un.org/goals>, accessed March 27th 2022.
- Valenti, W.C., Kimpara, J.M., Preto, B.L., 2011. Measuring aquaculture sustainability. *World Aquaculture* 42 (3), 26–30.
- Valenti, W.C.; Kimpara, J.M.; Preto, B.L. & Moraes-Valenti, P. 2018. Indicators of sustainability to assess aquaculture systems. *Ecological Indicators*, 88:402-4013.
- Walton, M.E.M., Vilas C., Cañavate J.P., Gonzalez-Ortegon E., Prietob, A., van Bergeijk S.A., A.J. Greenc, S.A., Librero M., Mazuelos N., Le Vay L. 2015. A model for the future: Ecosystem services provided by the aquaculture activities of Veta la Palma, Southern Spain. *Aquaculture* 448: 382–390.
- World Bank (2021) Carbon Pricing Dashboard. Gold Standard mechanism. Available at <[https://carbonpricingdashboard.worldbank.org/carbon\\_crediting](https://carbonpricingdashboard.worldbank.org/carbon_crediting)>. Accessed in December 2022.
- WWF. 2020. Living Planet Report 2020 - Bending the curve of biodiversity loss. Almond, R.E.A., Grooten M. and Petersen, T. (Eds). WWF, Gland, Switzerland.
- Yuan, J., Xiang, J., Liu, D.,....et al. 2019. Rapid growth in greenhouse gas emissions from the adoption of industrial-scale aquaculture. *Nature Climate Change*, 9:318–322.
- Ziegler, F., Langeland, M., Guillen, J. & Druon, J.N. 2022. Scientific, Technical and Economic Committee for Fisheries (STECF) – Marketing standards: review of proposed sustainability criteria/indicators for aquaculture (STECF-22-13). Publications Office of the European Union, Luxembourg, 2022.

Appendix 12) to the AV IRG, AV CS and WP leaders, and other stakeholders.

To compensate for the limited data availability for environmental, social and economic indicators, alternative sources of data were explored, and a cooperation with the Aquaculture Sustainability Research Network in Brazil was established. This cooperation enabled access to the required data for analysis of environmental, social and economic sustainability from a number of production systems already available in a database.

Consequently, this inferred a necessary adjustment of the objective of the deliverable to focus less on the main weaknesses and strengths of the LTS aquaculture sector around the Atlantic in favour of a similar analysis limited to systems in Brazil. These systems were then used to evaluate the applicability of the framework for analysis of the environmental, social and economic sustainability dimensions of LTS aquaculture. The analysis of the main weaknesses and strengths of the governance sustainability dimension of different LTS production systems was still possible to achieve.

## 3.2 Data Analyses

### 3.2.1 Analysis of environmental, social and economic data

Primary data collected directly in each culture system and obtained from the Aquaculture Sustainability Research Network database were used. The general methodology to obtain environmental, social and economic data is described in Flickinger et al. (2019; 2020), David et al. (2021), Pereira et al. (2021), Fialho et al. (2021) and Henry-Silva et al. (2022), but were in short:

- Water quality was determined in situ using multiparameter probes.
- Total nitrogen (N) and carbon (C) content in the yield, water, sediment, diet, other supplies, and other compartments, as well as exchanged with the environment, were obtained by elemental analyses.
- Total phosphorus (P) and energy contents in each compartment and exchanged with the environment were obtained by spectrophotometry and combustion in calorimeters, respectively.
- In open-water farming systems, such as the culture of macroalgae and filtering mollusks on longlines, control points away from the culture were used to contrast data on water and sediment obtained inside the culture area.
- All costs and revenues were obtained in the real markets used by farmers.

All data were reviewed and checked for inconsistencies. Environmental data were standardized when appropriate and converted into the same units to allow comparisons among farms and systems. Economic data were primarily obtained in Reals, the Brazilian currency, in different years. All original values were updated to November 2022 using official monetary indices (IPCA) and converted into US\$. The exchange rate was R\$ 1.00 = US\$ 0.19. The converted values (in US\$) were used to compute the economic parameters, which were further used to calculate the economic indicators and some social indicators that depend on economic data. The current values of some revenue prices and costs were obtained in the market (in November 2022) to verify the consistency and robustness of the transformations applied.

The ecosystem services and disservices (see D6.2; Marinho et al., 2022) provided by the LTS aquaculture systems considered in the present study were the absorption or emission of greenhouse gases, N, P and C. Thus, the services evaluated were water purification from N, C and/or P through retention inside the system or in the yield, and climate regulation, by greenhouse gas absorption. The disservices evaluated were eutrophication, potentially caused by the nutrient-rich effluents generated by some production and global warming potential, by the emissions of greenhouse gases. The boundary limits were the production systems and their surrounding environment.

The absorptions and emissions of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O by diffusion and emissions by bubbling were measured in each system during the day and at night. Then, the total emission/absorption of each gas during a culture cycle were determined. Next, all values were converted into CO<sub>2</sub> equivalents (CO<sub>2</sub>e) using the Global Warming Potential (GWP) for 100 years, according to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2021). Finally, the emission or absorption associated with the production of 1 tonne of the farmed organisms (in CO<sub>2</sub>e) was computed for each system.

Monetized estimates of the ecosystem services and disservices values were obtained by quantifying total greenhouse gases, N, P and C absorption or emission during a culture cycle and their respective values in the marketing, when it existed, and/or their removal costs. It was agreed that monetary values estimated by WP7 should be used in this deliverable. However, in the end this was not possible because both D6.3 and D7.5 were scheduled to be finalized by the same deadline and as different CSs were selected for the two deliverables. Therefore, the ecosystem services and disservices were estimated using the method developed by the UNESP team in the past ten years. This same method was used to determine the values of ecosystem services and disservices in D7.5 for the oyster sector. The carbon price adopted was US\$ 3.94/t of CO<sub>2</sub>e, which was obtained from the Carbon Pricing Dashboard (World Bank, 2021). The value of US\$ 10.67/kg of N released was obtained from the Nitrogen Control Program of the Connecticut Department of Energy and Environmental Protection (CTDEEP, 2021). The average P value of US\$ 35.84/kg of phosphorous retained was obtained from Molinos-Senante et al. (2011). These values were used as positive and negative externalities for computing economic sustainability indicators (Valenti et al., 2018).

In total, 61 indicators were calculated: 25 environmental, 20 social, and 16 economic (Appendix 1). Each indicator reflects one aspect of sustainability and the desired states/sustainability aspects previously defined (Appendix 1, D6.1, Lindblom et al., 2021). All desired states defined in D6.1 (Lindblom et al., 2021) except for one (Shows capacity to keep a skilled staff, Economic domain) were covered by at least one indicator. Indicators are generally interpreted using a comparative approach (EC, 2021). Thus, benchmarks and performance scales were used to compare indicators among the systems defined in section 3.2.1 and detect the strengths and weaknesses of the sustainability of LTS aquaculture. The procedures are described below.

The value of each indicator was standardized using the following equation:

$$S_i = [(O_i)/(\sum_1^n O_i)/n]$$

in which:

S<sub>i</sub> = Standardized value of the indicator for the system *i*

$O_i$  = Obtained value of the indicator for the system  $i$

$n$  = number of systems analyzed

To provide a more holistic assessment, each indicator was converted into a performance scale, with scores ranging from 0 to 1, according to Valenti et al. (2018). This procedure follows the rationale used in multivariate analyses and allows combining indicators of different features, measured in different unities and magnitudes. Thus, indicators can be consolidated according to categories and domains of interest. This also allows computing sub-indices for specific groupings, in this case either sustainability aspects, sustainability domains or overall sustainability performance. Values close to zero contribute little to sustainability, and close to 1 contribute strongly to sustainability.

If an indicator measured an increase in sustainability, the original values were transformed according to the following equation:

$$P_{i,j} = \sqrt{I_{i,j}} / \text{Max}\sqrt{I_{i,j}}$$

Conversely, if an indicator measured a decrease in sustainability, the following equation was used:

$$P_{i,j} = \text{Min}\sqrt{I_{i,j}} / \sqrt{I_{i,j}}$$

in which:

$P_{i,j}$  = performance value of the indicator  $i$  in the system  $j$ ,  $j = 1, \dots, n$

$I_{i,j}$  = original value of the indicator  $i$  in the system  $j$

$\text{Max}$  = the largest value of the indicator  $i$  within the  $n$  studied systems

$\text{Min}$  = the lowest value of the indicator  $i$  within the  $n$  studied systems

Indicators that assume negative values were coded by summing a constant to obtain positive numbers, according to Sokal & Rolf (1995). It should be noted that  $P_{i,j}$  is not an indicator, but only a transformation of all indicators to standardize the scale. The two formulae were used to obtain values in which sustainability increase from zero to 1.

All indicators were compared among the systems defined in section 4.1.1. To facilitate analysis of strengths and weaknesses in different systems, the sustainability aspects and associated indicators were consolidated into six categories per sustainability domain as illustrated in figure 6.

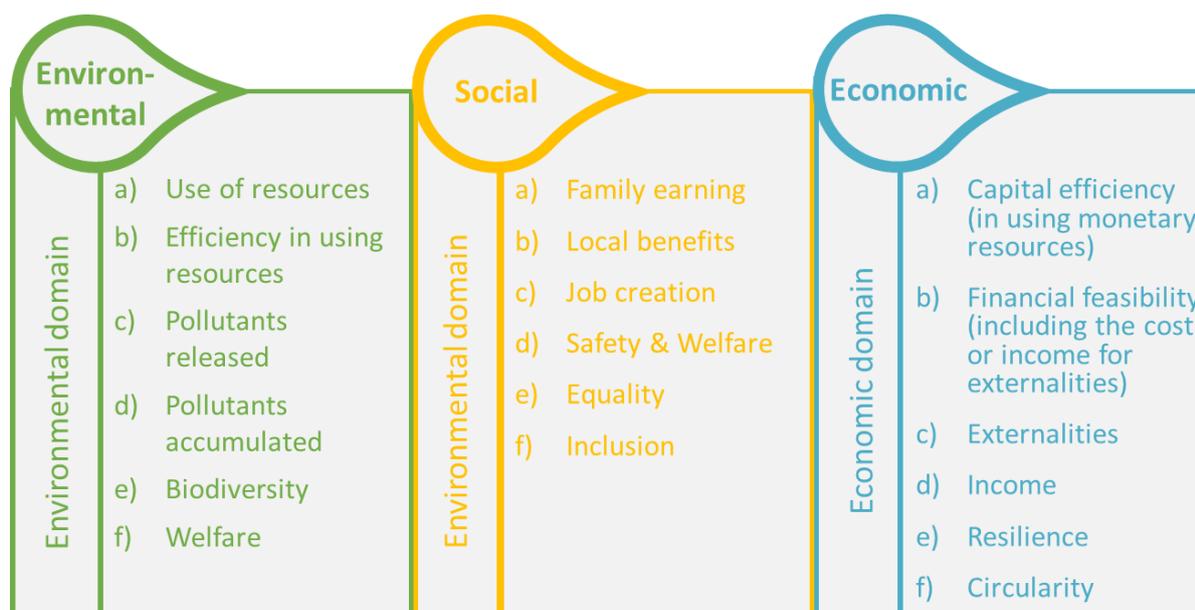


Figure 6. Categorisation of the sustainability aspects and associated indicators per sustainability domain.

For clarification of which indicator was included in which group, please refer to table 4 and appendix 1. Sub-indices were computed for each category by calculating the arithmetic mean of the indicators included in each category. The arithmetic mean of the six sub-indices represented the subindex of each dimension. Multidimensional diagrams of species groups were made for comparisons.

### 3.2.2 Reference systems for environmental, social, and economic analysis

To assess the strengths and weaknesses of LTS aquaculture, the analysed LTS production systems were compared to the production of higher trophic species (HTS). For this, the production of tilapia (*Oreochromis niloticus*) and whiteleg shrimp (*Litopenaeus vannamei*) were chosen as models of vertebrates and invertebrates, respectively. In intensive production systems, tilapia have been fed with diets containing fish meal and thus, the effective trophic level increases compared to in nature. Both species are produced in high volumes worldwide and, thus, are relevant for comparisons. Data for these species were acquired from the database of the Sustainable Aquaculture Research Network and were obtained for area 41 (Atlantic, Southwest) to correspond to the other analysed systems. Updates on economic values were done when necessary, as described in section 3.2.1. Tilapia data were obtained from 8 farms operated in land-based ponds and surface-based net-cages in tropical and subtropical regions. More information on the systems and data collection is available in Moura et al. (2016), Fialho et al. (2021), Godoi et al. (2022) and Henry-Silva et al. (2022). Whiteleg shrimp data were obtained from 8 land-based marine farms of 11 to 550 ha in size, placed in a tropical region, and stocked at 10 to 100 juveniles/m<sup>2</sup>. Details from such farms and data collected were provided by Costa (2019). When data cited in the text came from other sources, citations are provided.

### 3.2.3 Analysis of governance data

The governance data were semi-quantitative and ordinal, and in addition, qualitative data was received as comments provided in the questionnaire after attribution of the score for each question. All assessments were consolidated and analysed together. The ordinal data were analyzed by descriptive statistics. Each question was planned to correspond to data needed to compute one

indicator of governance sustainability. All sustainability aspects (Appendix 1; D6.1; Lindblom et al., 2021) were covered.

In addition, multivariate analyses were performed using the R Statistical analysis software (R core Team, 2021). The ggbiplot and factoextra packages were used in the analyses. A principal component analysis (PCA) was carried out to summarize the governance characteristics associated to the different production systems. The PCA (prcomp function) analysis was based on a matrix correlation, for which all evaluated attributes were standardized and had the same importance. For standardization (scale function), each data was subtracted from the mean of the corresponding variable and, subsequently, this value was divided by the standard deviation of the variable. Standardization makes the evaluated characteristics more comparable, making those with greater deviations not stand out in the analysis. A hierarchical cluster analysis (hclust function) was also applied to group the observations based on their similarities, and pairs of clusters were merged as one moved up the hierarchy. To do so, the Ward method and the Euclidean distance were used, with standardized data (scale function). The Ward method considers the sum of squares of the differences between each individual and the average of individuals in a class, and the Euclidean distance measure dissimilarity. The results were presented in a dendrogram (fviz\_dend function). Additionally, a partitioned cluster analysis, using the k-means method (kmeans function), was also applied to categorize the production systems from the dissimilarities of the evaluated aspects. The k-means method aims to partition n observations into k clusters by minimizing the within-cluster sum of squares of the Euclidean distances. The results were plotted in a graph (fviz\_cluster function). Five cluster groups were identified in the analysis, and data from each group were pooled and compared among the groups.

The data were also pooled for all Atlantic systems studied for a general analysis of sustainability. As for the environmental, social and economic domain, the indicators were clustered in sub-groups, each describing one specific aspect of governance (Figure 7). For each category, a subindex of governance was computed. A general index of governance of LTS aquaculture around the Atlantic was also computed as described in section 3.2.1. Moreover, the level of sustainability of each feature of a desired governance represented by each indicator was computed, and the frequency distribution of each score obtained in the questionnaires was illustrated using bar diagrams (Appendix 3).

### 3.2.4 Calculation of the index of sustainability

The weighted mean of the environmental, social, economic and governance sub-indices of sustainability was used to compute a general sustainability index for each system or group of systems.

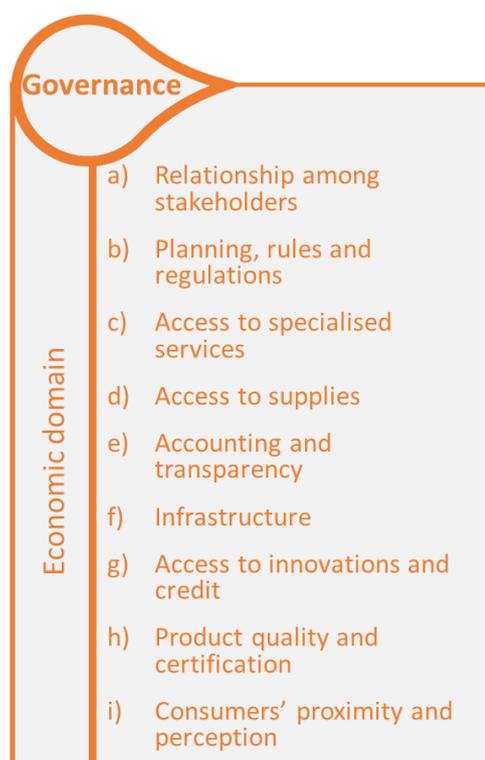


Figure 7. Categorisation of the sustainability aspects and associated indicators in the governance domain.

Considering models 1 and 2 of sustainability (see section 2.2), this index was computed by assigning the same weights to each dimension. For model 3, the weighted mean was calculated, weighing 1.5 for environmental, 1.25 for social and 1 for economic and governance dimensions. These weights were arbitrarily attributed, assuming that the importance of the environmental dimension was 50% higher than the importance of economic and governance dimensions and 20% higher than the social dimension. Similarly, the social dimension was assumed to be 25% more important than the economic and governance dimensions. The values were computed according to the following equation:

$$IS = \left( \sum_{i=1}^4 Subindex_i \times w_i \right) / \sum_{i=1}^4 w_i$$

In which IS = Index of sustainability, i = each of the four dimensions of sustainability, i = environmental, social, economic and governance, and  $w_i$  = weight assigned to the dimension i of sustainability.

## 4. Results and Discussion

Indicators are variables defined to reflect a phenomenon or a process in a simplified way (Valenti et al., 2018). They measure specific attributes of a system by reducing its complexity and can be used to describe a system, compare different systems or the evolution of the same system over time (Fezzardi et al., 2013). Their fluctuations reveal the variation in the elements that they represent. In the present study, the indicators of sustainability measured different features of the LTS aquaculture systems analysed as models to understand the sustainability in LTS production. The scope of the study was the systems themselves, and hence, the boundary of the study was the farms. For IMTA systems, the indicators were computed taking into account the production of all species, although the target species was the tambaqui fish.

### 4.1 Aquaculture systems analyzed

#### 4.1.1 Data for environmental, social and economic indicators

Based on the above-described approach, data from the grow-out stage of production was obtained from 34 farms and 48 culture units (longlines, surface-based rafts and net-cages, bottom-based tables and inland ponds) for the environmental, social, and economic dimensions. Farms were located in the South-Atlantic region (Area 41 Southwest Atlantic – See the Assessment Domain (AD), Strand et al., 2022). This area was further subdivided into tropical and subtropical areas because of the widely varying climatic conditions. The systems were grouped into nine different arrangements based on the AD characteristic elements (Table 1), as follows:

1. Red Macroalgae, monoculture, tropical, near-shore, surface-based ropes (longlines)
  - *Hypnea pseudomusciformis* (hypnea, red seaweed)
  - 1 farm (3 longlines)
  - Annual production about 2 t
2. Filtering mollusks (bivalves), monoculture, tropical (Amazon region), near-shore, suspended-based rafts
  - *Crassostrea gazar* (mangrove oyster)
  - 15 farms (in the same community)

- Annual production about 0.4 t/farm
3. Filtering mollusks (bivalves), monoculture, sub-tropical, near-shore, bottom-based rafts
    - *Crassostrea gazar* (mangrove oyster)
    - 9 farms (in the same community)
    - Annual production about 0.5 t/farm
  4. Freshwater fish, monoculture, tropical, land-based ponds (fresh water)
    - *Colossoma macropomum* x *Piaractus brachipomum* (hybrid, tambatinga)
    - 3 farms (9 ponds)
    - Annual production about 49 t/farm
  5. Freshwater fish, monoculture, tropical, surface-based (net-cages) inside freshwater reservoir
    - *Colossoma macropomum* (tambaqui)
    - 3 farms (3 net-cages)
    - Annual production about 2 t/farm
  6. Freshwater fish, monoculture, sub-tropical, land-based ponds (fresh water)
    - *Colossoma macropomum* (tambaqui)
    - 1 farm (3 ponds)
    - Annual production about 5.3 t
  7. Freshwater fish, polyculture (IMTA), sub-tropical, land-based ponds (fresh water)
    - *Colossoma macropomum* (tambaqui) + *Macrobrachium amazonicum* (Amazon river prawn)
    - 1 farm (3 ponds)
    - Annual production about 5 t
  8. Freshwater fish, polyculture (IMTA), sub-tropical, surface-based (net-cages) inside ponds (fresh water)
    - *Colossoma macropomum* + *Macrobrachium amazonicum* (Amazon river prawn)
    - 1 farm (3 ponds)
    - Annual production about 3.8 t

Table 1. Summary of the LTS aquaculture systems for which enough data was obtained to calculate environmental, social and economic indicators. The organism groups are colour coded with red, green and blue for macroalgae, filtering mollusks and freshwater fish, respectively, and species names are colour coded similarly to illustrate organism group association in polyculture systems. All major organism groups are monoculture systems; polyculture systems are labeled "IMTA" and denoted in yellow. Production location, near-shore or land-based, is denoted with light-blue and brown, respectively, and region, tropical or sub-tropical, is denoted in red and orange, respectively. No. = number.

Organism group	Species	Production location	Region	Production system	Total No. farms	Total No. of culture unities
Macroalgae (Red & Green)	<i>Hypnea pseudomusciformis</i> ( <i>Hypnea</i> , red seaweed)	Near-shore	Tropical	Surface-based ropes (longlines)	1	3
Filtering mollusks (bivalves)	<i>Crassostrea gazar</i> (mangrove oyster)	Near-shore	Tropical	Suspended-based rafts	15	15
		Near-shore	Sub-tropical	Bottom-based rafts	9	9
Freshwater fish	<i>Colossoma macropomum</i> x <i>Piaractus brachipomum</i> (hybrid, tambatinga)	Land	Tropical	Land-based ponds (fresh water)	3	9
	<i>Colossoma macropomum</i> (tambaqui)	Land	Sub-tropical	Land-based ponds (fresh water)	1	3
		Land	Tropical	Surface based (net-cages) inside freshwater reservoir	3	3

IMTA	<i>Colossoma macropomum</i> (tambaqui)	Land	Sub-tropical	Land-based ponds (fresh water)	1	3
	<i>Macrobrachium amazonicum</i> (Amazon river prawn)	Land	Sub-tropical	Surface based (net- cages) inside ponds (fresh water)	1	3

No data were obtained for brown macroalgae, abalone and echinoderms; therefore, they were excluded from further analysis of environmental, social, and economic indicators.

#### 4.1.2 Data for governance indicators

The governance questionnaire was filled by representatives of 37 aquaculture systems. The systems were defined as the combination of different domain elements, in this case, organism groups and geographical regions in the areas covered by the AV scope: Europe = Area 27 Atlantic, Northeast; North America = Area 21 Atlantic, Northwest; Brazil = Area 41 Atlantic, South west; South Africa and Namibia = Area 47 Atlantic, Southeast. Data were obtained from Canada, USA, Sweden, Norway, Denmark, Faroe Island, France, Spain, South Africa, Namibia, and Brazil. Data from CS2 (macroalgae), CS3 (land-based IMTA with abalone, algae and fish), CS4 (sea-based IMTA with abalone, algae, bivalve mollusks and sea cucumber), CS5 (bioflock IMTA with shrimp, filtering mollusks, macroalgae and marine fish), CS6 (sea urchin), CS8 (oysters), CS9 (mussels), CS10 (freshwater fish) and WP7 was obtained. In addition, data were obtained from the IRG and other stakeholders around the Atlantic Ocean. The data were pooled by organism group and by geographical areas as defined in the AD (Strand et al., 2022) as follows (Table 2 and 3):

##### 1. Red and Green Macroalgae

- Brazil – 3 regions  
Hypnea (*Hypnea pseudomusciformis*), elkhorn sea moss (*Kappaphycus alvarezii*), farmed in suspension (longline) culture

##### 2. Brown Macroalgae

- USA – 2 regions  
Sugar Kelp (*Saccharina latissima*), farmed in suspension (longline) culture
- Faroe Island – 1 region  
Sugar Kelp (*Saccharina latissima*), farmed in suspension (longline) culture
- Sweden – 1 region  
Sugar Kelp (*Saccharina latissima*), farmed in suspension (longline) culture

##### 3. Filtering Mollusks (Bivalves)

- Brazil – 11 regions  
Mangrove oyster (*Crassostrea gazar*), brown mussel (*Perna perna*), scallop (*Nodipecten nodosus*), farmed in suspension (longline) and bottom (trays, tables) systems
- USA – 8 regions  
Eastern oyster (*Crassostrea virginica*), blue mussel (*Mytilus edulis*), hard clam (*Mercenaria mercenaria*), Farmed in off-bottom cages in mid-water columns and floating longlines
- Canada - 2 regions  
Pacific oysters (*Crassostrea gigas*), eastern oysters (*Crassostrea virginica*), blue mussels (*Mytilus edulis*), Manila clam (*Ruditapes phillipinarum*) and other clams, and scallops, [mainly the giant or sea scallop (*Placopecten magellanicus*), the Northern Bay Scallop (*Argopecten irradians irradians*) and the Pacific or Qualicum scallop (*Patinopecten caurinus* x *P. yessoensis* hybrid)], farmed in suspension (longline) and bottom (trays, tables) system culture
- Namibia – 1 region

Pacific oyster (*Crassostrea gigas*), mainly farmed on long lines and some in ponds

- Sweden - 2 regions

European flat oyster (*Ostrea edulis*), farmed in surface-based cages (floating) and suspended longlines (floating)

#### 4. Abalone

- France – 1 region

South African abalone (*Haliotis tuberculata*) and European abalone (*Haliotis midae*), farmed in land-based IMTA together with *Ulveella lens* (Green algae), *Ulva* sp and *Gracilaria* sp (Green & red macroalgae), *Holothuria forskali* and *Holothuria sanctori* (Sea cucumber)

- South-Africa – 1 region

*Haliotis midae* & *Haliotis tuberculata*, farmed in IMTA with macroalgae and filtering mollusks

#### 5. Echinoderms (sea urchins)

- Norway – 1 region, farmed in land-based indoor tanks

Green sea urchin (*Strongylocentrotus droebachiensis*)

- Spain – 1 region,

Purple sea urchin (*Paracentrotus lividus*), farmed in land-based indoor tanks

#### 6. Freshwater Fish

- Brazil – 1 region

Tambaqui (*Colossoma macropomum*), farmed in ponds & net-cages

#### 7. General Mariculture

- Norway – 1 region

Mainly Atlantic salmon (*Salmo salar*), farmed in ocean net-cages

Table 2. Distribution in the geographical area defined in D6.1 (Lindblom et al. 2021) and the number of responses per organism group and geographical area.

Organism group/ geographical area	Europe (Area 27 Atlantic, Northeast)	North America (Area 21 Atlantic, Northwest)	Brazil (Area 41 Atlantic, Southwest)	South Africa and Namibia (Area 47 Atlantic, Southeast)
Red/green macroalgae			3	
Brown macroalgae	2	2		
Filtering Mollusks (Bivalves)	2	10	11	1
Abalone	1			1
Echinoderms (sea urchins)	2			
Freshwater fish (tambaqui)			1	
Total number of responses by area	7 (8 including general mariculture)	12	15	2

Table 3. Summary of the LTS aquaculture systems for which data was obtained to calculate governance indicators. The organism groups and species are colour-coded with red and brown for macroalgae, green for filtering mollusks, pale pink and orange for abalone and holothurians, respectively, and greyblue for freshwater fish. Species names are colour coded similarly to illustrate organism group association in polyculture systems. All major organism groups are farmed in monoculture and polyculture systems, except holothurians, which are only farmed in monoculture. No. = number.

Organism group/ geographical area	Europe (Area 27 Atlantic, Northeast)	North America (Area 21 Atlantic, Northwest)	Brazil (Area 41 Atlantic, Southwest)	South Africa and Namibia (Area 47 Atlantic, Southeast)
Red/green macroalgae			<i>Hypnea</i> ( <i>Hypnea pseudomusciformis</i> ) Elkhorn sea moss ( <i>Kappaphycus alvarezii</i> )	

<b>Brown macroalgae</b>	Sugar Kelp ( <i>Saccharina latissima</i> )	Sugar Kelp ( <i>Saccharina latissima</i> )		
<b>Filtering Mollusks (Bivalves)</b>	European flat oyster ( <i>Ostrea edulis</i> )	Eastern oyster ( <i>Crassostrea virginica</i> ) Pacific oysters ( <i>Crassostrea gigas</i> ) Blue mussel ( <i>Mytilus edulis</i> ) Hard clam ( <i>Mercenaria mercenaria</i> ) Manila clam ( <i>Ruditapes philippinarum</i> ) Giant or sea scallop ( <i>Placopecten magellanicus</i> ) Northern Bay Scallop ( <i>Argopecten irradians irradians</i> ) Pacific or Qualicum scallop ( <i>Patinopecten caurinus</i> x <i>P. yessoensis</i> hybrid) Other clams and scallops.	Mangrove oyster ( <i>Crassostrea gazar</i> ) Brown mussel ( <i>Perna perna</i> ) Scallop ( <i>Nodipecten nodosus</i> )	Pacific oyster ( <i>Crassostrea gigas</i> )
<b>Abalone</b>	South African abalone ( <i>Haliotis tuberculata</i> ) and European abalone ( <i>Haliotis midae</i> ).			South African abalone ( <i>Haliotis tuberculata</i> ) and European abalone ( <i>Haliotis midae</i> ).
<b>Echinoderms (sea urchins)</b>	Green sea urchin ( <i>Strongylocentrotus droebachiensis</i> ) Purple sea urchin ( <i>Paracentrotus lividus</i> )			
<b>Freshwater fish (tambaqui)</b>			Tambaqui ( <i>Colossoma macropomum</i> )	

## 4.2 Environmental, social and economic sustainability of LTS aquaculture

### 4.2.1. Environmental sustainability

Natural resources are limiting factors for all production systems (FOESA, 2010). Therefore, systems that use less natural resources to produce the same yield are more sustainable. Space, fresh water, energy and essential nutrients, such as N and P, are critical resources. The results per indicator in this study is presented in tables 4 and 5 and are the basis for the results discussions in this chapter. The results are presented by indicator, yet reported in sections related to the classification into major themes as discussed in section 3.2.1.

Table 4. Indicators of environmental sustainability obtained for the 8 LTS systems studied. Negative values of PGW mean that, in balance, the system absorbs greenhouse gases from the atmosphere, whereas positive values indicate that the system emits them. Monoc. = monoculture; sub-trop. = subtropical; IMTA = integrated multi trophic aquaculture; "-" = no data. Letters a to f means the subgroups cited in section 3.2.1.

Case		1.	2.	3.	4.	5.	6.	7.	8.	
Analysis category	Organism group	Red macro-algae	Filtering moluscs				Fish			
	Type of production <sup>1</sup>	M	M	M	M	M	M	IMTA	IMTA	
	Climate <sup>2</sup>	T	T	ST	T	T	ST	ST	ST	
	System type <sup>3</sup>	SBR	SR	BBT	LBP	SBNC	LBP	LBP	SBNC	
	N farms (N total units)	1 (3)	15 (15)	9 (9)	3 (9)	3 (3)	1 (3)	1 (3)	1 (3)	
a	Use of space	ha/t	1.25	2.34	0.03	0.10	<0.01	0.24	0.26	0.92
a	Dependence of water	m <sup>3</sup> /t	0	0	0	2 425 000	88	18 464	15 353	77 576

a	Use of energy	MJ/t	2.61	0.017	5 641	25 800	-	107 125	116 554	344 510
a	Proportion of Renewable Energy	%	100	100	13	97	-	90	90	97
a	Use of Nitrogen	kg/t	2.9	3.1	1.1	72	102	59	50	40
a	Use of Phosphorous	kg/t	0.13	0.60	0.19	24	20	13	11	8.6
b	Efficiency in the Use of Energy	%	383	109	31	22	21	22	18	4.8
b	Efficiency in the Use of Nitrogen	%	894	2820	722	32	20	46	52	74
b	Efficiency in the Use of Phosphorous	%	1860	2354	637	22	20	18	23	33
b	Production actually used	%	100	23	23	45	45	51	51	51
c	Potential of Global Warming	kg/t	-852	6.2	-2 630	-459	-6.1	-301	-254	2 334
c	Potential of Organic Pollution	kg/t	5.2	-	0.33	4	0.34	43	58	131
c	Potential of Eutrophication of Phosphorous	kg/t	-	-	<0.01	0.08	<0.01	14	22	45
c	Potential of Eutrophication of Nitrogen	kg/t	1.0	-	0.02	2.3	0.03	-	-	-
c	Potential of Siltation	kg/t	8.4	-	3 310	40	15	86	771	662
c	General Chemical Pollution	kg/t	0	0	0	0	0	0	0	0
c	Pollution by hormones	kg/t	0	0	0	0	0	0	0	0
c	Pollution by heavy metals	kg/t	0	0	0	0	0	0	0	0
d	Accumulation of Phosphorous	kg/t	6.2	-	0.03	13	-	1.4	1.6	2.4
d	Accumulation of Particulate Material	kg/t	3 189	-	3 310	-	-	-	-	-
d	Accumulation of Organic Matter	kg/t	0.69	-	1 160	1 016	-	194	220	860
e	Risk of Farmed species	-	2	2	2	10	11	11	11	11
e	Impacts of seed acquisition	9	9	9	9	2	2	2	2	2
f	Fulfillment Natural Needs	%	100	83	83	67	50	67	67	50
f	Environmental comfort	%	100	67	86	75	71	71	71	71

<sup>1</sup> M=Monoculture, IMTA=polyculture

<sup>2</sup> T=tropical, ST=sub-tropical

<sup>3</sup> SBR: surface-based ropes, SR: suspended rafts, BBT: bottom-based tables, LBP: land-based ponds, SBNC: surface-based net-cages.

*Table 5. Benchmarking values obtain after data standardization. Each value represents the proportion in relation to the mean of all systems. Values higher than 1 indicate that the system showed larger values than the mean of the 8 systems, whereas data below 1 indicate values lower than the mean. Monoc. = monoculture; sub-trop. = subtropical; IMTA = integrated multi trophic aquaculture; "-" = no data. Letters a to f means the subgroups cited in section 3.2.1.*

Case		1.	2.	3.	4.	5.	6.	7.	8.
Analysis category	Organism group	Red macro-algae	Filtering moluscs				Fish		
	Type of production <sup>1</sup>	M	M	M	M	M	M	IMTA	IMTA
	Climate <sup>2</sup>	T	T	ST	T	T	ST	ST	ST
	System type <sup>3</sup>	SBR	SR	BBT	LBP	SBNC	LBP	LBP	SBNC
	N farms (N total units)	1 (3)	15 (15)	9 (9)	3 (9)	3 (3)	1 (3)	1 (3)	1 (3)
a	Use of space	1.94	3.66	0.05	0.16	<0.01	0.37	0.40	1.43
a	Dependence of water	<0.01	<0.01	<0.01	7.65	<0.01	0.06	0.05	0.25
a	Use of energy	<0.01	<0.01	0.07	0.30	-	1.25	1.36	4.02
a	Proportion of Renewable Energy	1.19	1.19	0.16	1.16	-	1.07	1.08	1.15
a	Use of Nitrogen	0.07	0.08	0.03	1.74	2.47	1.43	1.20	0.98

a	Use of Phosphorous	0.01	0.06	0.02	2.50	2.05	1.34	1.12	0.89
b	Efficiency in the Use of Energy	4.16	1.18	0.34	0.27	0.29	0.24	0.19	0.05
b	Efficiency in the Use of Nitrogen	1.50	4.74	1.22	0.03	0.03	0.08	0.09	0.12
b	Efficiency in the Use of Phosphorous	2.96	3.74	1.01	0.03	0.03	0.03	0.04	0.05
b	Production actually used	2.07	0.47	0.47	0.92	0.92	1.05	1.05	1.05
c	Potential of Global Warming	0.75	1.12	<0.01	0.92	1.11	0.99	1.01	2.10
c	Potential of Organic Pollution	0.15	<0.01	0.01	0.12	0.01	1.25	1.67	3.80
c	Potential of Eutrophication of Phosphorous	<0.01	-	<0.01	0.01	-	1.03	1.62	3.34
c	Potential of Eutrophication of Nitrogen	1.20	-	0.02	2.74	0.04	-	-	-
c	Potential of Siltation	0.01	-	4.74	0.06	0.02	0.12	1.10	0.95
c	General Chemical Pollution	0	0	0	0	0	0	0	0
c	Pollution by hormones	0	0	0	0	0	0	0	0
c	Pollution by heavy metals	0	0	0	0	0	0	0	0
d	Accumulation of Phosphorous	1.51	-	0.01	3.17	-	0.34	0.39	0.59
d	Accumulation of Particulate Material	1.47	-	1.52	0.01	-	<0.01	<0.01	<0.01
d	Accumulation of Organic Matter	<0.01	-	2.02	1.77	-	0.34	0.38	1.50
e	Risk of Farmed species	0.27	0.27	0.27	1.33	1.47	1.47	1.47	1.47
e	Impacts of seed acquisition	1.95	1.95	1.95	0.43	0.43	0.43	0.43	0.43
f	Fulfillment Natural Needs	1.41	1.18	1.18	0.94	0.71	0.94	0.94	0.71
f	Environmental comfort	1.31	0.87	1.12	0.98	0.93	0.93	0.93	0.93

<sup>1</sup> M=Monoculture, IMTA=polyculture

<sup>2</sup> T=tropical, ST=sub-tropical

<sup>3</sup> SBR: surface-based ropes, SR: suspended rafts, BBT: bottom-based tables, LBP: land-based ponds, SBNC: surface-based net-cages.

#### 4.2.1.a. Use of resources

Competition for space in coastal and inland areas is intense. The indicator **use of space** measures the area necessary to produce 1 tonne (t) of product (live fresh weight, i.e. macroalgae before drying and the full mollusk, i.e., meat plus shell in live animals). In this study, red macroalgae and filtering mollusks in the tropical region were found to use more area (> 1 ha) to produce 1 t of the product than the culture of filtering mollusks and fish in the subtropical region. The most efficient system per area used was the culture of fish in net-cages inside reservoirs in the tropical region (0.002 ha/t). Net-cages fish culture is a highly intensive system. The large difference observed between the two systems of fish culture in net-cages (0.92 vs. 0.002 ha/t) and the two systems of oyster culture (2.34 vs. 0.03 ha/t) showed that the efficient use of space varies with species, but also depends on the level of intensification, effective management of stocking density and area use. In the case of the two oyster systems, the large difference was related to the space availability and the optimization in the use of space by farmers in the two regions, with suboptimal space use in the tropical area. In comparison, one t of tilapia is produced on 0.002 ha in net-cages or 0.06 ha in land-based ponds, whereas 0.24 to 1.1 ha is necessary to produce 1 t of shrimp. Thus, **the space used to produce LTS is similar to those to produce higher trophic levels species.**

The **dependence of water** indicator measures how much fresh water is necessary to produce a tonne of aquatic organisms (live fresh weight). In the culture of macroalgae and bivalves, the value is negligible compared to freshwater fish production. This is undoubtedly a significant advantage. As a comparison, the HTL Atlantic salmon (*Salmo salar*) production in net-cages in Norway consumes about 2 000 m<sup>3</sup>/t (Marine harvest, 2017). Fresh water consumption in low trophic (LT) freshwater fish species

is quite variable and depends on the system and management. This may be 80 m<sup>3</sup>/t in floating net-cages inside public reservoirs, between 15 000 - 87 000 m<sup>3</sup>/t in stagnant land-based ponds, or as high as 2.5 million m<sup>3</sup>/t in flow-through pond monoculture subjected to sub-optimal management. This last number, obtained as an average of three farms that produce tambaqui hybrids, can be decreased significantly by improving management. In comparison to other HTL species, tilapia culture in net-cages uses only 1 - 5 m<sup>3</sup> of fresh water/t of production, whereas in land-based ponds, this value reaches 16 000 - 34 000 m<sup>3</sup>. Similarly, shrimp culture in land-based ponds uses about 15 000 m<sup>3</sup>/t. Freshwater fish is the group of organisms most produced in aquaculture worldwide (FAO, 2022). Replacing them with marine invertebrates or marine fish may save fresh water for other uses. Fresh water use in other animal based food production sectors is about 4 000, 6 000 and 15 000 m<sup>3</sup>/t for poultry, pork and beef edible meat, respectively (Marine harvest, 2017).

In terms of freshwater use, ***marine species will obviously present significant strengths compared to freshwater species, however, LT and omnivorous fed, freshwater species cultured in cage systems yet require less freshwater compared to predatory fed species and terrestrial animal production, while land based aquaculture has higher fresh water use compared to terrestrial animal production.***

The **use of energy** in the culture of macroalgae and bivalves to produce 1 t of yield was found to be orders of magnitude lower than the energy used to produce 1 t of low trophic (LT) fish. In this study the energy use for production of LT fish ranged from approximately 26 000 (land based ponds, tropical region) to 344 000 MJ/t (land-based, sub-tropical). This large difference is associated with the intensification level and production technology used. Aerators, trucks and other equipment significantly increase the use of energy. Tilapia culture in general uses 30 000 - 70 000 MJ/t in net cages or land-based ponds and shrimp 25 000 - 30 000 MJ/t in land-based ponds. Except for the culture of bivalves in the subtropical region, all studied systems use 90-100% of renewable energy, which includes the input of human labor, allochthonous diets, fuel obtained from live organisms and renewable electricity. This indicator did not compute energy from the sun, wind and tide used directly, without any transformation. Electricity renewability is controversial. Thermopower can be classified as unrenovable, hydropower either as renewable or unrenovable, and photovoltaic or wind power as renewable. In Brazil, primarily hydropower is used. The culture of tilapia and shrimp usually uses more than 80% renewable energy. The culture of bivalves in the subtropical region uses only 13% of renewable energy because of the large consumption of fossil fuel in boats, while the culture in the tropical region and macroalgae culture use rowing boats. Thus, LTS farmed in open systems can increase sustainability by replacing motorboats with rowing or paddle boats. This change is possible close to the coast and in small scale production systems. Renewable fuels, such as ethanol or biodiesel, or electrification, may be alternatives in other regions and for other culture practices. To conclude, ***the use of energy for extractive culture was minimal related to that for culture of fish, and a high proportion of renewable energy was used.***

The culture of macroalgae and filtering mollusks use less N and P to produce 1 t of yield than low trophic (LT) fish, tilapia and shrimp as no formulated feed or nutrients are needed for seabased culture systems of these organism groups. The N and P usage in macroalgae and filtering mollusks are restricted to the contents in the seeds placed in grow-out systems. Tilapia and shrimp use a similar amount of N and P used by LT fish studied here. However, in poor management conditions, pond tilapia culture may use up to 300 kg N/t in ponds. These nutrients can be proxies of many others (Valenti et

al., 2018). In addition, the culture of macroalgae and bivalves also recover other nutrients from the environment, transforming them into a form available to higher trophic organisms, including human beings. This is because they are extractive species, while fish and shrimp need live organisms, particulate organic matter or formulated feed to supply their energy and nutrient requirements in intensive culture systems. Most energy, N and P used in fish and shrimp culture come from the allochthone diets. The nutrient uptake of extractive species was quantified and related to nutrient release during production of land based food production, salmon culture and shrimp culture in D6.2, Marinho et al. (2022). As expected, ***extractive species have significant advantages in terms of N and P usage in relation to fed culture of both LT and HT fish species.***

#### 4.2.1.b. Efficiency in using the resources

The efficiency indicators, i.e., **efficiency in the use of energy, nitrogen and phosphorous**, measure the capacity of a system (or species) to incorporate the energy and nutrients supplied into the biomass of the target farmed species. The addition of energy and nutrients in the culture of unfed species is very low because no artificial diets are used. Resource use are usually restricted to the contents in the seeds placed in grow-out systems, and the energy spent by human labor, boat power, or other machinery. In open sea-based aquaculture, fertilizers are also not supplied. Therefore, the energy assimilation by macroalgae from the sun, and uptake of nutrients from the water, generate indicator values above 100 %. In some cases, assimilation can be 20 times the amount of these resources added to the system, as observed in the present study. These results reinforce the role of biomitigation and nature's contribution to people of macroalgae and filtering mollusks as described in D6.2 (Marinho et al., 2022).

In contrast, the efficiency of fish and shrimp monocultures is low. Generally, less than 20 % of the nutrients supplied are incorporated in the biomass (Boyd et al., 2020). In the present work, efficiencies in energy and P use were approximately 20% in fish monocultures but reached 20 to 45 % for N. Tilapia monoculture in surface-based net-cages showed similar efficiency (~20 %), whereas lower values of about 5 % efficiency was obtained in land-based ponds. Shrimp monoculture showed an efficiency of about 20 % for energy, 35 % for N and 15% for P.

In IMTA systems, the assimilation of nutrients by tambaqui plus prawns increased in comparison to fish monocultures. The rates were 52-74 % for nitrogen and 23-33 % for phosphorus. Adding prawns, which are benthic-feeders, improved the general IMTA system efficiency. Efficiency in using energy, nutrients, water and space can be highly increased by choosing the suitable species with complementary functions stocked in the best proportion (Thomas et al., 2021). For instance, including two benthic-feeder species with the culture of tambaqui decreased the feed conversion ratio (FCR) from ~1.2 to 0.42 (Franchini et al., 2020). Also, in marine open sea-based systems, a combination of fed and extractive species can increase the system efficiency highly (Chopin, 2013). Organisms that occupy the same trophic level can also be produced together if they exploit different food sources or spaces. This type of production is often referred to as monotrophic polyculture (Thomas et al., 2021). Consequently, integrated mariculture may be an innovative strategy to increase resource use efficiency in the production of aquatic organisms. Although there is much scientific literature on marine IMTA, commercial practices are still incipient worldwide. On the other hand, freshwater commercial IMTA systems are well developed (Boyd et al., 2020), and practical lessons can be transferred also to marine systems. To conclude, ***macroalgae outrank all other organism groups in terms of energy efficiency, although extractive species in general performs very well. Resource use efficiency in fed aquaculture can be enhanced using polyculture systems.***

Much energy and material contained in the body of the farmed organisms are not consumed as food or used by the industry as raw material. These wastes are often discarded unused, carrying large amounts of energy and materials supplied during production. Examples of waste are fish guts and heads, shrimp heads and shells, and mollusk shells. Systems that lose less energy and materials as wastes are more efficient and more sustainable. The **Production Actually Used** indicator shows the proportion of the yield exploited by the society (see section 2.1) and, consequently, the yield waste fraction. The production actually used for LTS in this study was 100% in macroalgae culture, about 20% in bivalves and 50% in the fish. For tilapia, the value is about 35% considering only the use for food, but it can increase to almost 100% when it includes the use of skin, scales and the gut, head and fins for silage outcome as raw material. For shrimp, the PU is about 45%, which may increase if the shell is exploited to extract chitin, calcium and other co-products. Consequently, the efficiency of some of the LTS production systems can be increased by increasing circularity through development of economically-valuable technologies for transforming discarded wastes into co-products. The 100% PU value observed in the present study for macroalgae was attained because the product's target market was human consumption, fresh or dried; water loss in the drying process was not considered waste. The shells of bivalve mollusks have agricultural, industrial, environmental and engineering applications (Silva et al., 2019; Alonso et al., 2021; Álvarez-Salgado et al., 2022), although this industry is still incipient. Consequently, ***circular economy processes show great promise to enhance the resource use of LTS production. This is particular important for filtering mollusks, which in comparison to macroalgae and fish show low efficiency due to the low meat to shell ratio.*** In fact, the main compound class produced by bivalves is not proteins, lipids, etc. but calcium carbonate.

#### 4.2.1.c. Pollutants released

Pollution is the addition of any kind of substance or any form of energy to the environment at a rate faster than it can be dispersed, diluted, decomposed, recycled, or stored in some un-hazardous form (Afolalu, 2022; Nathanson, 2023), and that consequently can accumulate to levels where adverse changes can be observed. Pollutants can be external or naturally occurring contaminants (Ajibade et al., 2022), however, generally, pollutants are by-products of human activities. Examples of pollutants are greenhouse gases, organic matter, nutrients, heavy metals, pesticides, silt, heat, sound, and radioactivity. One of the objectives of the AquaVitae is to develop technology to produce LTS with minimum waste according to the zero waste objective, and consequently this category of indicators is essential to assess thoroughly.

The **Potential of Global Warming** measures the emission or absorption of the major greenhouse gases, i.e., CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O transformed into equivalents of CO<sub>2</sub> (CO<sub>2</sub>e) and summed. The actual flow of gases in the air-water interface is measured on-farm, and the load during the entire culture period is estimated. Most of the evaluated systems showed absorption of the greenhouse gases; bivalve culture in bottom-based tables absorbed 2 630 kg of CO<sub>2</sub>e/t of oyster produced, whereas bivalve culture in suspended-based rafts emitted 6.2 kg of CO<sub>2</sub>e/t of oyster produced. The IMTA of fish in surface-based net-cages emitted 2 334 kg of CO<sub>2</sub>e/t of tambaqui plus prawn yielded, whereas the IMTA of fish plus prawn in land-based ponds absorbed 254 kg of CO<sub>2</sub>e by tonne yielded. Generally, tilapia culture emits 300 to 7 000 kg of CO<sub>2</sub>e/t yield. Data available on shrimp culture in land-based ponds showed absorption of 3 000 to 9 000 or emission of 7 000 to 17 000 kg of CO<sub>2</sub>e/t of shrimp yielded. Large variations, alternating absorptions and emissions of greenhouse gases have been observed in aquaculture systems (Soares & Henri-Silva, 2019). Some studies report emissions (Yuan et al., 2019; Kosten et al., 2020), others absorption (Boyd et al., 2010) and others both (Soares & Henri-Silva, 2019;

Flickinger et al., 2020; David et al., 2021). Many factors can substantially affect GHG emissions from aquaculture, such as the system used, scale, farmed species, stocking density, general management (fertilization, aeration, drainage, feed supply), changes in the surrounding environment or land/water use, and others (Chen et al., 2023). Therefore, there is no general pattern of greenhouse gas flow in aquaculture systems. ***The considerable variation observed, both in filtering mollusk systems, in IMTA systems, and in shrimp systems, concur with the scattered observations throughout the literature and highlights the need for further studies of the effects of production system on greenhouse gas emissions. In general, however, LTS production systems may absorb greenhouse gases or have comparable low emissions compared to other production systems.*** Methodological standardization are necessary to achieve data with high enough quality for generalizations (Kosten et al., 2020; Chen et al., 2023).

Macroalgae absorb CO<sub>2</sub> by photosynthesis, but the role of filtering mollusks in the CO<sub>2</sub> balance is still controversial (Álvarez-Salgado, 2022). Marinho et al. (2022, D6.2) concluded that oyster culture releases CO<sub>2</sub>, similar to what was observed in the present study in suspended-based rafts and contrary to what was observed in bottom-based tables. It can be hypothesised that bottom culture reduced the diffusion time of gases to the surface, and allows for biological processes to compensate for the release of greenhouse gases in the production, however, this remains to be evaluated. According to Frankignoulle & Canon (1994), phytoplankton could use the CO<sub>2</sub> released from bivalve respiration and calcification. The observed differences may also be a consequence of differences in the environment and culture management, as well as in methodological and scope differences (Kosten et al., 2020). Moreover, macroalgae, bivalve and net-cage fish cultures lead to sediment accumulation on the farm area's seabed or reservoir bed. This stems from the reduction of water flow, the deposit of suspended material and fouling of non target species on culture ropes, rafts and tables, bivalves pseudofeces and fish feces. The organic matter fraction of the sediment may generate CO<sub>2</sub> by aerobic decomposition or CH<sub>4</sub> and N<sub>2</sub>O by anaerobic decomposition and incomplete nitrification, respectively. These processes certainly should be investigated, and the release of such gases into the atmosphere should be measured in situ to provide a holistic assessment of the potential contribution to greenhouse gas emissions of macroalgae, filtering mollusk and LTS net-cage fish production.

Organic matter, nutrients and suspended solids produced by aquaculture and liberated into the environment can cause eutrophication and sedimentation in receiving water bodies (Boyd et al., 2007). Eutrophication in marine environments is caused mainly by the increase in N, whereas in freshwater ecosystems, it is primarily due to increasing P. The negative impacts on the receiving water are more related to the overall load of pollutants than their concentration in the effluents (Boyd et al., 2007). The **Potential of organic pollution, eutrophication, and siltation** indicators measure the particulate and organic material and nutrients released to the environment and reflect a potentially negative environmental impact of aquaculture. The potential of organic pollution indicator measures the fraction of particulate material, live or dead, which can be rapidly decomposed, consuming dissolved oxygen and releasing nutrients. In open sea-based aquaculture, such as surface-based ropes, suspended- or bottom-based rafts or tables and surface-based net-cages, pollutants, such as organic material and nutrients, are liberated directly to the surrounding environment. Thus, the effluent load can be estimated by subtracting the content of a pollutant in the culture area from the content in a control point outside the production area. If there is a clear directional flow of water, measures can be taken before and after the culture area.

In the present study, organic pollution and eutrophication were generally low, except in the cultures of tambaqui in monoculture and IMTA in sub-tropical regions, where organic matter released in the environment ranged from 42.9 to 130.8 kg/t and P from 13.8 to 44.6 kg/t. Siltation was high only in the filtering mollusk culture, and reached 3 310 kg of particulate matter/t of oyster produced. In tilapia farms, more than 1 000 kg of organic matter is released/t of fish produced, whereas in shrimp, this ranges around 100 kg/t. P release is about 60 kg/t in tilapia farms and about 1 kg/t in shrimp farms. Siltation is about 1 500 kg/t in tilapia farms and 500 kg/t in shrimp culture. Pollution by chemicals, hormones and heavy metals was absent in the LTS systems analysed but occurs in tilapia and shrimp farms in low levels, such as 1 kg/t. In summary, ***different production systems showed different strengths and weaknesses in this category. All LTS systems had 0 release of chemicals, hormones and heavy metals, however, filtering mollusks contributed to high levels of siltation, and fed culture systems generally contributed to high eutrophication potential.***

#### *4.2.1.d. Pollutants accumulated*

In aquaculture production, pollutants may accumulate in association to the culture system, e.g. as particulate matter on the pond bottoms, in inland water body beds, or on the seabed under floating cultures. This material can reach high levels, decreasing water quality and limiting the production. This pollution may also impact the benthic community. In this study, the accumulation of particulate matter on the seabed under the farms was higher than 3 000 kg/t in macroalgae and oyster culture, however, the sediment was almost inorganic under the macroalgae culture and had about 35% of organic matter in the oyster culture. The P accumulation in the sediments below the farms was low, except in the macroalgae (6.2 kg/t) and tropical fish land-based ponds (13 kg/t). Unfortunately, this pollutants accumulation data was mainly missing for the sea-based fish cage culture systems, hence no comparison to LTS fed aquaculture could be performed. In general, however, site selection is a very important aspect for sea based, fed, cage culture to avoid detrimental effects on bottom substrates as a consequence of organic matter deposition. The accumulation of particulate and organic matter and P were similar in tilapia and shrimp cultures, and was about 100, 80 and 2 kg/t for each substance, respectively. The organic material accumulated in freshwater ponds contains much nutrients, and some attempts to use this material as soil enhancement in agriculture or even replacing soil in plant potting have demonstrated high potential (unpublished data). Studies on the culture of halophytes in marine sediments collected from land-based biofloc tanks or earthen ponds have also shown promising results (Fierro-Sanudo et al., 2020). However, commercial implementations and halophyte markets have not yet been established (Lothmann & Sewilam, 2023). In these cases, accumulated sediment becomes a co-product instead of pollution, increasing the circularity of the system. Additionally, integrated mariculture is, as highlighted in section 4.2.1.2, a vital research avenue for enhancing resource use efficiency and the sustainability of LTS aquaculture.

#### *4.2.1.e. Biodiversity*

Aquaculture can have both negative and positive effects on the biodiversity of the surrounding ecosystem. Among the most common negative impacts are that open seabased aquaculture can introduce invasive species, i.e. non native species with negative economic and/or ecological effects, into an area, either as a direct effect of the cultured species being non-native, or as a consequence of associated species in, or on, translocated culture organisms. The accidental escape of farmed species into the surrounding environment can occur due to storms, human error, or other disturbances. Escaped farmed species can compete with native species for resources, or adversely affect the genetic composition of wild populations if the farmed organisms have been exposed to selective breeding to

enhance specific traits desirable in the culture situation. Hybridization and introgression between farmed and wild species can lead to a decrease in the genetic variation of wild populations or alteration of the genetic setup in the wild populations, which can lead to decreased fitness and thereby reproductive success. This is also a problem for non-native species and genetically selected species that reproduce in open seabased systems during the culture cycle. Aquaculture can also lead to the introduction of pathogens, parasites, and diseases, and intensive culture with high densities increases the risk of disease and parasite outbreaks, that can spill over to adjacent wild populations. Finally, seed production in aquaculture may have far-reaching implications for wild populations. Harvest of large numbers of wild juveniles or broodstock can e.g. lead to a decrease in populations as the recruitment is reduced. Hatchery produced seed may, on the other hand, infer a biosecurity, and genetic, risk if translocated over large geographical areas, and if the seed have been exposed to selection processes. Consequently, the culture of local strains using undomesticated broodstock, and seed production using deployment of sea-based seed collectors for capture of species with pelagic larvae, is generally less impactful to the environment and, consequently, more sustainable.

The **Risk of farmed species** and **Impacts of seed acquisition** indicators use an ordinal variable (ranging from 1 to 12) that represents the risks of impact from the production based on the genetic characteristics of the farmed species and the source of seeds (see Valenti et al., 2018 and D6.1, Lindblom et al. 2021 for details). In this study, the macroalgae *Hypnea pseudomusciformes* and the oyster *Crassostrea gazar* are native in Brazil and present in the same region as the farms, but seeds are collected from the local environment. Therefore, these cases have a low genetic risk (RFS = 2) but a high risk of overexploiting natural populations (ISA = 9). An effort to improve the production of *C. gazar* seeds in commercial hatcheries has been made in CS8 of AquaVitae with success, contributing to increasing the sustainability of oyster culture in Brazil. In contrast, Tilapia and whiteleg shrimp are generally farmed in regions outside of their natural occurrence, and the seeds are typically produced in hatcheries, but may be exposed to genetic selection. Thus, these cases show inverse values (RFS = 8-11; ISA = 1-2). Tambaqui, *Colossoma macropomum*, is native to the Amazonia, and therefore, their culture in other regions, such as those in the studied systems, leads to high risk to local communities. The seeds are produced in hatcheries but no genetic selection is implemented at this stage. Thus, the indicator values (RFS = 10-11; ISA = 2) are similar to those obtained for tilapia and shrimp. Consequently, ***culture of local strains using undomesticated broodstock should be used to increase environmental sustainability*** (although not always economic sustainability), ***and development of suitable and economically feasible seed production systems***, e.g. of macroalgae and filtering mollusks as was done in case study 1 and 8 in AV, ***is essential to increase the sustainability of LTS farming***.

#### 4.2.1.f. Welfare

Consumer concerns have made fish welfare increasingly important in global aquaculture (Barreto et al., 2022). They want to know how fish are kept and managed in captivity, mainly in cultures for human consumption (Pedrazzani et al., 2022). The concept of welfare for plants and invertebrates is less acknowledged, and care for the welfare of such organisms is frequently disregarded. Sustainability documents often cite animal welfare as an essential subject to assess sustainability (e. g., Ziegler et al., 2022). Reaching standards of welfare in the culture allows for obtaining certifications, adding value to the products, and reaching premium markets, thus increasing sustainability. Welfare includes that the farmed organisms should be reared in an environment adequate for their development, the water quality should be within the range suitable for the species and life stage, and facilities should allow the fulfillment of their physiological and ethological needs. The indicator **Fulfillment Natural Needs**

measures if the facilities and management provide a suitable feeding schedule, space for performing natural movements, such as walking (e.g. for shrimps) or swimming, conditions for reproduction, and low stress by reducing handling time lower than 5% of the culture cycle, avoiding agonistic behavior, and providing stunning and humanitarian (caring) slaughtering. The **Environmental comfort** indicator measures if water quality is within the range defined as suitable for the species and life stage. The minimum measured variables are temperature, salinity, dissolved oxygen, pH and ammonia. In intensive cultures, turbidity and nitrite are also mandatory (See D6.1; Lindblom et al. 2021 for details). Both indicators meet the recommendations of the Scientific, Technical and Economic Committee for Fisheries of European Commission (Ziegler et al., 2022). All the LTS farming systems in this study meet more than 50 % and 70 % of the requirements of fulfilment of natural needs and environmental comfort, respectively. No data on tilapia and shrimp were available for comparison. Most of the criteria assigned to both indicators also allow computing them for plants and mollusks, thus, it was possible to calculate them for macroalgae and filtering mollusks cultures too.

#### 4.2.1.g. General sustainability performance of the evaluated systems

The analysis of each sub category (a-f) showed that **Welfare** and **Biodiversity** conservation were strengths in all analysed LTS systems, whereas organic matter and nutrient (**pollutants**) **accumulation** were significant weaknesses. The studied farmed fish is exotic in the culture area, which lead to an intermediary score. However, this is compensated for by the use of seeds produced in simple hatcheries which commands to a high score. On the contrary, macroalgae and filtering mollusks are native, but the seeds were captured in the wild, which leads to a low score. The most environmentally sustainable systems were the culture of *Hypnea pseudomusciformes* (red macroalgae) and *Crassostrea gazar* (filtering mollusk) in tropical and subtropical regions (Figure 6). Their environmental sustainability subindices were 0.70, 0.72 and 0.63, respectively. Efficiency in using natural resources is a strength in macroalgae and filtering mollusks in tropical zone because they are extractive species. However, this group of indicators were lower in the filtering mollusks in subtropical regions. This variation is mainly due to different management, reinforcing that farm management is major drive toward sustainability. It should be noted that there is no data on pollutant accumulation in *C. gazar* in tropical region. The fish (tambaqui) culture systems showed environmental sustainability subindices ranging from 0.45 to 0.55 (Figure 8). In both monoculture and IMTA fish systems, the **use of resources** and **accumulation of organic matter and nutrients** were the most significantly weaknesses while welfare and biodiversity was the most strengths.

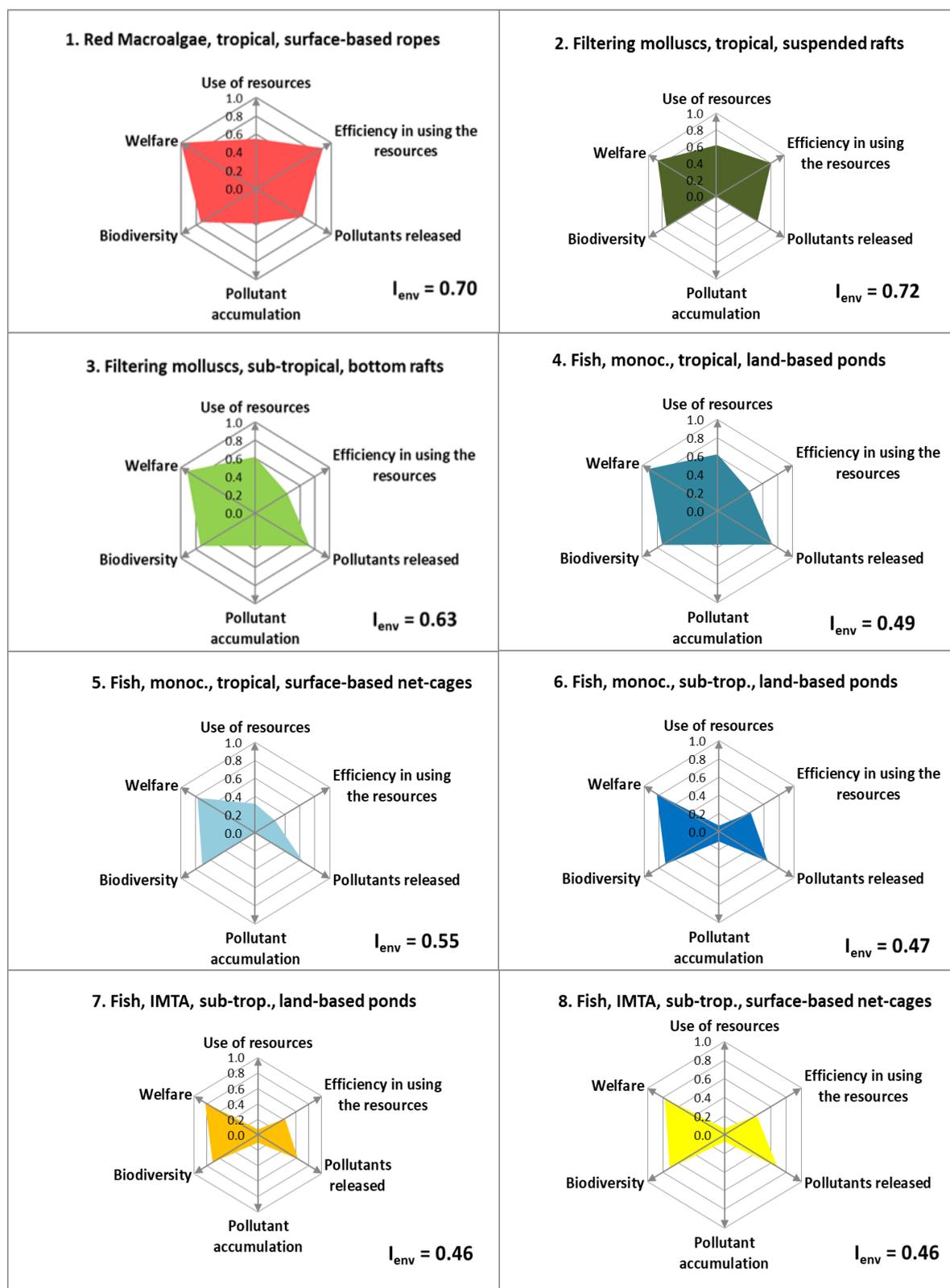


Figure 8. Multidimensional diagrams showing 6 sub-dimensions of environmental sustainability. Sustainability increases from the center to the extreme of each axis. The colored area represents the environmental sustainability of each system. No data on pollutant accumulation were available for systems 2 and 5.  $I_{env}$  = sub-index of environmental sustainability.

#### 4.2.2. Social sustainability

Social sustainability should be based on human rights and improving human well-being. Agenda 21 (UN, 1992) and Agenda 2030 (UN, 2015) emphasize that sustainable development should create social benefits for the local population, especially vulnerable groups. Therefore, social sustainability is mostly related to the social benefits that the aquaculture of LTS can provide to the local population. Farms that generate more input for the local community and distribute wealth are more sustainable. The results per indicator in this study are presented in tables 6 and 7 and are the basis for the discussion in this chapter. The results are presented by indicator, yet reported in sections related to the classification into major themes as discussed in section 3.2.1.

Table 6. Indicators of social sustainability obtained for the 8 systems of LTS studied. Monoc. = monoculture; sub-trop. = subtropical; IMTA = integrated multi trophic aquaculture; PHY = person-hour per year; PH = person-hour, “-“ = no data. Letters a to f means the subgroups cited in section 3.2.1.

Case		1.	2.	3.	4.	5.	6.	7.	8.	
Analysis category	Organism group	Red macro-algae	Filtering moluscs				Fish			
	Type of production <sup>1</sup>	M	M	M	M	M	M	IMTA	IMTA	
	Climate <sup>2</sup>	T	T	ST	T	T	ST	ST	ST	
	System type <sup>3</sup>	SBR	SR	BBT	LBP	SBN C	LBP	LBP	SBNC	
	N farms (N total units)	1 (3)	15 (15)	9 (9) <sup>4</sup>	3 (9)	3 (3)	1 (3)	1 (3)	1 (3)	
a	Earning family ratio	NA	3.7	2.4	0.5	10.6	-	3.2	6.9	5.2
b	Development of local economy	%	51	96	100	100	-	83	54	53
b	Use of local workers	%	100	80	100	100	100	100	100	100
b	Local consumption of production	%	26	100	20	37	100	-	-	-
c	Investment to create direct employment	US\$. job <sup>-1</sup>	1 237	769	2 196	16 856	-	30 784	30 992	40 476
c	Proportion of self-employments	%	100	100	100	48	-	50	50	50
c	Permanence in the activity	years	16	10	9	-	7	20	20	20
c	Required work per unit of occupied area	PHY. m <sup>-2</sup>	0.26	3.41	3.13	0.12	-	0.18	0.18	0.18
c	Required work per unit of production	PH.t <sub>1</sub>	490	7 980	1 000	100	-	340	360	510
d	Safety at workplace	%	43	18	30	23	-	35	35	35
d	Access to health-insurance programs	%	100	100	100	100	100	100	100	100
d	Schooling	%	0	7	0	0	-	100	100	100
d	Participation in outside community activities	%	100	100	100	100	100	100	100	100
e	Proportion cost of work	%	36	26	87	14	-	46	20	37
e	Remuneration of work per unit of production	US\$. kg <sup>-1</sup>	1.38	0.41	0.92	0.14	-	0.89	0.95	1.32
e	Pay equality	%	100	100	100	74	-	100	100	100
e	Income distribution	%	28	156	55	62	-	55	44	56
f	Gender inclusion	%	89.0	67.4	87.0	49.0	22.0	-	-	-
f	Racial inclusion	%	74	93	4	66	-	-	-	-
f	Age inclusion	%	72	73	78	39	-	-	-	-

<sup>1</sup> M=Monoculture, IMTA=polyculture

<sup>2</sup> T=tropical, ST=sub-tropical

<sup>3</sup> SBR: surface-based ropes, SR: suspended rafts, BBT: bottom-based tables, LBP: land-based ponds, SBNC: surface-based net-cages.

<sup>4</sup> Some data were updated from Fernandes (2013).

Table 7. Benchmarking values obtain after data standardization. Each value represents the proportion in relation to the mean of all systems. Values higher than 1 indicate that the system showed larger values than the mean of the 8 systems, whereas data below 1 indicate values lower than the mean. Monoc. = monoculture; sub-trop. = subtropical; IMTA = integrated multi trophic aquaculture; “-“ = no data. Letters a to f means the subgroups cited in section 3.2.1.

Case		1.	2.	3.	4.	5.	6.	7.	8.
Analysis category	Organism group	Red macro-algae	Filtering moluscs				Fish		
	Type of production <sup>1</sup>	M	M	M	M	M	M	IMTA	IMTA
	Climate <sup>2</sup>	T	T	ST	T	T	ST	ST	ST
	System type <sup>3</sup>	SBR	SR	BBT	LBP	SBNC	LBP	LBP	SBNC
	N farms (N total units)	1 (3)	15 (15)	9 (9)	3 (9)	3 (3)	1 (3)	1 (3)	1 (3)
a	Earning family ratio	0.8	0.5	0.1	2.3	-	0.7	1.5	1.1
b	Development of local economy	0.7	1.3	1.3	1.3	-	1.1	0.7	0.7
b	Use of local workers	1.0	0.8	1.0	1.0	1.0	1.0	1.0	1.0
b	Local consumption of production	0.5	1.8	0.4	0.7	1.8	-	-	0.0
c	Investment to create direct employment	0.1	0.04	0.1	1.0	-	1.7	1.8	2.3
c	Proportion of self-employments	1.4	1.4	1.4	0.7	-	0.7	0.7	0.7
c	Permanence in the activity	1.1	0.7	0.6	-	0.5	1.4	1.4	1.4
c	Required work per unit of occupied area	0.2	3.2	2.9	0.1	-	0.2	0.2	0.2
c	Required work per unit of production	0.3	5.2	0.6	0.1	-	0.2	0.2	0.3
d	Safety at workplace	1.4	0.6	1.0	0.7	-	1.1	1.1	1.1
d	Access to health-insurance programs	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
d	Schooling	0.0	0.2	0.0	0.0	-	2.3	2.3	2.3
d	Participation in outside community activities	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
e	Proportion cost of work	1.0	0.7	2.3	0.4	-	1.2	0.5	1.0
e	Remuneration of work per unit of production	1.6	0.5	1.1	0.2	-	1.0	1.1	1.5
e	Pay equality	1.2	-	1.2	0.9	-	1.2	0.5	1.2
e	Income distribution	0.4	2.4	0.8	0.9		0.5	1.5	0.3
f	Gender inclusion	1.4	1.1	1.4	0.8	0.3	-	-	
f	Racial inclusion	1.2	1.6	0.1	1.1	-	-	-	
f	Age inclusion	1.1	1.1	1.2	0.6	-	-	-	

<sup>1</sup> M=Monoculture, IMTA=polyculture

<sup>2</sup> T=tropical, ST=sub-tropical

<sup>3</sup> SBR: surface-based ropes, SR: suspended rafts, BBT: bottom-based tables, LBP: land-based ponds, SBNC: surface-based net-cages.

#### 4.2.2.a. Family earning

The indicator **Earning family ratio** measures the number of persons a farm can support living according to the local standards. It is likely that farmers will continue aquaculture if they can give their families an acceptable lifestyle based on that activity. Therefore, this indicator relates the net revenues to the per capita income in the farm region. The system filtering mollusks in the sub-tropical region showed a value of 0.52, indicating that the earnings are insufficient to provide income for one person living according to the medium regional lifestyle. Culture of filtering mollusks in the tropical region, however, could support 2 persons and algae culture generated a net income to maintain a family with about 3-4 persons. The capacity of fish culture varied with culture system, climate zone and type of production, but ranged between 3 to 10-11 persons. Except for fish culture in land based systems in sub-tropical areas, all fish production could support higher number of people compared to extractive species.

Increasing the production scale or improving management using a cost-effective technology (such as those that have been developed in AV) may increase the net income and improve the sustainability of the systems. This indicator is quite variable for tilapia and shrimp, depending on the farm scale. **All culture systems and organisms with one exception were found to be able to provide income for at least 2 or more people, although fish culture appeared to generate a higher net income.** This is not unexpected given the higher market value of fed species compared to extractive species.

#### 4.2.2.b. Local benefits

Aquaculture should develop the local economy to provide social development. The indicator **Development of local economy** measures the proportion of expenditures for goods and services acquired in local markets, giving capital input in regional value chains. In the systems of farming filtering mollusks in the subtropical region and fish monoculture in tropical land-based ponds, the development of local economies values were 100 %. This means that all goods and services were purchased in local marketing. Projects conceived to concentrate purchases in local trade are considered more sustainable than others that need to import products and services. All systems studied here received scores above 50 %, indicating medium to high sustainability regarding this feature. Tilapia culture had 30 to 50 % values, while shrimp farming scored as low as 5 % because the culture uses specific diets and more complex equipment.

The indicator **use of local workers** measures the proportion of workers recruited among the local population. The systems analysed in this study, including the tilapia and shrimp cultures, recruited 80 to 100% of the labor among local persons, contributing to generating wealth locally. These scores indicate that the ability level required to operate the farms matches local people's skills. Companies using technologies planned according to local population competencies should be encouraged to promote sustainable development.

The culture of LTS should promote local food security and, thus, contribute to attaining SDG number 2, zero hungry (UN, 2015). In this way, aquaculture systems that sell food for local consumption are considered more sustainable than others that export the production. The **Local Consumption of Production** indicator measures the improvement in food availability for the local community. The values obtained for the systems evaluated in this study showed that the tropical oyster farms and net-cage tambaqui farm produced in tropical areas sold all production in local markets, and thus, were more sustainable than the other systems that sold 20 to 37 % only in the local markets. Tilapia and shrimp sectors usually have local consumption of production values as low as 10 %. This may be related to scale of production, target markets and local consumption patterns, but nevertheless, in this study **the LTS production systems demonstrated higher local benefits compared to the tilapia and shrimp production systems.**

#### 4.2.2.c. Job creation

The **Investment to create direct employment** indicator measures the social use of capital and can assist policy-makers and governments in prioritizing support systems that generate more job positions with lower investments. Table 6 shows that investing in the production of algae and filtering mollusks is more efficient in creating jobs than investments in fish culture. The investment to create 1 job in systems to farm algae or oysters may be 20 to 50% lower than that in fish farms, corresponding values for producing tilapia or shrimp in land-based ponds was similar to those obtained to produce fish in the present study. However, the value was lower for farming tilapia in net-cages inside reservoirs.

The **Proportion of self-employment** indicator measures the inclusion of staff from outside of a family in an operation. Generally, self-employment allows more autonomy for local people in making decisions, driving their businesses and receiving all profits, and can consequently be considered more sustainable. This indicator can be measured on different scales, but is more suitable for sectorial or regional scale. In the present study, the proportion of self-employment of 100 % in the extractive culture activities indicates that only the owners and their families work in the farm. This was in contrast to all fish farms for which the corresponding number was 50%. In comparison, self-employment in tilapia culture ranged from 0 to 100% between regions and was generally low in shrimp culture, about 10%. The indicator **Permanence in the activity** measures the time owners and workers have worked in the same aquaculture activity. In this study, the shortest time was obtained for filtering mollusks, with about 10 years, while subtropical fish and algae cultures showed values close to 20 years, similar to shrimp culture which in the analysed cases demonstrated 20-30 years. This indicates that such farms have perennity, a good sign in terms of sustainability.

Space is, as discussed in the environmental indicator section (4.2.1.a) an essential natural resource that should be used for promoting social development. Thus, aquaculture systems that use more labor per area unit can be considered more sustainable compared to systems with few employees per area. Similarly, systems that use more human labor per production unit create more jobs and are therefore more sustainable, although, as discussed above, sustainability will also be impacted by the origin of the workforce. They were assessed using the indicators **Required work per unit of occupied area** and **Required work per unit of production**, and the data showed that filtering mollusk culture provided more jobs per area and production unit compared to all other production systems. This is not unexpected as filtering mollusk culture require regular handling (size sorting and tumbling) and is exposed to fouling, and therefore requires regular management. In comparison, tilapia and shrimp culture showed slightly lower values of required work per unit occupied area (2) as filtering mollusks (2), and was lower in terms of required work per unit production (150) than all (except for one) other systems evaluated.

To summarise, it was found that ***extractive production demonstrated benefits in terms of investments needed for job creation and self employment, and in addition filtering mollusks production systems provided more jobs per area and production unit compared to fish culture systems, indicating higher sustainability in these systems.***

#### 4.2.2.d. Safety & Welfare

Creating economic development with decent jobs is essential for developing socially sustainable systems. Therefore the work environment should be planned to allow workers good quality of life, health, safety and dignity. The indicator **Safety at workplace** measures the availability of equipment pieces, actions, and practices that provide safety for workers on the farm, measured as 15 different action points. In this study, none of the analysed systems reached a score of 50% or higher, indicating low sustainability in this indicator. In comparison, tilapia and shrimp culture are relatively well-organized sectors, and the indicator reached about 80% for these organisms. Consequently, ***more effort should be put into ensuring workers safety in LTS aquaculture.***

**Access to health-insurance programs** is essential for the health of farmers and employees. In Brazil, all people can use public health system, which includes free health care, including a program of free medicines. Therefore, all farms received a grade 100%. Nevertheless, in countries without similar care programs, farm incomes should provide access to health care for owners and employees. This is

essential to contribute to attaining good health and well-being for all population. For tilapia and shrimp cultures, values for this indicator are site-specific.

The **Schooling** and **Participation in outside community activities** indicators are interconnected to mental health and good quality education. They measure if the owners and employees have a good style and free life, with access to capacitation and social interactions, which is essential for people to develop their human potential (Bennett et al., 2022). In this study, all people engaged in the production of tambaqui in subtropical regions had access to capacitation. This was in contrast to people engaged in extractive species culture, for which almost no one had access to capacitation. The participation in social activities was, on the other hand, very high. Corresponding values for the two indicators in tilapia and shrimp culture was close to 10% and 90-100% for schooling and participation in outside community activities, respectively, indicating that access to capacitation may be a problem also in other aquaculture sectors than LTS aquaculture. Therefore, ***formal or informal education and training programs should be implemented to improve sustainability in LTS aquaculture.***

#### 4.2.2.e. Equality

Equity and equality are essential for sustainable development. Nevertheless, the blue economy profits are still concentrated in a few corporations, and only a few benefits, but many social problems, are shared with coastal communities (Bennett et al., 2022). Therefore, it is essential to develop aquaculture systems that promote a fair distribution of wealth. These indicators are most suitable for analysis of larger companies, sector, regional or national scale, but can be applied also on farm level. The **proportion cost of work** indicator measures the fraction of production cost represented by human labor. Technologies that use more human labor than equipment are socially more sustainable. This indicator shows if the system is work-intensive or uses machines and automation, reducing the number of jobs and/or paying meager salaries. The **remuneration of work per production unit** indicator measures the fraction of the selling price of the farmed products used to pay for labor. High value products infer higher possibilities for distribution of wealth to employees. **Pay equality** indicator measures the dispersion of salary values and owner draws, which measures if the farm practices a fair distribution of wealth or if it is concentrated in the hands of a few persons who receive much more than others. Finally, **income distribution** indicator measures how the profit (the owner's compensation) relates to the salaries paid to those who work to generate wealth, including owner draws or wages (if the owners work at the company). In the present study, many farms were family owned and were operated only by the owners and their families, making the computation and interpretation of these indicators more difficult. In these cases, the regular owner draws was used as salary and the annual profit as owner compensation.

The proportion cost of work value ranged between 14 - 46% for the studied systems, with the exception of filtering bivalves in the subtropical area for which a value of 87% was observed. This indicates that labor was the principal production cost in oyster culture in the area which makes sense given the low investment costs in culture system infrastructure and the high demand for management during the culture cycle. In comparison, in the tilapia and shrimp culture the proportion cost of work were 20 - 25% and 15 - 20%, respectively.

However, the algae culture showed a higher remuneration of work per production unit indicator value (US\$ 1.38/kg) because of the high selling price obtained in the human food local market. It should be noted that the remuneration of work per production unit for LTS were more similar to that of tilapia (US\$ 0.4 /kg) compared to that for shrimp which was approximately US\$ 2.00 to 4.00/kg.

Moreover, the salaries paid to employees or the owner draws were equal in all systems (pay equality = 100%), except in tropical monoculture of fish in ponds. It should be noted that in systems 1, 2 and 3 only the owners and their families work on farms. In contrast, the indicator income distribution demonstrated some variability. In all fish culture systems and in oyster culture in the subtropical area, income distribution ranged between 44 and 62%, which is the normal range as the owner normally should receive double compensation compared to the employees (i.e. income distribution = 50%). Values > 100% are desirable for sustainable systems. Two cases deviated from this, one displaying lower values (macroalgae, 28%) and one showing higher values (oyster in tropical region, 156%), meaning that in the macroalgae culture, the owner compensation was more than three times the salary paid to the workers, while in the tropical oyster culture, the owner compensation was about 1.5 times lower than the salary paid to the workers. In comparison, in the tilapia and shrimp culture pay equality was 80% and 20%, respectively.

#### 4.2.2.f. Inclusion

Including minorities, vulnerable people, gender, or marginal ethnic age groups are central sustainable development points. This is clear in SDG 5: gender equality and SDG 10: reducing inequalities (UN, 2015). The **Gender inclusion**, **Racial inclusion** and **Age inclusion** indicators measure if the gender, race and age composition of employees at a farm reflects the composition of the local population. The identity of sexual minorities should be included if data are available. Ethnic groups vary in regions and countries, and the degree of segregation may be based on skin color, religion, language, ethnic origin, etc. Therefore, site-specific ways of measuring inclusion may be needed. Groups should be constituted according to their qualitative and quantitative occurrence in each specific country or region. In the present study, classification by ethnic origin was used: caucasian-descendants, sub-Sahara African descendants, caucasian plus sub-Sahara African descendants, Asiatics, and Indigenous. Moreover, young adults and senior adults are frequently excluded from work opportunities. The age classes are site-specific. In the present study, four age groups were considered: young (16–21 years), adults (22–40), middle-aged (40–60) and elders (> 60). Generally, the inclusion was high in all systems studied, except the racial inclusion in the system of oyster culture in the subtropical region. This is because the nine studied farms were placed inside a community of slave descendants; thus, most people in the area are sub-Sahara Afro-descendants. The fish culture in tropical regions also indicated the exclusion of women in net-cage systems and older people in land-based systems. Similarly, tilapia and shrimp culture showed the exclusion of women and senior adults.

#### 4.2.2.g. General sustainability performance of the evaluated systems

The overall social sustainability was similar in all systems, but was slightly higher in the culture of *Hypnea pseudomusciformes* (red macroalgae, index 0.67, Figure 9) compared to the other cases. The oyster and fish culture systems showed social sustainability subindices ranging from 0.58 to 0.64, excluding tropical monoculture systems in net-cages with many data missing (Figure 9). The analysis of each sub category (a-f) showed that **Local benefits** were a strength in all LTS systems, whereas **Family earning** was a significant weakness, except in the tropical land-based fish monoculture. In fish culture, both monoculture and IMTA systems, **Job creation** was the most significant weakness, indicating that these systems should generate more work positions to increase sustainability. Data on family earning, inclusion and equality were absent for fish monoculture in net cages in tropical areas,

hence reducing the social sustainability sub-indices for that case. Similarly, all but one fish culture case did not have data on inclusion.

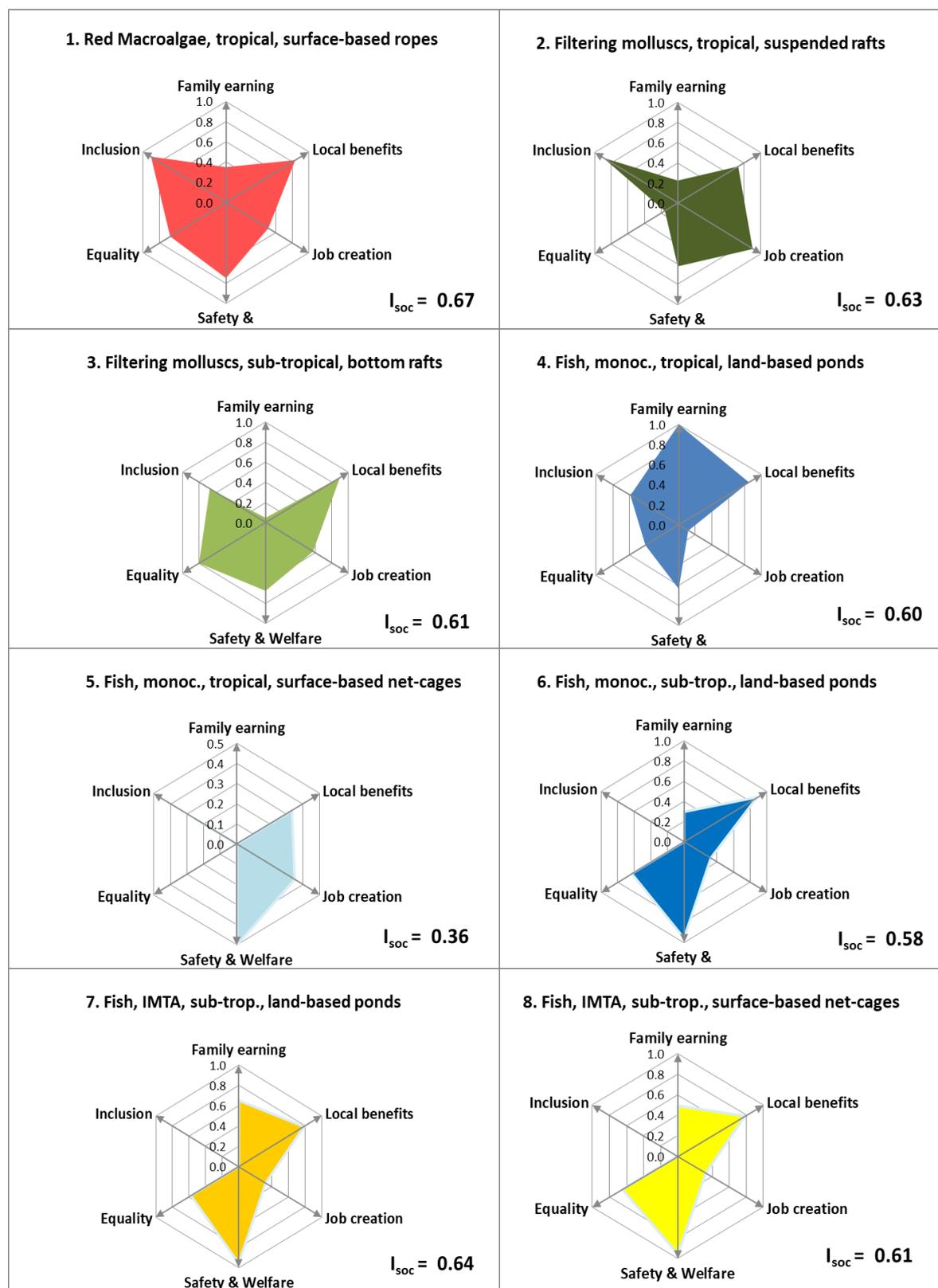


Figure 9. Multidimensional diagrams showing six sub-dimensions of social sustainability. Sustainability increases from the center to the extreme of each axis. The colored area represents the social sustainability of each system. No data on family earning, inclusion and equality were available for system 5, and no data on inclusion were available for systems 6, 7 and 8. Therefore, comparisons should be made carefully.  $I_{soc}$  = sub-index of social sustainability.

### 4.2.3. Economic sustainability

Sustainable aquaculture farms should be productive and cost-effective to generate and distribute benefits to improve the lifestyle of all enrolled stakeholders perennially. Thus, it is necessary to optimize the biological, other environmental and economic components holistically. Therefore, the bioeconomy is essential to channel the aquaculture industry toward sustainable development (Martinel et al., 2020). However, economic sustainability differs from the neoclassical economy theories by assuming that natural resources are finite, contrary to the vision that there are no limits to growth, and the companies and institutions should be perennial for at least the time of one human generation (Valenti et al., 2018). In addition, the concept of economic sustainability revived the concept of externalities introduced in the neoclassic economy by Pigou in 1936 (Pigou, 2005) that had been dormant. Including externalities in economic sustainability analysis allows incorporation of the current concepts of nature's contribution to people (NCPs) or ecosystem services and disservices (see D6.2; Marinho et al., 2022) into the bioeconomy. The economic sustainability indicators used in the present study meet the above rationale. In this way, natural resources are assumed to limit economic growth. All financial indicators include negative externalities as costs and positive externalities as income. Moreover, the farm lifetime was considered to have a baseline of 20 years, which is approximately the duration of a human generation. The results per indicator in this study is presented in tables 8 and 9 and are the basis for the discussion in this chapter. The results are presented by indicator, yet reported in sections related to the classification into major themes, as discussed in section 3.2.1.

Table 8. Indicators of economic sustainability obtained for the 8 systems of LTS studied. Monoc. = monoculture; sub-trop. = subtropical; IMTA = integrated multi trophic aquaculture; "-" = no data. Letters a to f means the subgroups cited in section 3.2.1.

Case		1.	2.	3.	4.	5.	6.	7.	8.	
Analysis category	Organism group	Red macro-algae	Filtering moluscs				Fish			
	Type of production <sup>1</sup>	M	M	M	M	M	M	IMTA	IMTA	
	Climate <sup>2</sup>	T	T	ST	T	T	ST	ST	ST	
	System type <sup>3</sup>	SBR	SR	BBT	LBP	SBNC	LBP	LBP	SBNC	
	N farms (N total units)	1 (3)	15 (15)	9 (9) <sup>4</sup>	3 (9)	3 (3)	1 (3)	1 (3)	1 (3)	
a	Ratio net income and initial invest	NA	2.63	0.27	0.56	0.44	-	0.39	0.86	0.49
a	Internal rate of return <sub>e</sub>	%	149	25	21	37	-	37	73	46
b	Payback period <sub>e</sub>	Years	0.90	4.21	3.9	2.9	-	2.80	1.60	2.30
b	Benefit-cost ratio <sub>e</sub>	US\$	15.0	1.2	0.5	1.9	-	1.7	4.7	2.3
b	Net present value per tonne	US\$/t	7 332	4 105	406	1 689	-	19 329	58 324	53 438
c	Positive externalities	US\$/t	49	36	137	<0.01	-	287	287	333
c	Negative externalities	US\$/t	<0.01	0.9	0.2	3.6	-	495	495	774
d	Net profit <sub>e</sub>	US\$/t	1 091	261	-569	299	-	2 572	8 608	8 318
d	Investment generated by the activity	%	0.71	0.33	0.67	0.11	0.00	0.29	0.30	0.51
d	Annual income	US\$/t	1 384	919	496	396	-	4 528	10 716	11 263
e	Permanence of the farmer in the activity	years	16	10	9	-	7	20	20	20
e	Risk rate	%	18	42	67	35	-	9	9	9
e	Diversity of products	unit	1	1	1	1	1	1	2	2
e	Diversity of markets	unit	5	2	2	1	1	1	3	3

e	Potential of Economic Resilience	%	87.1	14.3	85.9	53.7		54.3	58.3	40.5
f	Number of circular processes	unit	4	4	4	0	0	0	2	2

<sup>1</sup> M=Monoculture, IMTA=polyculture

<sup>2</sup> T=tropical, ST=sub-tropical

<sup>3</sup> SBR: surface-based ropes, SR: suspended rafts, BBT: bottom-based tables, LBP: land-based ponds, SBNC: surface-based net-cages.

<sup>4</sup> Some data were updated from Fernandes (2013)

Table 9. Benchmarking values obtain after data standardization. Each value represents the proportion in relation to the mean of all systems. Values higher than 1 indicate that the system showed larger values than the mean of the 8 systems, whereas data below 1 indicate values lower than the mean. Monoc. = monoculture; sub-trop. = subtropical; IMTA = integrated multi trophic aquaculture; “-” = no data. Letters a to f means the subgroups cited in section 3.2.1.

Case		1.	2.	3.	4.	5.	6.	7.	8.
Analysis category	Organism group	Red macro-algae	Filtering moluscs				Fish		
	Type of production <sup>1</sup>	M	M	M	M	M	M	IMTA	IMTA
	Climate <sup>2</sup>	T	T	ST	T	T	ST	ST	ST
	System type <sup>3</sup>	SBR	SR	BBT	LBP	SBNC	LBP	LBP	SBNC
	N farms (N total units)	1 (3)	15 (15)	9 (9)	3 (9)	3 (3)	1 (3)	1 (3)	1 (3)
a	Ratio net income and initial invest	1.61	0.52	0.75	0.66		0.62	0.93	0.70
a	Internal rate of return <sub>e</sub>	2.69	0.44	0.38	0.67	-	0.66	1.32	0.83
b	Payback period <sub>e</sub>	0.34	1.58	1.47	1.09	-	1.05	0.60	0.86
b	Benefit-cost ratio <sub>e</sub>	3.86	0.30	0.12	0.48	-	0.43	1.20	0.60
b	Net present value per tonne	0.35	0.20	0.02	0.08	-	0.94	2.82	2.59
c	Positive externalities	0.30	0.22	0.85	0	-	1.78	1.78	2.06
c	Negative externalities	0.00	0.00	0.001	0.014	-	1.958	1.958	3.061
d	Net profit <sub>e</sub>	0.37	0.09	-0.19	0.10	-	0.88	2.93	2.83
d	Investment generated by the activity	1.95	0.90	1.84	0.30	0	0.80	0.82	1.40
d	Annual income	0.33	0.22	0.12	0.09	-	1.07	2.53	2.65
e	Permanence of the farmer in the activity	1.09	0.70	0.64	0	0.49	1.36	1.36	1.36
e	Risk rate	0.67	1.54	2.48	1.31	-	0.34	0.34	0.34
e	Diversity of products	0.80	0.80	0.80	0.80	0.80	0.80	1.60	1.60
e	Diversity of markets	2.24	1.41	1.41	1.00	1.00	1.00	1.73	1.73
e	Potential of Economic Resilience	1.55	0.25	1.53	0.95		0.96	1.04	0.78
f	Number of circular processes	2	2	2	0	0	0	1	1

<sup>1</sup> M=Monoculture, IMTA=polyculture

<sup>2</sup> T=tropical, ST=sub-tropical

<sup>3</sup> SBR: surface-based ropes, SR: suspended rafts, BBT: bottom-based tables, LBP: land-based ponds, SBNC: surface-based net-cages

#### 4.2.3.a. Capital efficiency (Efficiency in using monetary resources)

The **Ratio net income and initial investment** indicate the efficiency in managing capital, according to the concept of sustainability (section 2.1). Enterprises with a lower initial investment that generate the same net income as an enterprise with a higher initial investment optimize the use of the resource capital and may therefore be considered more sustainable. In this study, the technological and infrastructure requirements of macroalgae culture were low cost, yet the farms generated an annual income of more than two times the initial investment. Therefore, **macroalgae culture surpassed all the other studied systems in managing capital** by 2 to 3 fold. The other systems demonstrated ratios of net income to initial investment of < 1. The corresponding values for tilapia were 1.0 to 2.5 and for

shrimp production 0.7 to 2.6. These differences are due to different expenditures during building facilities and equipment purchase.

#### 4.2.3.b. Financial

The economic feasibility indicators **Internal Rate of Return**, **Payback Period**, **Benefit-Cost Ratio** and **Net Present Value** are generally used in neoclassical economics to assess investments and new technologies (Engle, 2010). They provide important and understandable information to entrepreneurs and investors. Therefore, similar indicators, including externalities and life-cycle, were defined to assess large culture operations economic sustainability or make projections and simulations. Internal rate of return measures the return rate of investments.

In this study, all systems showed acceptable internal rate of return. Macroalgae culture even generated a return of 149% annually, which can be regarded as very high for any investment. Money opportunity costs is generally many times lower. The IMTA cases showed internal rate of returns of 46 and 73%, which is also regarded as high. The remaining fish cases demonstrated an average internal rate of returns at 37, while oyster culture demonstrated the lowest values (21 - 25%). This was also reflected in the payback period, which measures the required return time of the invested money. For macroalgae, the return time was < 1 year, for fish culture 2 – 3 years and for oysters 3-4 years. The capital was, in other words, recovered 5 times faster in the macroalgae production than in the oyster culture. The low return time for macroalgae was a result of the low initial investment in facilities and the rapid production cycle (about 45 days), while in oyster culture the comparative long production cycle (approximately 8 months) and low selling price limits the return time on investment. In comparison, the values for tilapia and shrimp were generally similar to those observed in the present study, with internal rate of return ranging from 20 to more than 100% and payback period from 1.5 to 6.0 years. Even so, payback periods lower than 5 years is acceptable.

The indicator **Benefit-cost ratio** measures the money that returns per money unit invested. Each USD invested in macroalgae culture generated US\$ 15 but only US\$ 0.46 in subtropical oyster culture. Values of < 1 indicates that the production is not profitable, as in the case of oyster culture. Again, IMTA systems showed higher returns than fish monoculture. The **Net present value** measures how much money the entrepreneur will receive during 20 years of culture discounted to the present day value. The values were divided by tonne produced (live wet weight) to allow comparisons of production in different scales. The IMTA culture generated very high values, reaching about US\$ 60 000, i.e., 3 times the value obtained in subtropical fish monoculture and about, or more than, 10 times the values of the other cultures studied. It is mainly due to the high value of the prawns and the high productivity obtained in IMTA that compensate for the fixed costs. Benefit costs ranging from < US\$ 1.00 to US\$ 5.00 and net present values higher than US\$ 50000/t are commonplace in tilapia and shrimp culture. To summarise, **among the evaluated cases, macroalgae culture showed significant benefits with the highest return on investments delivered quickly, although the fish IMTA cases also performed well, in particular for the estimated net present value.**

#### 4.2.3.c. Externalities

Externalities are the benefits or damage caused by the production system to unrelated third parties (Pigou, 2005). Ecosystem services and disservices of any economic activity (see D6.2, Marinho et al., 2022) are positive and negative externalities. In this study, positive externalities are the benefits provided to unrelated third parties due to aquaculture. Negative externalities are the damages caused to unrelated third parties, such as traditional economic activities in the region (e.g., artisanal fisheries,

tourism) and to the environment. The major positive externalities of aquaculture are the environmental services provided, such as sequestering P and N from a water body, which are retained in the biomass produced, accumulation of water inside ponds, improvement of air relative humidity (in the case of dry regions), absorption of CO<sub>2</sub> from the atmosphere and providing habitats for different aquatic and terrestrial species. Negative externalities include the removal of vegetation and soil erosion during land-based pond construction, displacement or elimination of extractive areas used by local communities (such as areas previously used to capture of wild crabs or bivalves), disrespect of common properties affecting traditional communities, and release of pollutants and exotic species to the environment (Valenti et al., 2018). Both positive and negative externalities can be quantified and valued in US\$ per unit of production and included in the costs and incomes of the relevant production system.

Overall, in this study, fish culture demonstrated the highest positive externalities compared to culture of extractive species, yet fish culture also demonstrated the highest negative externalities. In fact, for fish culture, the negative externalities were twice as high as the positive externalities. In extractive culture, the positive externalities, however, greatly outweighed the negative externalities. These results should, however, be interpreted carefully. Only absorption and emissions of N, P, C, and greenhouse gases were measured. These are some of the most important externalities, but many others certainly occur in aquaculture systems. As an example, Pereira et al. (2021) described 22 externalities in a culture of the red macroalgae *Hypnea pseudimusciformes*, but were able to measure only the same three as used in this study. Determining, measuring, quantifying and evaluating all externalities of a process or a farm remains a great challenge, as also observed during the work with D6.2, (Marinho et al., 2022). Despite the difficulties in determining externalities in aquaculture, they provide essential information for assessing sustainability. Assessments of externalities is also crucial for governance and policy-makers to prioritize what activities to support, and for defining taxes or compensations for farmers and the affected third parties. The lack of data is undoubtedly a critical gap that researchers, farmers, non-governmental organizations and different agencies must fill in the following years. In summary, ***extractive species display significantly higher positive than negative externalities while fish culture demonstrated the opposite results***. For more information about methods to value externalities in low trophic species aquaculture, please refer to D7.5.

#### 4.2.3.d. Income

The **Net profit indicator** measures the net income of a farm minus the opportunity costs. The values were divided by tonne produced (Live wet weight) to compare the cultures in different scales. The IMTA systems generated the highest profits, about US\$ 8 000/t/year, which were 3 to 10 times the algae and other fish cultures and more than 30 times the oyster culture. The subtropical oyster culture did not generate any profit. Values of net profit for shrimp and tilapia ranged from negative (lost money) to about US\$ 4 000/t/year. The **Investment generated by the activity indicator** measures the capacity of a farm to perform re-investments after paying all expenses. A sustainable farm should be perennial. Thus, it is necessary to generate capital to replace assets over the end of their useful life or obsolescence, introduce innovative technologies or make expansion. In this study, all systems generated capital to replace assets, but the values were < 1%, which is insufficient. In tilapia and shrimp culture the values ranged from zero to about 10%.

The **Annual Income indicator** is the sum of profit and opportunity costs. This value is close to the net revenue. This indicator is suitable for assessing small family farms. Small farmers are generally

interested only in maintaining a good standard of living for their families instead of high profit. Thus, the economic feasibility indicators are less relevant than for larger farms. A positive annual income indicates that the farm may be sustainable. Nevertheless, this is not sufficient. The annual income must ensure that the farmer can continue pursuing the activity, acquiring all or a substantial part of his maintenance needs from aquaculture. In the studied systems, the highest annual income was observed in the fish and US\$ 4 528/t for the other systems. This can be compared to the per capita income in the farm region and annual income, and makes it possible to calculate the capacity of an aquaculture farm to sustain families of different sizes living according to the region's mean lifestyle. The annual income values in the shrimp and tilapia systems studied ranged from negative (lost money) to about US\$ 5 000/t/yr. To summarise, **IMTA systems demonstrated the highest profits and annual incomes, yet all of the evaluated systems showed too limited investment capacity to maintain the activities in the long term.**

#### 4.2.3.e. Resilience

**Permanence of the farmer in the activity** indicator measures the average business lifetime based on the time that each company dedicates to aquaculture. This is an estimate of the perennity of each farm or sector. In this study, the IMTA systems showed permanence values of 20 years, and macroalgae culture of 16 years. The fish monoculture systems were variable (7-20 years), and oyster culture showed permanence of about 10 years. Values around 20 years indicate that the activities survive for about one human generation. In tilapia and shrimp farms, permanence values of 30 years is common, but values lower than 10 years are also frequent, indicating either low sustainability of newly started operations, or an establishment of new operations over time. Consequently, based on the data in this study it can be deduced that the establishment of the farms analysed varies but that fish culture in general seem to either have a longer tradition or to show higher sustainability compared to oyster culture.

The indicator **Risk rate** measures the risks observed in aquaculture, which may threaten the farm's perennity and, consequently, sustainability. The major economic risks in aquaculture production can be divided into three categories: yield, market or price, and financial risks (Engle, 2019). These categories were detailed in eleven risk factors analysed in the present study. Tropical filtering mollusk showed the highest value of risk rate (85.7 %), whereas in macroalgae culture the risk rate was only 12.9 %. Lowest risk was observed in the IMTA activities (9 %). In comparison, the risk rate in tilapia culture is about 75 % and in shrimp farms normally lower than 50 %. The control of risks is generally disregarded in the aquaculture business. However, mapping and monitoring risks are essential for resilience and persistence as discussed in D6.4 (Lindblom et al. 2022) and D6.7 (Hughes, in.prep), yet analyses of risks and methods to obtain valuable data are scarce in aquaculture literature. This is another important avenue for future research and are some of the topics included in AV.

Resilience is an essential characteristic of sustainable systems, and it is related to perennity. Diversity is a common feature in developing resilience because it allows adaptations to changes in the environment, production technology, market, legal and financial backgrounds. The indicators **diversity of products** and **diversity of markets** measure the capacity of an aquaculture farm to adapt to changes that affect the business, such as in the environment, production technology, market, and the legal and financial situation. The IMTA systems studied showed twice the number of products than other systems and explored three markets: human food, biomitigation and bait-fish. The macroalgae culture had one product but explored five markets: human food, carrageenan extraction, animal food

additive, fertilizer, and the cosmetic industry. Therefore, farmers can adapt to changes in the selling price and demand in different markets by moving their production between them. In comparison, both fish monoculture and oyster culture displayed a low number of products aimed for one or two specific markets, hence showing low potential to cope with changing conditions. Similarly, the diversity of products is generally one also in tilapia and shrimp monoculture, but the diversity of markets ranges from 1 to 6.

The indicator **potential of economic resilience** measures the capacity of a farm to pay all costs if the production or gross income decreases. Therefore, the potential of economic resilience indicates how economically resilient the system is to negative impacts on yield, markets, or financial health induced by any adverse factors. In this study, macroalgae and sub-tropical oyster cultures had potential of economic resilience of about 85 %, which means these farms can face high mortalities or a reduction in the market size of about 85 %, but it still can pay farm costs. Conversely, the tropical cultures of oysters had a value of 14.3 %, indicating that a reduction in income of 15 % leads the farm to a negative balance. Values > 50 % are desirable in sustainable systems, and most of the studied systems achieved this value. In tilapia farmed in net cages, this value is generally higher than 70 % and for shrimp it is higher than 60 %.

Overall, *the IMTA systems were found to show high permanence, low risk rate and high product and market diversity, hence having the capacity to withstand adverse changes. In contrast oyster culture showed low permanence, high risk rate and low product and market diversification, yet nevertheless, together with macroalgae production, showed high economic resilience.*

#### 4.2.3.f. Circularity

The circular economy concept is based on looping that takes a minimum amount of raw materials from nature and transforms them into products that are used, reused, remade, and finally recycled to make products again (Boyd et al., 2020). This new concept is founded on the responsible use of resources to promote sustainable development (Moraga et al., 2019). Therefore, systems based on the principles of circular economy are more sustainable. Integrated aquaculture with its theoretical objective of zero waste, clearly matches the concept of the circular economy. However, recycling can also include processes that convert energy and nutrients unavailable for rearing animals or humans into an assimilable form. The indicator **number of circular processes** measures the number of circular loops and recycling processes inside the farm. In this study, macroalgae and filtering mollusk farms were observed to have 4 such processes, as both organism groups recover N, P, C and energy from the environment. Each resource's recovery represents one process with one unit score in the indicator. The IMTA systems analysed displayed a value of 2, which was related to the utilisation of organic particulate matter, diet wastes and feces of the tambaqui production by the shrimps. Tilapia and shrimp monoculture typically have values of 1, but as in the present study, IMTA of tilapia with two filter-feeding species increases the value to 3. Consequently, *extractive species show significant benefits in terms of circular processes, and IMTA can be used to enhance the circularity of fed culture systems.*

#### 4.2.3.g. General sustainability performance of the evaluated systems

The system "5. Fish monoculture in tropical, surface-based net-cages" was not used in the aggregated analyses because of the lack of most indicators. The analysis of each sub category (a-f) for the rest of the systems showed that **Capital efficiency** was the major weakness in all systems. **Circularity** was a strength in macroalgae and filtering mollusk systems. In IMTA systems, **Resilience** and **Income** were strengths, and in addition to capital efficiency, **Externalities** were the major weaknesses (Figure 10).

The most sustainable system was macroalgae culture, which subindex of economic sustainability ( $I_{eco}$ ) was 0.75. The IMTA systems showed  $I_{eco}$  of about 0.70. In the other systems,  $I_{eco}$  was approximately 0.50 (Figure 8).

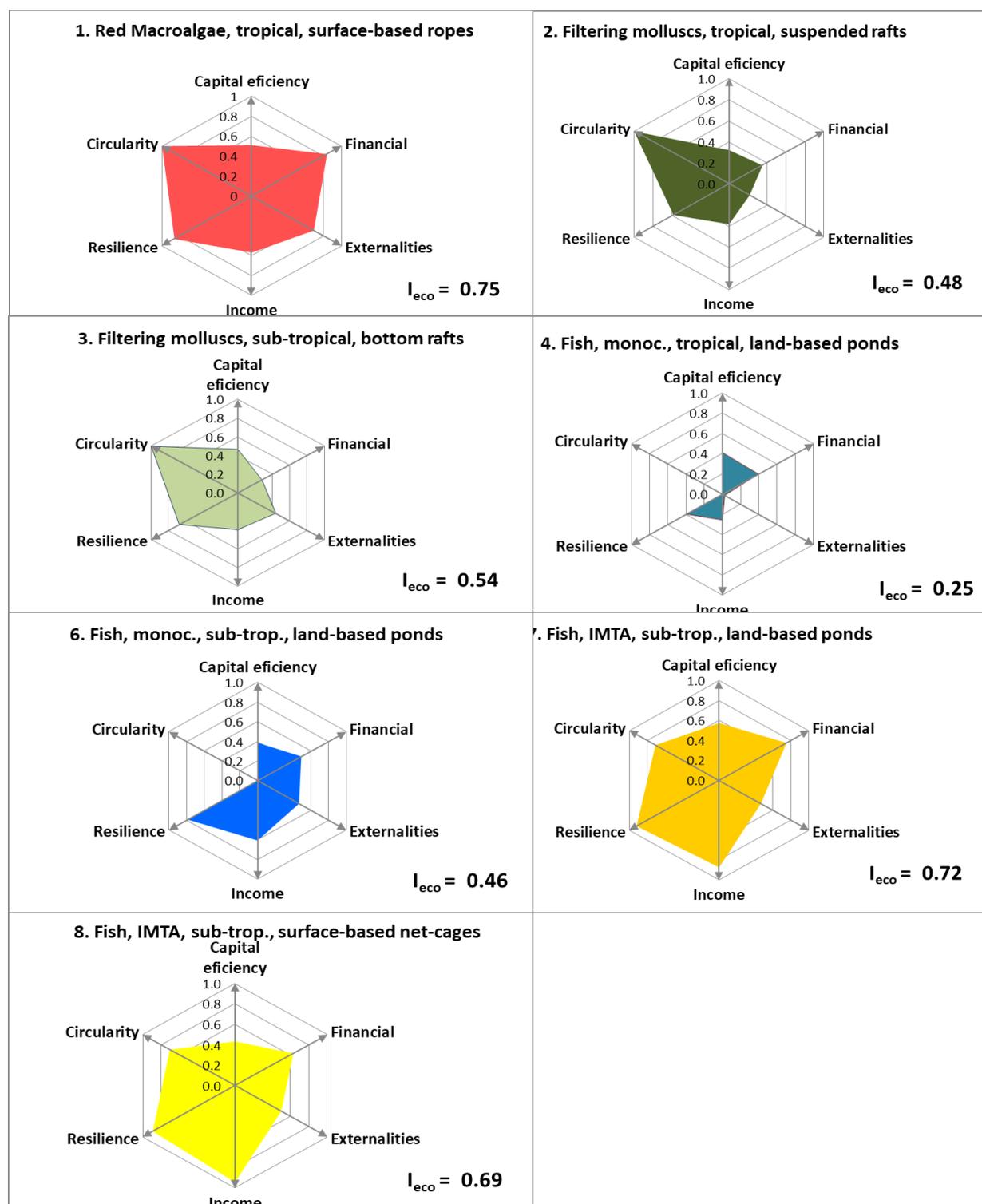


Figure 10. Multidimensional diagrams showing 6 sub-dimensions of economic sustainability. Please note that circularity was zero for fish monocultures, and the externalities value was 0.026 in fish land-based tropical monoculture. Sustainability increases from the center to the extreme of each axis. The colored area represents the economic sustainability of each system. Data from system 5 were insufficient to construct a multidimensional diagram.  $I_{eco}$  = sub-index of economic sustainability.

### 4.3 Governance

Governance has different characteristics from environmental, social and economic sustainability. Governance includes the farm, all supply chain stakeholders, and any other actors affected directly or indirectly by the business. Therefore, governance should be assessed at scale levels higher than a farm. Consequently, it is unsuitable to discuss the governance of each aquaculture system. The best approach describes governance by sector, political region, or for all Atlantic. Nevertheless, in the present study, stakeholders have answered the developed questionnaire based on the situation of the system in which they are engaged. These systems are set in the background of their relevant sectors and regions. Thus, these references to the systems were retained, but the data, in fact, refer to the sector and region level rather than the farm (or farm group) level. Thus, homogenous subgroups were determined, and general analyses were performed instead of investigations by systems to map and understand the governance of LTS aquaculture in the entire Atlantic Coast

#### 4.3.1. Subgroups with similar governance

The governance data was analysed using PCA to identify clusters or sub-groups related to the obtained answers. The PCA showed that most of the variables were associated to the first component (axis) but clear sub-groups could not be identified. Thus, this analysis did not help discriminate between the governance characteristics and identify the strengths and weaknesses of LTS aquaculture. The hierarchical cluster analyses showed results very similar to the partitioned cluster analysis, thus the partitioned cluster analysis was selected for the purpose of this report. This initial exploratory analysis was essential to determine whether to group the data by the AD (Lindblom et al. 2021), i.e., species groups, production mode (or culture systems), production location (land-based, near-shore, and off-shore), geographic areas (and regions, subregions). Five clusters were identified in the analysis: **purple, deep green, red, blue and pale green** (Figure 11, tables 10 to 14). The general homogeneity of each group was demonstrated by the frequency distribution of the scores inside the groups (Figure 12). The set of indicators for each cluster was computed to highlight the strengths and weaknesses of LTS aquaculture.

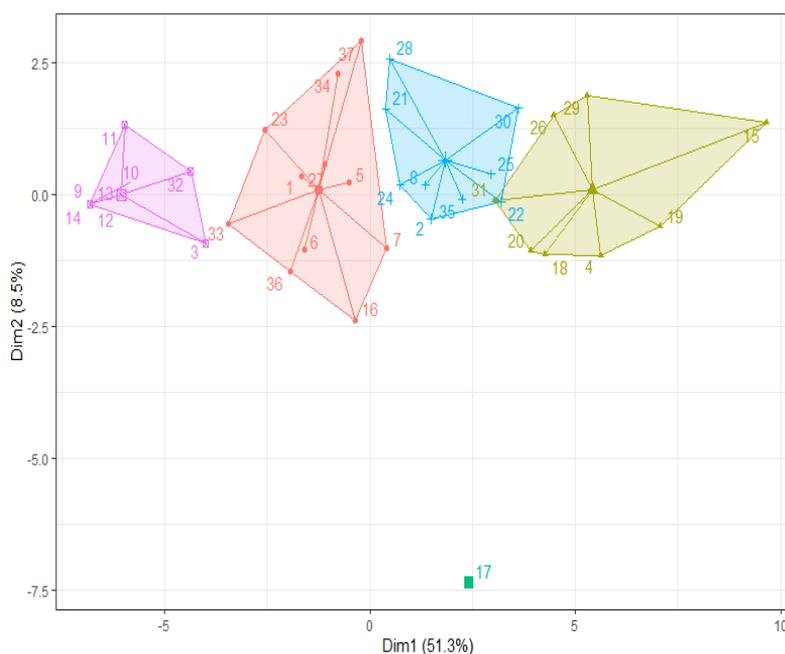


Figure 11. Cluster diagram showing the pooled systems (numbers 1 to 37), according to the level of governance. Governance decreased in the purple, deep green, red, blue and pale green sequence. See tables 10 to 14 to identify each system numbered 1 to 37. Dim1 and Dim2 are two major factors defined in the multivariate analyses.

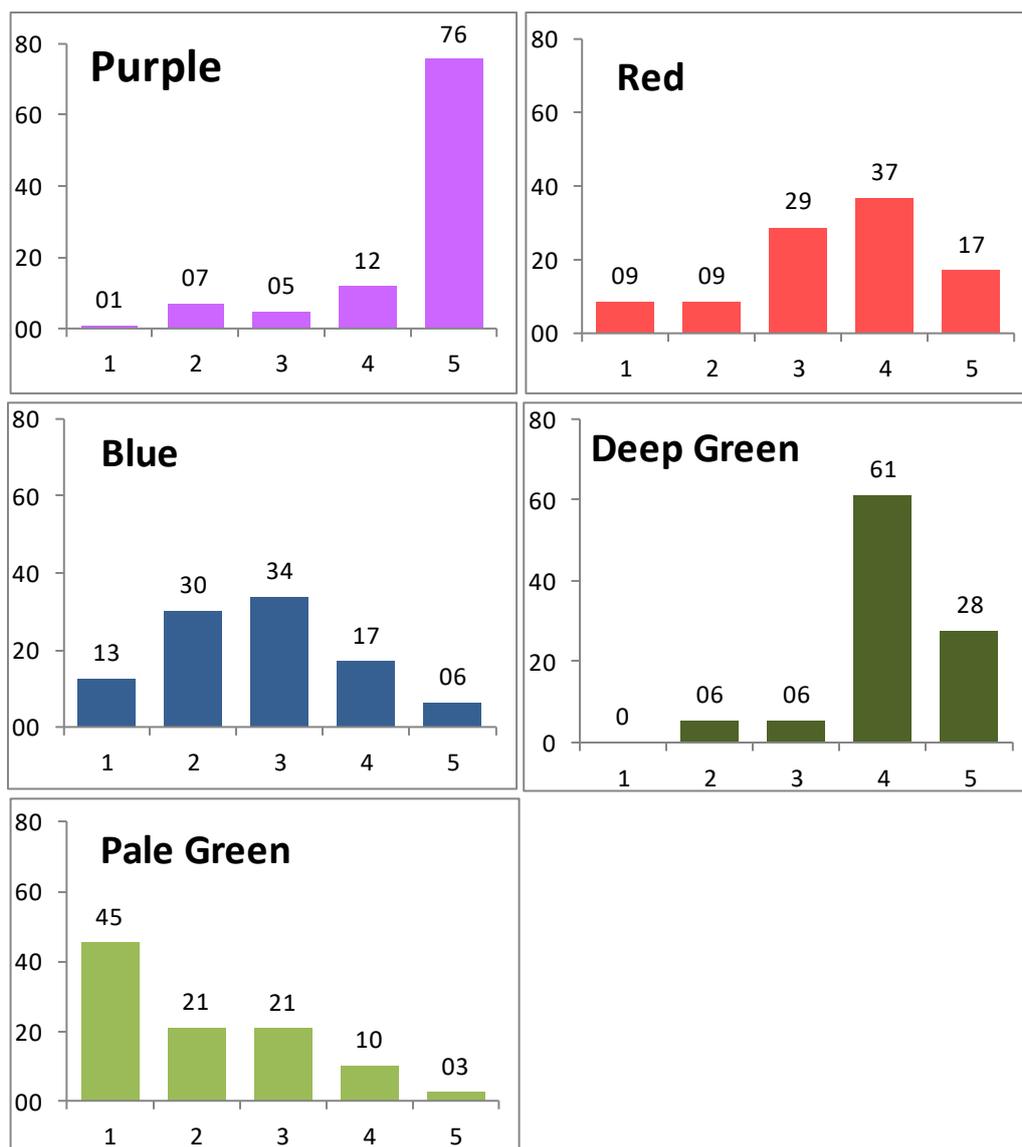


Figure 12. Relative frequency of the scores obtained for the analysed indicators in all aquaculture systems of the same cluster. The height of bars represent the relative frequency and figures above the bars are the absolute frequency of indicators that receive the relevant score. Sustainability increases from 1 to 5.

The **purple group** included the systems/sectors with more developed governance, which can be classified as **very high-levels** of governance (Figure 12). This group included abalone culture in France and the production of filtering mollusks in the USA (Table 10). The **red group** had **high-levels** of governance (Figure 12). This included the culture of brown macroalga in Faroe Island, filtering mollusks in Canada, Sweden, and some in Brasil, abalone in South Africa and sea urchin in Norway and Spain (Table 11). The **blue group** showed moderate governance and can be classified as **medium-level** governance. This group is comprised of the culture of abalone in South Africa, green-red algae and most of the filtering mollusk cultures in Brazil, filtering mollusks in Namibia and brown macroalgae in Sweden (Table 12). The **deep green group** contained only data from Norway's aquaculture sector, which is based on Atlantic salmon culture (Figure 12, Table 13). As only one questionnaire was obtained for this case, and as the questionnaire was incomplete, these data should be treated with care and was therefore excluded from further analysis. The **pale green group** had **low-levels** of governance and was comprised of red-green macroalgae, filtering mollusks and freshwater fish in Brazil, and filtering mollusks in Denmark (Table 14). System number 15, i. e.,

filtering mollusks in Maine, USA, appears in this group because about 50% of questions were not filled, thereby decreasing its score. Thus, this system was excluded from the subsequent analyses.

Table 10. Description of the organism groups, species, systems used, and the relevant areas of systems grouped in Purple Cluster, which showed high-level governance. Geographical Area 21 = North America, Atlantic Northwest; Geographical Area 27 = Europe, Atlantic Northeast; Geographical Area 41 = South America, Atlantic Southwest; Geographical Area 47 = Africa, Atlantic Southeast. CS = case study of AquaVtae.

Label in Fig. 10	Farmed organism group	Farm system	Region, Country	Geographical area			
				21	27	41	47
3	Abalone, (CS4) South African abalone ( <i>Haliotis tuberculata</i> ) and European abalone ( <i>Haliotis midae</i> )	Sea-based IMTA	France, Europe		x		
	<i>Ulvella lens</i> (Green algae), <i>Ulva</i> sp and <i>Gracilaria</i> sp (green & red macroalgae) <i>Holothuria forskali</i> and <i>Holothuria sanctori</i> (Sea cucumber)						
9	Filtering Mollusks Eastern oyster ( <i>Crassostrea virginica</i> )	Surface longlines	Maine, USA North America	x			
10	Filtering Mollusks Blue mussel ( <i>Mytilus edulis</i> )	surface longlines	Maine, USA North America	x			
11	Brown Macroalgae Sugar kelp ( <i>Saccharina latissima</i> )	surface longlines	Maine, USA North America	x			
12	Filtering Mollusks Eastern oyster ( <i>Crassostrea virginica</i> )	surface longlines	Rhode Island, USA North America	x			
13	Filtering Mollusks Eastern oyster ( <i>Crassostrea virginica</i> )	surface longlines	Connecticut, USA North America	x			
14	Filtering Mollusks Clam ( <i>Mercenaria mercenaria</i> )	surface longlines	Connecticut, USA North America	x			
32	Filtering Mollusks Eastern oyster ( <i>Crassostrea virginica</i> )	Off-bottom cages (mid-water column, floating)	Virginia, USA North America	x			
<b>Total</b>	-	-	-	<b>7</b>	<b>1</b>	<b>0</b>	<b>0</b>

Table 11. Description of the organism groups, species, systems used, and the relevant areas of systems grouped in the Red Cluster with medium-level governance. Geographical Area 21 = North America, Atlantic Northwest; Geographical Area 27 = Europe, Atlantic Northeast; Geographical Area 41 = South America, Atlantic Southwest; Geographical Area 47 = Africa, Atlantic Southeast. CS = case study of AquaVtae.

Label in Fig. 10	Farmed organism group	Farm system	Region, Country	Geographical area			
				21	27	41	47
1	Brown Macroalgae CS2 Sugar Kelp ( <i>Saccharina latissima</i> )	Offshore macroalgae cultivation	Faroe Island, Europe		x		
5	Filtering Mollusks Blue mussel ( <i>Mytilus edulis</i> )	surface and bottom based	Newfoundland, Canada, North America	x			
6	Filtering Mollusks General for the country Eastern oyster ( <i>Crassostrea virginica</i> ), Pacific oysters ( <i>Crassostrea gigas</i> ); Blue mussel ( <i>Mytilus edulis</i> ); Hard clam ( <i>Mercenaria mercenaria</i> ) and Manila clam ( <i>Ruditapes philippinarum</i> ); Giant or sea scallop ( <i>Placopecten magellanicus</i> ), Northern Bay Scallop ( <i>Argopecten irradians irradians</i> ), Pacific or Quahog scallop ( <i>Patinopecten caurinus</i> x <i>P. yessoensis</i> hybrid); Other clams and scallops	Suspension and Bottom culture and surface longlines	Canada, North America	x			

7	Shrimp + macroalgae + fish (CS5) <i>whiteleg shrimp (Litopenaeus vannamei)</i> + <i>Ulva sp</i> + Mulet ( <i>Mugil cephalus</i> )	Biofloc IMTA	Santa Catarina, Brazil	x
16	Filtering Mollusks European flat oyster ( <i>Ostrea edulis</i> )	Surface cages (floating) and suspended longlines	Sweden, Europe	x
23	Filtering Mollusks Brown mussel ( <i>Perna perna</i> )	Suspended longlines	Penha, Santa Catarina, Brazil	x
27	Filtering Mollusks Mangrove oyster ( <i>Crassostrea gazar</i> )	Suspended rafts, longlines and ponds	Curuperé, Pará, Brazil	x
33	Abalone (CS3) European abalone ( <i>Haliotis midae</i> ) and South African abalone ( <i>Haliotis tuberculata</i> ), together with macroalgae and filtering mollusks	IMTA	South Africa and Namibia, Africa	x
34	Filtering Mollusks European flat oyster ( <i>Ostrea edulis</i> )	Surface cages (floating) and suspended longlines	Sweden, Europe	x
36	Sea urchins (CS6) Green sea urchin ( <i>Strongylocentrotus droebachiensis</i> )	Land-based indoor tanks	Norway, Europe	x
37	Sea urchin (CS6) Purple sea urchin ( <i>Paracentrotus lividus</i> )	Land-based indoor tanks	Spain, Europe	x
<b>Total</b>	-	-	-	<b>2 5 3 1</b>

Table 12. Description of the organism groups, species, systems used, and the relevant areas of systems grouped in the Blue Cluster with a moderate-level of governance. Geographical Area 21 = North America, Atlantic Northwest; Geographical Area 27 = Europe, Atlantic Northeast; Geographical Area 41 = South America, Atlantic Southwest; Geographical Area 47 = Africa, Atlantic Southeast. CS = case study of AquaVtae.

Label in Fig. 10	Farmed organism group	Farm system	Region, Country	Geographical area			
				21	27	41	47
2	Abalone (CS3) South African abalone ( <i>Haliotis tuberculata</i> ) and European abalone ( <i>Haliotis midae</i> ) Abalone + <i>Ulvella lens</i> , <i>Ulva Gracilaria</i> + <i>Holothuria forskali</i> and <i>Holothuria sanctori</i>	Land-based IMTA	South Africa, Africa				x
8	Filtering Mollusks Pacific oyster ( <i>Crassostrea gigas</i> )	Surfacebased systems (longlines) and some in ponds	Namibia and South Africa, Africa				x
21	Filtering Mollusks Pacific oyster ( <i>Crassostrea gigas</i> ) and Mangrove oyster ( <i>Crassostrea gazar</i> )	Bottom based rafts	Cananeia, São Paulo, Brazil			x	
22	Filtering Mollusks Scalop ( <i>Nodipecten nodosus</i> ) and Brown mussel ( <i>Perna perna</i> )	Bottom-based Longlines (Scalop) and surface- based ropes (mussel)	Ilhabela, Sao Paulo, Brazil			x	
24	Filtering mollusks Mangrove oyster ( <i>Crassostrea gazar</i> )	Suspended rafts, longline and ponds	Augusto Correia, Pará, Brazil			x	
25	Mussels + Fish Brown mussel ( <i>Perna perna</i> ) with Cobia ( <i>Rachycentron canadus</i> )	IMTA surface based net-cages	Ubatuba, São Paulo, Brazil			x	

		(fish), suspended rafts, longlines					
28	Red macroalgae elkhorn sea moss ( <i>Kappaphycus alvarezii</i> ) mangrove oyster ( <i>Crassostrea gazar</i> ), scallop ( <i>Nodipecten nodosus</i> ) and cobia ( <i>Rachycentron canadus</i> )	IMTA and monoculture; surface based net cages (fish), suspended rafts, longlines	Angra dos Reis (Region 1), Rio de Janeiro, Brazil			x	
30	Filtering mollusks Mangrove oyster ( <i>Crassostrea gazar</i> ) and and Scallops ( <i>Nodipecten nodosus</i> )	Bottom-based longlines (Scallop) and surfacebased ropes (oyster)	Angra dos Reis (Region 3), Rio de Janeiro, Brazil			x	
35	Brown macroalgae Sugar Kelp ( <i>Saccharina latissima</i> )	Longlines	Sweden, Europe		x		
<b>Total</b>	-	-	-	<b>0</b>	<b>1</b>	<b>5</b>	<b>2</b>

Table 13. Description of the organism groups, species, systems used, and the relevant areas of systems grouped in Deep Green Cluster, which also showed high-level governance, but lower than the purple group. Geographical Area 21 = North America, Atlantic Northwest; Geographical Area 27 = Europe, Atlantic Northeast; Geographical Area 41 = South America, Atlantic Southwest; Geographical Area 47 = Africa, Atlantic Southeast. CS = case study of AquaVtae.

Label in Fig. 10	Farmed organism group	Farm system	Region, Country	Geographical area			
				21	27	41	47
17	General Aquaculture (mainly salmon - <i>Salmon salar</i> )	Sea-based net-cages	Norway, Europe		x		

Table 14. Description of the organism groups, species, systems used, and the relevant areas of systems grouped in the Pale Green Cluster, with low governance. Geographical Area 21 = North America, Atlantic Northwest; Geographical Area 27 = Europe, Atlantic Northeast; Geographical Area 41 = South America, Atlantic Southwest; Geographical Area 47 = Africa, Atlantic Southeast. CS = case study of AquaVtae.

Label in the cluster diagram	Farmed organism group	Farm system	Region, Country	Geographical area			
				21	27	41	47
4	Filtering mollusks (CS9) Not informed – probably Blue mussel ( <i>Mytilus edulis</i> )	Not informed	Not informed		x		
15*	Filtering mollusks <i>General for bivalve mollusks</i> Eastern oyster ( <i>Crassostrea virginica</i> ), Blue mussel ( <i>Mytilus edulis</i> ), Hard clam ( <i>Mercenaria mercenaria</i> )	Monocultures Surfacebased cages (floating) and suspended longlines	Maine, USA, North America	x			
18	Freshwater fish (CS10) Tambaqui ( <i>Colosoma macropomum</i> )	Monoculture and IMTA with prawns. Ponds and net-cages	General data for Brazil			x	
19	Red-green macroalgae Hypnea ( <i>Hypnea pseudomusciformis</i> ), elkhorn sea moss ( <i>Kappaphycus alvarezii</i> )	Tropical, surfacebased ropes and rafts	Flexeiras, Ceará, Brazil			x	
20	Red-Green macroalgae Hypnea ( <i>Hypnea pseudomusciformis</i> )	Surfacebased ropes and rafts	Comuraxatiba, Bahia, Brazil			x	
26	Filtering mollusks Scallop ( <i>Nodipecten nodosus</i> ) and Brown mussels ( <i>Perna perna</i> )	Suspendedbased rafts, ropes and ponds	Ubatuba, São Paulo, Brazil			x	
29	Filtering mollusks Mangrove oyster ( <i>Crassostrea gazar</i> ), Scallop ( <i>Nodipecten nodosus</i> )	Bottom-based longlines (Scallop) and surfacebased	Angra dos Reis (Region 2), Rio de Janeiro, Brazil			x	

		ropes and rafts (oyster)			
31	Filtering mollusks (CS5)				
	Mangrove oyster ( <i>Crassostrea gasar</i> ), Red macroalgae ( <i>Ulva intestinalis</i> ) and shrimp ( <i>Litopenaeus vannamei</i> )	Organic IMTA in land-based ponds	Tibau do Sul, Rio Grande do Norte, Brazil	x	
<b>Total</b>				1	1
				6	0

The divisions of the Assessment Domain (Lindblom et al. 2021) was found to have little correspondence with the clusters discriminated by the multivariate analysis. The species groups macroalgae and filtering mollusks appeared in all clusters. Abalone appeared in purple, red and blue clusters. The data for sea urchins and fish was not sufficient to analyse because data was based on only two and one questionnaires, respectively. Land-based culture appears in red, blue and green clusters, while nearshore cultures appear in all clusters. Only one questionnaire on off-shore culture was returned. Monoculture and polyculture appear in all clusters. Geographical area 21 (north america) appeared only in clusters purple and red, area 27 (Europe) in all clusters, and area 41 (Brazil) in red, blue and green clusters. Area 47 (South Africa and Namibia) appeared in red and blue clusters, but only three questionnaires was returned from this area, impairing any conclusions. The patterns observed in the clusters could also not be explained by climate zone (tropical, subtropical and temperate), or geographical divisions such as northern and southern Europe. Consequently, ***the results of the multivariate analyses indicate that governance is heterogeneous inside each division of the AD.*** Thus, grouping the systems in these categories does not make sense, and instead, each cluster should be analysed separately to identifying strengths and weaknesses of LTS aquaculture governance and learning lessons towards increasing governance sustainability. Thus, indicators of sustainability to assess governance were computed by each cluster (Table 15).

Table 15. Indicators of governance sustainability obtained for each cluster and for all studied systems pooled (All Atlantic). See tables 4.7 to 4.11 for details about the clusters. Sustainability increases from zero to 1. Note that All Atlantic column values are not the means for the clusters' scores for each indicator. Letters a to f means the subgroups cited in section 3.2.2. The top three and bottom three scores for the all Atlantic values are highlighted in yellow and grey, respectively. In the case of a draw (equal scores) between the third and fourth index, all cases with a similar score were marked. The deep green cluster is not marked due to only one replicate existing in this cluster and as data is missing.

Analysis category	Indicator Name	Cluster					
		Purple	Red	Blue	Deep Green	Pale Green	All Atlantic
		Indicator Value					
a	Coordination of collective interest	0.96	0.63	0.64	0.80	0.44	0.67
a	Interaction between public & private sectors	0.96	0.67	0.62	0.80	0.40	0.67
a	Transparency of stakeholders	0.98	0.63	0.64	-	0.48	0.68
a	Managing conflicts	0.93	0.67	0.40	0.60	0.28	0.58
a	Sharing power	0.95	0.63	0.60	0.80	0.40	0.65
a	Collaboration among stakeholders	0.91	0.72	0.56	-	0.40	0.64
a	Cooperatives and Associations	0.96	0.83	0.80	0.80	0.54	0.78
b	Obtention of permits	0.47	0.52	0.42	0.80	0.23	0.43
b	Tax policy	0.93	0.68	0.57	-	0.50	0.68
b	Clear rules and regulations	0.96	0.73	0.66	0.80	0.48	0.72
b	Inclusion in territorial management planning	0.98	0.77	0.70	1.00	0.33	0.75
b	Inclusion in land/water use planning	0.98	0.77	0.68	1.00	0.47	0.75
b	Inclusion in public planning	0.98	0.87	0.60	1.00	0.33	0.76
c	Access to workforce training	0.98	0.72	0.64	0.80	0.43	0.71
c	Access to Extension services	0.98	0.73	0.70	0.60	0.47	0.72
c	Access to equipment maintenance	1.00	0.62	0.52	0.80	0.28	0.62

c	Access to specialized services	0.98	0.73	0.52	1.00	0.30	0.66
d	Access to Equipment	1.00	0.67	0.44	0.80	0.38	0.63
d	Access to supplies	0.98	0.63	0.46	-	0.35	0.62
d	Share of costly equipment and services	0.40	0.62	0.50	0.40	0.30	0.47
e	Public social transparency	0.98	0.56	0.40	-	0.29	0.57
e	Public financial transparency	0.98	0.68	0.33	-	0.30	0.61
e	Farmers financial transparency	0.98	0.72	0.50	-	0.35	0.65
e	Non-farmer Stakeholders' financial transparency	0.96	0.68	0.33	-	0.50	0.65
f	Access to Transport	0.98	0.72	0.44	0.60	0.30	0.62
f	Access to Energy	0.98	0.60	0.46	0.80	0.35	0.61
g	Access to new technologies	1.00	0.70	0.54	0.80	0.28	0.64
g	Access to credit and loans	0.98	0.55	0.52	1.00	0.28	0.60
h	Sanitary and Biosecurity	0.96	0.90	0.46	0.80	0.40	0.71
h	Product quality control	0.93	0.82	0.44	0.80	0.23	0.65
h	Certification availability	0.96	0.67	0.30	-	0.40	0.59
h	Efficacy of certification	0.82	0.63	0.29	-	0.28	0.56
i	Consumers proximity	0.98	0.63	0.58	-	0.53	0.67
i	Local population perception	0.60	0.75	0.82	-	0.63	0.71
i	Consumer perception	0.69	0.75	0.80	-	0.78	0.76
Subindex of governance		0.91	0.69	0.54	0.73	0.39	0.65
N responses		8	11	8	1	8	36

All indicators in the purple (very high governance) group showed very high scores close to the maximum (0.9-1.0), except for the indicators:

- Obtention permit (0.40)
- Share of costly equipment and services (0.47)
- Local population perception (0.60)
- Consumer perception (0.69) of aquaculture

which were identified as the main weaknesses in this group (Table 15). The subindex of governance sustainability ( $I_{gov}$ ) was 0.91.

The major strengths (left) and weaknesses (right) of the red group were the existence of:

- Sanitary and Biosecurity (0.90)
- Inclusion of aquaculture in public plans (0.87)
- Cooperatives and associations (0.83)
- Obtention of permits (0.52)
- Access to credit and loans (0.55)
- Public social transparency (0.56)

The value of  $I_{gov}$  was 0.69.

The blue group had almost all indicators ranging close to 0.50, but the major strengths of the blue group were the existence of:

- Cooperatives and associations (0.80)
- Consumer perception (0.80) of aquaculture
- Local population (0.82)

Certification availability and Efficacy of certification were identified as the weakest points. The  $I_{gov}$  value was 0.54.

The pale green group had almost all indicators below 0.5 showing poor governance. However, Local population perception (0.63) and Consumer perception (0.78) were strengths and the values were even higher than those obtained in the purple group. The  $I_{Gov}$  was 0.39 (Table 15).

Moreover, some topics were general for several groups. This **included cooperatives and associations which was scored high in most groups, while obtaining permits was generally scored low in most groups**. Further studies should be done to refine the information inside every group to look for the actions that improve the governance of LTS aquaculture in the Atlantic region. Bar graphs illustrating the level of sustainability of each indicator are available in Appendix 3.

#### 4.3.2. Governance of LTS aquaculture around the Atlantic

As for the other sustainability domains, the indicators were also analysed in sub-groups as described in section 3.2.4. The subindex of governance computed for each of these aspects are presented in Figure 13. They ranged from 0.57 for Access to supply, to 0.71 for Consumers' proximity and Perception of aquaculture by consumers and neighbors.

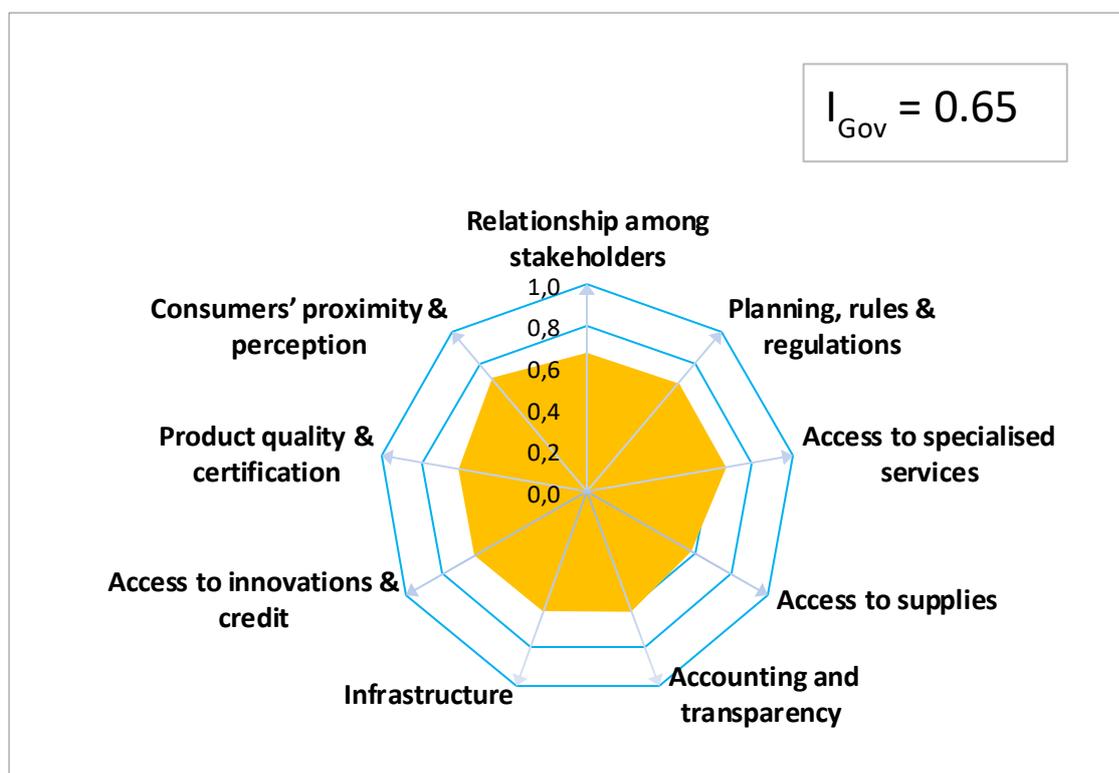


Figure 13. Subindices of Governance sustainability for all Atlantic LTS Aquaculture. The yellow area represents governance sustainability.  $I_{Gov}$  = Index of governance sustainability.

In general, the **Relationship among stakeholders** was found to be relatively sustainable in LTS aquaculture governance in the Atlantic (Figure A3.1, Table 15). This is mediated through proper coordination among all stakeholders and cooperation between public and private sectors, and farms are organized in cooperatives and associations. This last topic is a significant strength. Regional management is open and honest, but power is relatively concentrated in government decision-makers. The major weaknesses are lack of an effective arrangement to manage conflicts, and lack of collaboration driven to improve production. Aquaculture is included in the development and management of maritime and coastal plans (Figure A3.2, Table 5). This infers an opportunity to have

LTS culture included in government programs. Thus, it is necessary to show to policy-makers the environmental and economic advantages of LTS farming compared to the culture of high-trophic level species. Moreover, **Rules, regulations and environmental legislation** are generally suitable, yet the tax policies should be improved to match the interest of farms and other stakeholders and the licensing process was observed to be a major weakness (Figure A3.2). Unclear environmental legislation, high costs and bureaucracy in obtaining licenses and permits have been reported in USA and Brazil (Engle et al. 2019; Valenti et al., 2021; Engle & van Senten, 2022).

**Specialized services** are essential for perennial and sustainable aquaculture. Skilled persons from universities provide access to innovation, new technologies, and the capacitation of the workforce. Extension services are fundamental to following up the production, assisting farmers in solving problems, and improving management. Extensionists also spread new technologies and innovations. Specialized laboratories help farms control the quality of seeds, feed and organism health during production. Extension service is a major strength in the culture of LTS in the Atlantic and capacitation of the workforce is also available and provided by the public sector (Figure A3.3, Table 15). However, extension is deficient in some places, such as in Brazil (Valenti et al., 2021) and skilled workers or companies that provide equipment maintenance and perform specialized analyses may be unavailable in some regions.

**Access to supplies** is generally acceptable, but sharing expensive equipment among farms is not common, which is a weakness (Figure A3.4). This is surprising because farmers are generally organized in cooperatives and associations, which could promote the collective use of high-cost equipment. This situation also indicates low farm cooperation and, consequently, inadequate governance.

Financial and production **accounting** and **transparent** reports from all local stakeholders are critical topics for effective governance. The results related to these topics are variable in the culture of LTS around the Atlantic (Figure A3.5) and should be improved. Accounting of production and production costs associated with transparency is essential for farms to negotiate prices of supplies with the providers and the selling price of the yield with clients. In addition, public institutions should have organized financial and social accounts, which should be available to all stakeholder that pays taxes. These topics are well-developed in North American LTS value chains and meet stakeholders' expectations in the USA and Canada. However, it is quite variable in other Atlantic regions.

Access to **infrastructure** is site-specific and varies from country to country and even in different regions of the same country. Transport and energy are major elements. Generally, small farmers use trucks to transport their yield. Thus, the quality of roads and fuel prices are essential. Transport is usually suitable, but energy is expensive, which increases production costs (Figure A3.6).

Farms have opportunities to know and test new technologies and participate in **innovation** programs, but **credit access** is difficult in many regions (Figure A3.7). This means that producers may want to move to novelties to improve their products but have difficulty obtaining capital to promote the change. Specific credit programs with low-interest rates to finance aquaculture are necessary to modernize production processes. Sometimes the earmarked funding for the development of innovative solutions are available but not accessible (Valenti et al., 2021). The main bottlenecks in accessing credit are the difficulty of farmers in providing the requested documents and the low level of information from bank employees about aquaculture, which increases the uncertainties in the

sector. The European Maritime, Fisheries, and Aquaculture Fund<sup>6</sup> is a good example of industry relevant funding available to develop and implement innovations on industry scale.

**Quality control** in all the value chain elements is essential for delivering high-quality products and competing in the market. It includes regular sanitary inspection and biosecurity programs. Biosecurity should prevent the risk of biological contamination of broodstocks, seeds, or even the final yield. In general, biosecurity actions and sanitary inspection are practiced in LTS farms around the Atlantic (Figure A3.8). Programs to control the quality of aquaculture products are effective in several regions but weak or absent in others (Figure A3.8). Food safety perspectives and frameworks related to LTS aquaculture and the extent of monitoring, including for food safety purposes, has been explored both in WP5 and WP6 in AV. WP5 has developed guidelines for food safety in LTS aquaculture (D5.1 Report on health risk-benefit assessment based on selected Case Studies and D5.4 Guidelines on health risk benefit assessment of LTS aquaculture products, please refer to Edel O. Elvevoll, UiT, AV, for more information), and in WP6, consumer safety was highlighted both in the risk assessment of LTS aquaculture production (Lindblom et al., 2022) and in the census of monitoring programs under development (Hughes, in prep). However, in many places, quality standards and certification possibilities, especially certifications that incorporate the complex interactions between all different sustainability domains, are lacking, making it difficult to monitor and evaluate product sustainability. Quality programs should be audited, and farms that meet the requirements should have their products **certified**. However, certification is still scarce, expensive and mostly ineffective (Figure A3.8).

Farms of LTS in the Atlantic are often placed close to consumers allowing direct contact with them, their participation in the local decisions, and a locally better perception of aquaculture. In addition, farms can contribute to regional food security. The **perception of aquaculture for local people and consumers** was positive (Figure A3.9). This is undoubtedly a strength to reach good governance. The participation of consumers and people living around farmers is critical to achieving sustainable governance. The positive perception of the activity allows more participation and effective contributions to the process. The recorded survey responses, however, represents mainly the industry's view of the locals perception of LTS aquaculture as the local people were not interviewed or asked to respond to the survey. Similar results (a positive view of LTS aquaculture products) was, however, noted by WP5 during their work with D5.2 (Consumer acceptance of Low Trophic Aquaculture Products), which strengthens the results obtained in the present study.

Overall, the general index of governance in this study was 0.65 and the sub-index scores were well balanced in the nine different sub-categories analysed (Figure 15). Therefore, the governance in the Atlantic LTS aquaculture is acceptable. However, there is space for improvement in most regions. In the US, the index of sustainable governance was 0.91, showing that improving the LTS culture sector governance is feasible. Many experiences can be made from studying the North American governance system related to LTS aquaculture.

#### 4.4. Overall sustainability

To enable a calculation of the overall sustainability of the 8 LTS aquaculture systems previously analysed using the environmental, social and economic indicators, the governance domain sub-index of sustainability was also calculated for culture systems of macroalgae (governance system #19 (Table 10-14)), filtering mollusks (governance system #27, #21 and #24 (Table 10-14)), and fish (governance system #18 (Table 10-14)) in Brazil. The selected cases corresponded to the systems used in the

<sup>6</sup> [https://oceans-and-fisheries.ec.europa.eu/funding/emfaf\\_en](https://oceans-and-fisheries.ec.europa.eu/funding/emfaf_en)

analysis of the environmental, social and economic dimensions and were selected based on production system, production area and type of production (monoculture/IMTA). The analysis showed highest governance in filtering mollusks (0.59 and 0.61), while the macroalgae showed the lowest (0.26, Table 16).

The sub-indices of environmental (section 4.2.1.g), social (section 4.2.2.g) and economic (section 4.2.3.g) sustainability and governance (Table 16) were then combined to compute general indices of sustainability for each system analysed in section 4.1 (Table 16). The sustainability indices were calculated according to sustainability models 1 and 2 (see section 2.2), for which the same weights were assigned to each dimension, and according to model 3, for which weighted values for the environmental, social, economic and governance, were used. The models produced similar results both in terms of sustainability index values and in terms of the sequence of farms (from highest to lowest sustainability values).

The sustainability performance of macroalgae and bivalve systems was higher compared to that of fish (Figures 14 and 15). The most sustainable system was the tropical culture of filtering mollusks followed by the subtropical culture of filtering mollusks and red macroalgae (Table 16). Moreover, the sustainability performance of macroalgae and bivalve systems were higher than that of fish, and the two IMTA systems performed better than the monoculture of fish (Table 16, Figures 12 and 13). In general, it was not possible to detect any differences between climate zones based on the available data. It is essential to highlight that the sustainability indices integrate more than a hundred variables that were used to calculate the indicators of the four dimensions. Therefore, the information content in the specific numbers presented in table 16 is very high, and consequently, low differences may be highly significant. Statistical methods have not yet been developed to assess the significance of the differences between two or more sustainability indices.

Table 16. Subindices and indices of sustainability computed for the 8 LTS aquaculture systems. The indices of sustainability were computed considering the conceptual model of the three pillars (model 1), intersecting spheres (model 2) and hierarchical-dependent (model 3).

Case	1.	2.	3.	4.	5.	6.	7.	8.
<b>Organism group</b>	Red macro-algae	Filtering moluscs				Fish		
<b>Type of production<sup>1</sup></b>	M	M	M	M	M	M	IMTA	IMTA
<b>Climate<sup>2</sup></b>	T	T	ST	T	T	ST	ST	ST
<b>System type<sup>3</sup></b>	SBR	SR	BBT	LBP	SBNC	LBP	LBP	SBNC
<b>N farms (N total units)</b>	1 (3)	15 (15)	9 (9)	3 (9)	3 (3)	1 (3)	1 (3)	1 (3)
<b>Subindex of Environmental sustainability</b>	0.70	0.72	0.63	0.49	0.55	0.47	0.46	0.46
<b>Subindex of social sustainability</b>	0.65	0.67	0.59	0.58	0.36	0.58	0.64	0.61
<b>Subindex of Economic Sustainability</b>	0.75	0.48	0.54	0.25	0.29	0.46	0.72	0.69
<b>Subindex of governance</b>	0.26	0.58	0.60	0.39	0.39	0.39	0.39	0.39
<b>Index of sustainability Models 1 and 2*</b>	<b>0.59</b>	<b>0.61</b>	<b>0.59</b>	<b>0.43</b>	<b>0.40</b>	<b>0.47</b>	<b>0.55</b>	<b>0.53</b>
<b>Index of sustainability Model 3#</b>	<b>0.60</b>	<b>0.63</b>	<b>0.60</b>	<b>0.44</b>	<b>0.41</b>	<b>0.48</b>	<b>0.55</b>	<b>0.53</b>

<sup>1</sup> M=Monoculture, IMTA=polyculture

<sup>2</sup> T=tropical, ST=sub-tropical

<sup>3</sup> SBR: surface-based ropes, SR: suspended rafts, BBT: bottom-based tables, LBP: land-based ponds, SBNC: surface-based net-cages.

\*Unweighted data

# Weighted data.

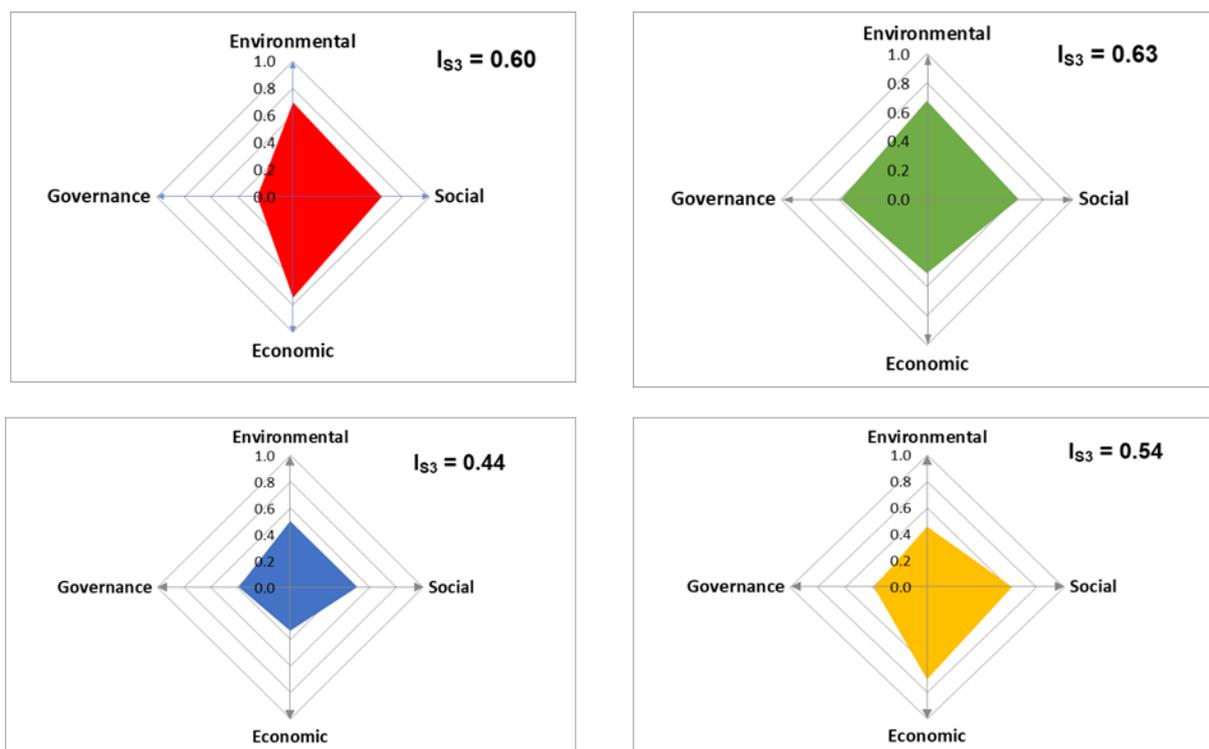


Figure 14. Multidimensional diagrams showing the sustainability of macroalgae (red), filtering mollusks (green), fish monoculture (blue) and fish IMTA (yellow). Sustainability increases from the center to the extreme of each axis. The colored area represents the sustainability of each system.  $IS_3$  = index of sustainability based on sustainability model 3.

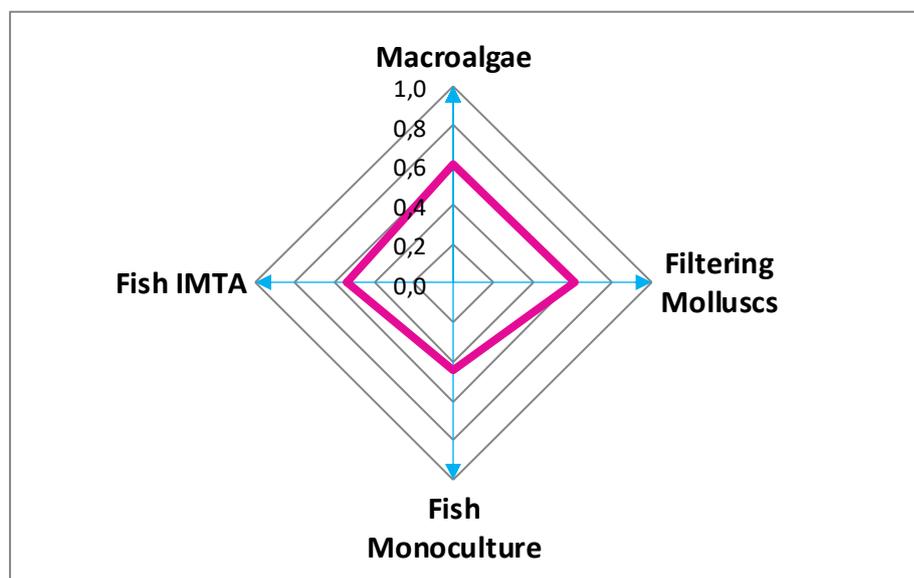


Figure 15. Multidimensional diagrams showing the indices of sustainability based on model 3 obtained for each LTS aquaculture system group. Sustainability increases from the center to the extreme of each axis.

All systems displayed specific strengths and weaknesses. For macroalgae, economic sustainability was a strength, as were environmental and social sustainability, while governance was a weakness (Figure 12). Pereira et al. (2020) observed that driving the production to the food market is profitable for small farms, however, focusing on the international carrageenan market is unfeasible. This scenario stems from the low international price of this raw material due to the large production with low cost in Asia, and consequently, the economic sustainability is tightly connected to local markets. The low

governance sustainability may be a result of macroalgae still being an incipient culture in Brazil, and thus, value chains and governance are not developed yet. For more discussion about the sustainability aspects of macroalgae culture in Brazil, please refer to sections 4.2.1, 4.2.2 and 4.2.3.

Filtering mollusks showed high environmental performance mainly because native species and local strains were farmed and as the farms released low quantities of nutrients and did not contribute to severe environmental pollution. The social and governance sustainability were also relatively high. The economic performance, on the other hand, was a weakness, partly because of the low diversity of products and market prices, but also due to high labour costs, and low permanence and high risk rate. The development of markets to make better use of waste products such as shells may be a necessary action to increase sustainability.

Fish in monoculture was the least sustainable production system, and economic performance was low due to the absence of circularity processes and diversification of products and markets. This scenario changed when fish culture was integrated in IMTA systems with prawns, which have high trade values and diverse markets, thereby increasing economic performance. Surprisingly, fish monoculture showed environmental sustainability slightly higher than fish polyculture in IMTA. This is unrelated to efficiency in producing biomass and reducing effluent nutrients. This stems from the combination with an exotic species of prawn (in the culture region) dependent on a complex hatchery protocol. Including a third native species, the curimbata (*Prochilodus lineatus*), substantially boosts yield and diet use efficiency (Franchini et al., 2020), increasing sustainability. Therefore, moving to IMTA system does not assure a sustainability increase, but the systems must be carefully planned and implemented to optimize the use of circular processed but also other aspects such as the potential risk to biodiversity and animal welfare. The LTS have an immense potential to be produced in IMTA.

## 5. Synthesis of major findings

Assessing the sustainability of production systems is a central point in developing the blue bioeconomy. The approach in this study to achieve such an assessment was based on analysis of sustainability indicators in the environmental, social and economic domains. Governance was added as a fourth domain in alignment with recent trends in sustainability analysis. A previously developed indicator set was used for analysis of the domains. Unfortunately, the present study concluded that environmental, social and economic data for LTS aquaculture in the Atlantic with a high enough resolution and, for environmental data related to open seabased culture, with suitable reference/control points, were not available to the extent needed to complete the analysis. Instead, the environmental, social and economic parts of the indicator set was evaluated using data from several different LTS aquaculture systems in Brazil. The results highlighted the validity of the indicator set as most indicators supported a discrimination between different production systems, illustrating strengths and weaknesses of the operations. Strengths and weaknesses differed between organism groups and production mode (monoculture/IMTA) and between and within sustainability domains, and are discussed more in detail in the following section. In contrast to the environmental, social and economic data, governance data could be obtained for systems across the Atlantic. Results indicated that there were differences in governance around the Atlantic, but the differences could not be connected to specific organism groups, geographical areas or culture systems.

## Overall strengths and weaknesses of LTS aquaculture systems

In accordance with what is generally assumed, culture of extractive species, such as macroalgae and filtering mollusks, was found in this study to be more sustainable than production of fed species (in this case freshwater fish). The culture of LTS freshwater fish in integrated culture was, however, found to be more sustainable than in monoculture. These results corroborate what has been forecasted in scientific literature during recent years. For governance, general strengths observed were the existence of cooperatives and producer associations, while general weaknesses were licencing procedures and stakeholders attitudes.

The generation of local social and economic development are important from the sustainability perspective, as well as the contribution to local food security as observed in our analysis. Sustainability may be considerably lower in farms that import and export supplies and yield or that use technology incompatible with local population abilities and culture. These aspects should be considered during technology development and the choice of systems and regions.

The use of native species, plans for properly combining species with complementary functional characteristics in IMTA systems, and good management to decrease natural resource use are essential topics to enhance sustainability in LTS aquaculture. These results raises the question if potential benefits can also be achieves through monotrophic polyculture. This concept focuses on combining species of the same level trophic that use different spaces or food sources inside the culture.

## Strengths and weaknesses illustrated by specific indicators

### *Environmental sustainability*

Generally, marine LTS farming tend to be more sustainable than terrestrial food production systems because of the very low use of fresh water. In contrast, freshwater LTS have high freshwater requirements, as do other land-based food production systems. Consequently, marine LTS aquaculture pose great advantages in this perspective. However, the use of space is a limiting factor for all food production systems, including for LTS aquaculture development (Walton et al., 2015). Access to space in costal areas is limited as a result of the intense use of this area by many different maritime activities. There is currently a drive to move aquaculture offshore (Krause et al., 2022; Morro et al., 2022), however, there are several challenges related to this. When going offshore the investment costs in infrastructure and costs associated to farm maintenance increases, which must be compensated for by high market values of the products which often are lacking for LTS. Moreover, the placement of LTS aquaculture should be chosen to optimize the ES provided, e.g. the nutrient extraction potential and biodiversity enhancement is best utilized in nearshore areas. Consequently, offshore expansion of LTS aquaculture may not be the best option from a LTS aquaculture and societal perspective. Additionally quantifications of the space needed to provide essential resources, such as nutrients and phytoplankton for macroalgae and filtering mollusks, and to buffer for released substances, is also necessary. These areas were considered in the present assessment of sustainability, but research should be done to define the best methods and standards to estimate these providing and buffer areas. This will clarify controversies, allowing more trustable and comparable estimates of area use and determine the environment carrying capacity for each specific culture.

The emission or absorption of greenhouse (GHG) gases by LTS aquaculture systems is a controversial but essential feature to attribute sustainability scores. The flows of GHG between the water of aquaculture systems and the atmosphere have been studied by theoretical and empirical estimates and many publications are available (e.g., Boyd et al., 2010; Soares & Henri-Silva, 2019; Yuan et al., 2019; Flickinger et al., 2020; Kosten et al., 2020; David et al., 2021; Chen et al., 2023). Many factors can substantially affect GHG emissions from aquaculture, such as the system used, scale, farmed species, stocking density, general management (fertilization, aeration, drainage, feed supply), changes in the surrounding environment or land/water use, and others (Chen et al., 2023). Empirical results have shown the difficulties in validating the theoretical forecasting, which often only focus on the target species and does not take into account associated ecosystem effects in actual culture situations. Absorption of GHG for fed species farmed in land-based ponds were demonstrated in the present and other studies (Soares & Henri-Silva, 2019; Flickinger et al., 2020; David et al., 2021) while fish culture in open cages were observed to emit GHG. Absorption of GHG was also observed by macroalgae while varying impacts (absorption and emissions) were observed for filtering mollusks, although the emissions were minor compared to the demonstrated absorption potential. These results should be verified in additional studies using standardised methodology and combined with Life Cycle Assessment (LCA) studies of operational carbon footprints to allow comparisons to other food production sectors. Methodological standardization is also necessary to enable comparisons and data exchanges (Chen et al., 2023). It is also imperative that variables impacting absorption or emission potential is identified in order to enhance the performance of the production. This will require strategic investments in industry/academia collaboration as such studies cannot be achieved in a laboratory setting. Moreover, large differences in energy consumption and GHG emissions related to operation of boats were noticed, and the use of fossil fuel in boats was observed to be an important factor in decreasing sustainability in some production systems. Alternatives to fossil fuels for boats should be investigated and implemented.

Moreover, the present study demonstrated that the accumulation of sediment, organic matter and nutrients on the seabed just below farm units is a topic that needs further attention. Accumulation of organic content may promote alterations in benthic fauna, and the water flow promotes modifications in the surrounding areas. There are tools to analyse the likelihood of this to occur and mitigate such impacts in open seabased systems.

In addition, extractive species are generally farmed in situations that allow fulfilling their natural necessities. This lead to high organism welfare. The concept of welfare was developed primarily for vertebrates although the interest for quantification of stress and improvements in farm operations to improve the welfare also of invertebrate species is increasing. The present study demonstrated that the indicators used to describe welfare in aquaculture could also be applied to invertebrates and macroalgae, which, in the case of invertebrates, may appeal to a segment of consumers concerned about animal welfare in food production. The development of the concept of welfare for LTS is an important avenue that can add value and open new markets for LTS.

There were several other important aspects noted during the analysis of specific indicators. Examples include the higher efficiency in resource use in extractive than fed LTS aquaculture, and the absence of pollution by chemicals, hormones and heavy metals in the LTS systems. Moreover, it concluded that determining, measuring, quantifying and evaluating all externalities of a process or a farm remains a great challenge, however, more emphasis should be put on this aspect. We also observed in this study

that analysis of specific indicators and comparisons between production systems can highlight suboptimal management practices, and may thereby be used as a tool to optimize system performance and sustainability. More specific points for specific systems can be extracted from the discussions in section 4.2.

### *Social sustainability*

In this study, LTS aquaculture was found to provide social benefits for local populations and contributing to local food security. Generally, farms of macroalgae and filtering mollusks use low levels of technology, which allow the enrollment of local fisheries communities and vulnerable populations. In accordance, the present study showed that LTS farming can support local job positions. Moreover, the investment for building facilities at start-up and hence generating job positions was also observed to be lower than other activities of the blue economy. Creating long-lasting and decent job positions is an essential topic for sustainability, and is mentioned as an objective in the SDGs (UN, 2015). In addition, the culture of algae was found to be inclusive for women and adults of all ages. Nevertheless, the use of safe work equipment and some mechanization is necessary to avoid work related injuries and allow the work of women and older adults. Such equipment is available but sometimes expensive. Research towards developing cheap, yet safe, equipment according to the necessities of the workers in macroalgae, molluscs and fish farms, as well as models to support the inclusion of vulnerable groups can further support sustainability, and innovation projects should consequently be encouraged and supported.

The analysis of the Brazilian farms also demonstrated that the culture of LTS may be attractive to small family farms and entrepreneurs. Although not formally analysed, similar patterns have been observed by the project team both in the US, in Scandinavia and in other areas. It has been observed that often, a diversity of operations at different scales co-exist, which may be beneficial as this contributes with different benefits in a local context.

### *Economic sustainability*

The economic valuation of ecosystem services provided by LTS aquaculture is a topic of increasing importance. As discussed in section 4.2.1, LTS aquaculture play an important role in providing important ecosystem functions, such as filtering water, providing habitat for other organisms, and cycling nutrients, and can also be used as a source of revenue for local communities. The economic value of mussel and oyster aquaculture has been studied in different geographical areas, and values of between 12 (in the Netherlands, Schepers et al., 2010) and 36 (in New Zealand, Rees et al., 2002) million \$ per year for mussels and 8 million \$ per year for oysters (in Japan, Asai et al., 2009) has been estimated to be generated not only through the sale of the products, but also through the provisioning of ecosystem services such as water filtration, habitat provision, and storm protection. LTS aquaculture may also be of significance even in emerging sectors, as illustrated by the estimated total economic value of 3.3 million \$ per year in Norway (Gulbrandsen et al., 2012). In concurrence, in this study, the analyses of extractive species culture showed economic feasibility with positive externalities massively outranking negative externalities despite only the three more critical externalities being included. Valuing ecological externalities is challenging, yet important, to fully release the potential of the blue bioeconomy. Further studies should be done to determine the negative or positive contribution of the other externalities, which may surpass 20 services and disservices (Pereira et al., 2021). Therefore,

innovative protocols should be developed to estimate externalities, and available methodology should be standardized.

It was apparent, that a weakness of some of the studied LTS aquaculture systems were the dependence on a limited number of markets and products. Diversifying markets and products and choosing the right markets compatible with the farm and products are essential to increase resilience in the sector. Development of new products and markets for LTS aquaculture products, including waste- and side stream products, has been one of the objectives in AV. This is of particular importance for low value, bulk products, such as kelp and blue mussels, for which the development of alternative, high value products, may enhance the economic sustainability significantly. Much work is therefore ongoing in this topic. For all LTS aquaculture production, the primary target should be food production, yet as exemplified by the low selling prices for carrageenan and agar in international markets, there is an incompatibility with the production costs (Pereira et al., 2020). Similarly, for filtering mollusks, developing a market to trade the shells is essential, as technology for their use is available (Silva et al., 2019; Alonso et al., 2021; Álvarez-Salgado et al., 2022). Diversification of markets is also important for fish LTS farming in both monoculture and IMTA. Technologies to use the skin, bones and gut are under development and enhanced use of such processing side-streams should be encouraged to increase circularity and achieve the zero waste objective. Such activities may also enhance sustainability as a result of farm product diversification as observed for the IMTA case analysed in this study.

### *Governance sustainability*

The present study showed some general and specific strengths and weaknesses for the LTS sector, which policy-makers and stakeholders should use to define actions and government policies to enhance sustainability in this respect. Although governance is not a traditional dimension of sustainability, creating an enabling governance environment is key to expand production and to move toward more sustainable production. From the industry stakeholders' perception, governance is relatively well developed around the Atlantic. Geographic region 21 (North America) was the most developed area showing a very-high level of governance. Consequently, there is good reason to explore the beneficial aspects highlighted in the survey further in an effort to identify if similar structures could be implemented also elsewhere. It is important to note that there is no "one-size-fits-all" solution in terms of governance, as systems must always be adjusted to local conditions and prerequisites, however, inspiration can always be found in successful examples. Generally, the cooperation among stakeholders was identified as a major strength as all regions had farmer cooperatives and associations.

Some common weaknesses identified in the study include difficulties in obtaining permits, a lack of arrangements for sharing the cost of expensive equipment or services, and obtaining certifications that could add value to the products. Permits especially are an important issue. Environmental laws are usually unclear, making compliance difficult, and regulatory systems are generally complex and uncertainties generate difficulties in obtaining permits and legalizing aquaculture. Typically, the sector has little representation in committees and regulatory agencies.

### *The path ahead*

The primary constraint for performing sustainability analysis through the use of indicators as identified in this study was the large amounts of specific data required, and the effort to find essential

information revealed a mismatch in data availability compared to data requirements for the analysis. There was also a lack of standardized methods for obtaining environmental, social and economic data. In addition to the procedures for collecting field data, standards on the nomenclature and computation of each variable must be established. Examples from the data collection performed in this study are inconsistencies in whether data of nitrogen in water included both organic and inorganic nitrogen, or nitrogen compounds and dissolved nitrogen or only dissolved nitrogen, and it was often unclear if salaries included taxes and social benefits or not. Consequently, standardization of these, and many other, aspects is urgent and essential.

It was also observed that there is the lack of empirical data. Although the literature on aquaculture sustainability has increased vastly recently, many articles focus on theoretical discussions and extrapolations, while for using sustainability analysis in industry and governance development, primary data are still necessary. Quantifications of ecosystem services and disservices that measure positive and negative externalities are required, not only for the environmental domain, but also for social and economic aspects, yet data that allow these estimates are scarce or absent (as also discussed in Marinho et al. 2022). Although sustainability is not a new field, data availability for marine systems is lagging behind that of terrestrial systems, and acquisition of primary data in all sustainability domains should be prioritised in order to confirm or refute the theoretical frameworks already developed.

It was apparent from the Brazilian cases that data availability for sustainability analysis was dependent on long-term, strategic, investments in industry oriented research activities aimed at primary data collection, coordinated through a center formation with a well developed structure for data collection (in terms of methodology, calculations and terminology) and data storage in a database developed specifically for the purpose. The collection of the needed data has, through the Brazilian example, been proven to be feasible. To date, more than 70 farms in Brazil have been assessed using an earlier version of the proposed framework. Moreover, a certification company was created in 2020 based on the methodology, and it has been observed that the cost for obtaining the certificate is lower than that of traditional aquaculture certification. The technology of a set of indicators is now on the TRL 8. Consequently, implementing a similar structure in Europe may facilitate future sustainability analysis, refinement and development of existing, and new, aquaculture practices, and may support identification of strengths and weaknesses of LTS aquaculture also in a European context. Data collection for sustainability analysis could also be facilitated by development of a handbook including a pre-structured data collection template, describing the various data needed, definitions of such data, and suitable methodologies for collection of the required data. This would enable standardised data collection and analysis, and could, in the longer term, lead to the establishment of certifications and performance monitoring based on the most relevant indicators.

## Conclusions

This study demonstrated that the desired states and the developed indicator set developed in previous work (D6.1; Lindblom et al., 2021) were appropriate and suitable to assess LTS aquaculture sustainability during the grow-out phase. Several strengths and weaknesses of different production systems in Brazil, and for governance also for systems around the Atlantic, were identified using the framework. In previous work (D6.2, Marinho et al., 2022), it was concluded that ES provided by LTS aquaculture may show conflicting impacts (i.e., both services and disservices) even within each analysed organism group. Consequently, methods to assess the net impact on sustainability, e.g. through the use of indicator sets as in this study, is crucial for informed governance decisions. Based on

sustainability analysis covering the environmental, economic, societal and governance aspects, financial actors and government policy-makers may define priorities and support the enhancement of sustainable practices in LTS aquaculture. A detailed analysis of specific indicators may also support the strategic and targeted enhancement of farm practices and management as this can highlight improvement needs in different aspects of the farm operations. If repeated over time, this analysis may also allow for monitoring of farm development to ensure longevity of the enterprise and enhancement of sustainability. Consequently, more focus should be put on this kind of analysis also in Europe, considering the importance, the robustness and soundness of the outcomes, and the fact that the framework has already been tested. A challenge for this development is to fund and encourage the generation of primary data needed to compute the indicators for operations in Europe according to a standardized protocol.

## Acknowledgments

We are grateful to the following colleagues for the valuable contributions: Sandra Shumway (USA), Jay Parsons (Canada), Harry M. Murray (Canada), Carrie Byron (USA), Felipe Vieira (Brazil), Fernando Gonçalves (USA), Anton Salgado (Spain), João Carlos de Azevedo Manzella Jr (Brazil), Johannes Itembu (Namibia), Marcia Kafenszok (Brazil), Carlos Alberto Martins Cordeiro (Brazil), Eirik Mikkelsen (Norway), Janaina M. Kimpara (Brazil), Stefany A. Pereira (Brazil), Iracy L. Pecora (Brazil), Juliana B. Fernandes (Brazil). This research was also funded by São Paulo Research Foundation —FAPESP, Brazil processes #10/52210-3 and 2015/19451-8 and by National Council for Scientific and Technological Development—CNPq, Brazil processes # 562820/2010-8, 406069/2012-3, and 306361/2014-0; CAPES-EMBRAPA, Brazil public notice: 15/2014, project number 24; FINEP, Brazil, agreement n01.10.0578.00/10.

## Data management

### Datasets used

#### *Environmental, social and economic data*

The literature references are present in the references section. In addition to referenced information, the data collected or generated to write this deliverable are confidential as the data was collected within other projects performed in Brazil. The dataset description can be found in the D4.8 Data Management Plan final of AquaVitae under the name “Quantification of environmental, social, and economic indicators of sustainability for LTS aquaculture around the Atlantic (T6.2.2)”.

#### *Governance data*

The literature references are present in the references section. In addition to this, the data collected or generated to write this deliverable will be uploaded to Zenodo under the AV community <https://zenodo.org/communities/aquavitae/?page=1&size=20> by May 2023. The data description can be found in the D4.8 AquaVitae Data Management Plan final. The name will be “Quantification of governance indicators of sustainability for LTS aquaculture around the Atlantic (T6.2.2)”.

## References

- Afolalu, S.A., Ikumapayi, O.M., Ogedengbe, T.S., Kazeem, R.A., Ogundipe, A.T. 2022. Waste pollution, wastewater and effluent treatment methods – An overview. *Materials Today: Proceedings*, 62, Part 6:3282-3288.
- Ajibade, F.O. Adelodun, B. Lasisi, K.H. Fadare, O.O. Ajibade, T.F. Nwogwu, N.A. Sulaymon, I.D. Ugya, A.Y. Wang, H.C. Wang, A. 2021. Environmental pollution and their socioeconomic impacts, in: Kumar, A. Singh, V.K. Singh, P. Mishra, V.K. (Eds.), *Microbe Mediated Remediation of Environmental Contaminants*. Woodhead Publishing. pp. 321 -354.
- Alonso, A.A, Álvarez-Salgado, X.A, Antelo, L.T. 2021. Assessing the impact of bivalve aquaculture on the carbon circular economy. *Journal of Cleaner Production* 279. e12387.
- Álvarez-Salgado, X.A., Fernández-Reiriz, M.J., Fuentes-Santos, I., Antelo, L.T., Alonso, A.A., Labarta, U. 2022. CO<sub>2</sub> budget of cultured mussels metabolism in the highly productive Northwest Iberian upwelling system. 2022. *Science of the Total Environment* 849, e157867.
- Asai, H., Yamamoto, Y., Takeuchi, T., Ito, T., Sato, T., & Okazaki, S. 2009. Economic value of oyster aquaculture in Japan. *Aquaculture*, 295: 27-33.
- Barreto, M.O.; Planellas, S.R.; Yang, Y., Phillips, C. Descovich, K. 2022. Emerging indicators of fish welfare in aquaculture. *Rev. Aquac.*, 14:343-361.
- Bennett, N.J., Villasante, S. Espinosa-Romero, M.J., Lopes, P.F.M., Selim, S.A., Allison E. H. 2022. Social sustainability and equity in the blue economy. *One Earth* 5:964-968.
- Biely, K., Maes, D., Passel, S. V., 2018. The idea of weak sustainability is illegitimate. *Environment, Development and Sustainability*, 20: 223:232.
- Boyd CE, Tucker C, McNevin A., Bostick, K., Clay, J., 2007. Indicators of resource use efficiency and environmental performance in fish and crustacean aquaculture. *Rev Fish Sci* 15:327–360.
- Boyd, C.E., Wood, C.W., Chaney, P.L., Queiroz, J.F., 2010. Role of aquaculture pond sediments in sequestration of annual global carbon emissions. *Environ. Pollut.* 158, 2537e2540.
- Brugere, C., J. Aguilar-Manjarrez, M. Beveridge, and D. Soto. 2018. The ecosystem approach to aquaculture 10 years on — a critical review and consideration of its future role in blue growth. *Reviews in Aquaculture*, 11.
- Brundtland, G. H. 1987. *Our Common Future: The World Commission on Environment and Development*. Oxford: Oxford University Press.
- Brusseu, M.L., 2019. Sustainable development and other solutions to pollution and global change. In: *Environmental and pollution science* (pp. 585-603). Academic Press.
- Bush, S. R., Belton, B., Hall, D., Vandergeest, P., Murray, F. J., Ponte, S., Oosterveer, P., Islam, M. S., Mol, A.P.J., Hatanaka, M., Kruijssen, F., Ha, T. T. T., Little, D. C., Kusumawati, R., 2013. Certify Sustainable Aquaculture? *Science*, 341(6150): 1067-1068.
- Chen, G., Bai, J., Bi, C., Wang, Y., Cui, B. 2023. Global greenhouse gas emissions from aquaculture: a bibliometric analysis. *Agriculture, Ecosystems and Environment* 348, e108405.
- Chofreh, A. G., Goni, F. A., 2017. Review of Frameworks for Sustainability Implementation. *Sustainable Development*, 25(3): 180-188.
- Chopin, T. (2013a). Integrated multi-trophic aquaculture. Ancient, adaptable concept focuses on ecological integration. *Global Aquaculture Advocate*, 16(2), 16–19.
- Costanza, R., De Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., Farber, S., Grasso, M., 2017. Twenty years of ecosystem services: How far have we come and how far do we still need to go? *Ecosystem Services* 28: 1–16.
- Costanza, R., Folke, C., 1997. Valuing Ecosystem Services with Efficiency, Fairness, and Sustainability as Goals. *Nature's Services: Societal Dependence on Natural Ecosystems*. G. C. Daily. Washington D.C., Island Press: 49–69.
- Costa-Pierce, B. A., 2021. The Principles and Practices of Ecological Aquaculture and the Ecosystem Approach to Aquaculture. *World Aquaculture Magazine*, 52:25-31.

- CTDEEP (2021) Cost of Equalized Nitrogen Credit for Buyers 2021. Available at <  
[https://portal.ct.gov/-/media/DEEP/water/nitrogen\\_credit\\_advisory\\_board/Cost-of-Equalized-Nitrogen-Credits-for-Buyers-2021.pdf](https://portal.ct.gov/-/media/DEEP/water/nitrogen_credit_advisory_board/Cost-of-Equalized-Nitrogen-Credits-for-Buyers-2021.pdf)>. Accessed in December 2022.
- David, F.S.; Proença, D.C.; Flickinger, D.L.; Bueno, G.W.; Valenti, W.C. 2021. Carbon budget in integrated aquaculture systems with Nile tilapia (*Oreochromis niloticus*) and Amazon river prawn (*Macrobrachium amazonicum*). *Aquaculture Research*, 52:5155–5167.
- David, F.S.; Proença, D.C.; Flickinger, D.L.; Bueno, G.W.; Valenti, W.C. 2021. Carbon budget in integrated aquaculture systems with Nile tilapia (*Oreochromis niloticus*) and Amazon river prawn (*Macrobrachium amazonicum*). *Aquaculture Research*, 52:5155–5167.
- Díaz, S., Pascual, U., Stenseke, M., Martín-López, B., Watson, R. T., Molnár, Z., et al. 2018. Assessing nature's contributions to people. *Science* 359, 270–272.
- EAS, 2005. Defining indicators for sustainable aquaculture development in Europe, CONSENSUS – A multi-stakeholder platform for sustainable aquaculture in Europe. Workshop report, Oostende, Belgium, November 21–23, 2005.
- Ecological Footprint Network, 2022. How the footprint works. Available at: (<https://www.footprintnetwork.org/our-work/ecological-footprint/>, accessed on April 9th, 2022).
- Engle C. R. 2019. *Aquaculture businesses: a practical guide to economics and marketing*. 5m Publishing, Sheffield.
- Engle, C. R. & van Senten, J. 2022. Resilience of Communities and Sustainable Aquaculture: Governance and Regulatory Effects. *Fishes* 7, e268. <https://doi.org/10.3390/fishes7050268>
- Engle, C. R. , van Senten, J. Fornshell, G. 2019. Regulatory costs on U.S. salmonid farms. *J. World Aquacult Soc.* 2019, 1–28.
- Engle, C.R., 2010. *Aquaculture Economics and Financing: Management and Analyses*. Wiley-Blackwell, Oxford.
- EU (European Commission), 2021a. Strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021 to 2030. Communication COM/2021/236 final.
- EU (European Commission), 2021b. Sustainability criteria for the blue economy. European Climate, Infrastructure and Environment Executive Agency (CINEA). B-1049 Brussels.
- Fabris, M. 2023. Correlação jurídica entre os objetivos de desenvolvimento sustentável (ODS) e os indicadores de sustentabilidade para avaliação dos sistemas de aquicultura no Brasil. Universidade Estadual Paulista (UNESP), Centro de Aquicultura, Jaboticabal, Brazil. (Master Thesis). 83 p.
- FAO 2022a. Shanghai Declaration. Global Conference on Aquaculture: Aquaculture for Food and sustainable development. 22-25 September 2021, Shanghai, China.
- FAO 2022b The State of World Fisheries and Aquaculture 2022. Rome, FAO, Towards blue transformation.
- FAO, 1999. Indicators for sustainable development of marine capture fisheries. FAO Technical Guidelines for Responsible Fisheries. No. 8. FaO, Rome. pp. 68.
- FAO. 2017. The 2030 Agenda and the Sustainable Development Goals: The challenge for aquaculture development and management, by John Hambrey. FAO Fisheries and Aquaculture Circular No. 1141, Rome, Italy.
- FAO. 2020. The State of World Fisheries and Aquaculture 2020. Sustainability in action. Rome. Pp. 224
- Fernandes, J. B. 2013. Análise da sustentabilidade econômica e social na produção extensiva de ostras em uma região subtropical. Universidade Estadual Paulista, Jaboticabal. 78p. (Master Thesis).
- Fezzardi, D., Massa, F., Àvila-Zaragoza, P., Rad, F., Yücel-Gier, G., Deniz, H., Hadj Ali Salem, M., Hamza, H.A., Ben Salem, S., 2013. Indicators for sustainable aquaculture in Mediterranean and Black Sea countries. Guide for the use of indicators to monitor sustainable development of aquaculture. Studies and Reviews. General Fisheries Commission for the Mediterranean. No 93. Rome, FAO. pp. 60.

- Fialho, N.S.; Valenti, W.C.; David, F.S.; Godoy, E.M.; Proença, D.C.; Roubach, R.; Bueno, G.W. 2021. Environmental sustainability of Nile tilapia net-cage culture in a neotropical region. *Ecological Indicators*, 129, e108008.
- Fierro-Sanudo, J.F., Oca, G.A.R.M, Paez-Osuna, F.P. 2020 Co-culture of shrimp with commercially important plants: a review. *Reviews in Aquaculture* (2020) 12, 2411–2428.
- Flickinger, D.L., Costa, G.A., Dantas, D.P., Moraes-Valenti, P., Valenti, W., 2019. The budget nitrogen in the grow-out of the Amazon river prawn (*Macrobrachium amazonicum* Heller) and tambaqui (*Colossoma macropomum* Cuvier) farmed in monoculture and integrated multitrophic aquaculture systems. *Aquaculture Research*, 50:3444–3461.
- Flickinger, D.L., Costa, G.A., Dantas, D.P., Proença, D.C.; David, F.S.; Durborow, R.M.; Moraes-Valenti, P., Valenti, W.C. 2020. The Budget of carbon in the farming of the Amazon river prawn and tambaqui fish in earthen pond monoculture and integrated multitrophic systems. *Aquaculture Reports*, 17, e100340, p.1-14.
- Flickinger, D.L., Costa, G.A., Dantas, D.P., Proença, D.C.; David, F.S.; Durborow, R.M.; Moraes-Valenti, P., Valenti, W.C. 2020. The Budget of carbon in the farming of the Amazon river prawn and tambaqui fish in earthen pond monoculture and integrated multitrophic systems. *Aquaculture Reports*, 17, e100340, p.1-14.
- FOESA, 2010. Defining sustainability indicators for Mediterranean Aquaculture. Spanish Aquaculture Observatory Foundation (FOESA), Madrid, Spain.
- Franchini, A. C., Costa, G. A., Pereira, S. A., Valenti, W. C., & Moraes-Valenti, P. 2020. Improving production and diet assimilation in fish-prawn integrated aquaculture, using *Iliophagus* species. *Aquaculture*, 521, 735048.
- Frankignoulle, M. & Canon, C. 1994. Marine calcification as a source of carbon dioxide: Positive feedback of increasing atmospheric CO<sub>2</sub>. *Limnol. Oceanogr.*, 39(2), 1994, 458-462.
- Giannetti, B. F., Almeida, C. M. V. B., Bonilla, S. H., 2010. Comparing Emergy accounting with well-known sustainability metrics: The case of Southern Cone Common Market, Mercosur. *Energy Policy*, 38: 3518–3526.
- Gulbrandsen, L., Husa, V., & Nordrum, S. 2012. Economic valuation of seaweed aquaculture in Norway. *Aquaculture Economics & Management*, 16: 116-132.
- Henry-Silva, G.G., da Silva Cacho, J.C., Moura, R.S.T., Flickinger, D.L., Valenti, W.C., 2022. Economic, social, and environmental assessment of farming Nile tilapia in net-cages in a reservoir in hot semi-arid region during an extended drought event. *Environ Sci Pollut Res*.
- Henry-Silva, G.G.; da Silva Cacho, J.C.; Moura, R.S.T.; Flickinger, D.L.; Valenti, W.C.. 2022. Economic, social, and environmental assessment of farming Nile tilapia in net-cages in a reservoir in hot semi-arid region during an extended drought event. *Environ Sci Pollut Res*.
- IPBES. 2019. Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. S. Díaz, et al. (eds.). IPBES secretariat, Bonn, Germany. 56 pages.
- IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R., Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press.
- IPCC. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R., Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press. 2021.
- Johnston, P., Everard, M., Santillo, D., & Robèrt, K. H. (2007). Reclaiming the definition of sustainability. *Environmental science and pollution research international*, 14(1), 60-66.
- Kobryn, C., 2000. Modeling components and frameworks with UML. *Communications of the ACM* 43: 31–38.

- Kosten, S., Almeida, R.M., Barbosa, I.,.....et al. 2020. Better assessments of greenhouse gas emissions from global fish ponds needed to adequately evaluate aquaculture footprint. *Science of the Total Environment*, 748, e141247.
- Krause G., Le Vay L., Buck B.H., Costa-Pierce B.A., Dewhurst T., Heasman K.G., Nevejan N., Nielsen P., Nielsen K.N., Park K., Schupp M.F., Thomas J.-B., Troell M., Webb J., Wrange A.-L., Ziegler F., Strand Å. 2022. Prospects of Low Trophic Marine Aquaculture Contributing to Food Security in a Net Zero-Carbon World. *Frontiers in Sustainable Food Systems*, 6, pp10.
- Lindblom et al. 2021. Recommendation of indicators to be used in sustainability analysis of new and underutilized low-trophic species in aquaculture. (D6.1)
- Lindblom et al. 2023. Fact sheets describing environmental effects from and on aquaculture. AquaVitae Deliverable 6.5. Grant agreement No: 818173. (D6.5).
- Lindblom, E., Bengtsson, L., Rydstedt, A., Strand, Å., Strandberg, J. 2022. Assessment of environmental risks exerted upon, and by, low-trophic aquaculture in the Atlantic Region. (D6.4)
- Lothmann, R. & Sewilam, H. 2023 Potential of innovative marine aquaculture techniques to close nutrient cycles. *Reviews in Aquaculture*. First published on line: 28 December 2022.
- Marine Harvest. 2017. Salmon farming industry handbook 2017. Retrieved from
- Marinho, G. S., Álvarez-Salgado, A., Fuentes-Santos, I., Burgués, I., Sousa-Pinto, I., Strand, Å. 2022. Quantification of Ecosystem Services. AquaVitae Deliverable 6.2. 12/04/2022. Grant agreement No: 818173. (D6.2).
- Martinell, D.P., Vergara-Solana, F.J., Almendarez-Hernandez, L.C., Araneda-Padilla, M.E. 2020. Econometric models applied to aquaculture as tools for sustainable production. *Reviews in Aquaculture* (2020) 12, 1344–1359.
- Millennium Ecosystem Assessment (MEA)., 2005. *Ecosystems and Human Well-Being: Synthesis*. Island Press.
- Molinos-Senante M, Hernández-Sancho F, Sala-Garrido R, Garrido-Baserba M (2011) Economic feasibility study for phosphorus recovery processes. *Ambio* 40: 408– 416.
- Moraga, G., Huysveld, S., Mathieux, F., Blengini, G. A., Alaerts, L., Van Acker, K., ... Dewulf, J. (2019). Circular economy indicators: What do they measure? *Resources, Conservation & Recycling*, 146, 452–461.
- Morro, B., Davidson, K., Adams, T.P., et al. 2022. Offshore aquaculture of finfish: Big expectations at sea. *Rev Aquac.*, 14: 791– 815.
- Moura, R.S.T., Valenti, W.C., Henry-Silva, G.G., 2016. Sustainability of Nile tilapia netcage culture in a reservoir in a semi-arid region. *Ecol. Ind.* 66, 574–582.
- Nathanson, J. A. 2023. Pollution. *Encyclopedia Britannica*.  
<https://www.britannica.com/science/pollution-environment>. (Accessed 24 February 2023).
- Odum, H.T. (Ed.) 1996. *Environmental Accounting: Emery and Environmental Decision Making*, 1st ed.; John Wiley & Sons: New York, NY, USA.
- Osmundsen, T.C., Amundsen, V.S., Alexander, K.A., Asche, F., Bailey, J., Finstad, B., Olsen, M.S., Hernández, K., Salgado, H. 2020. The operationalisation of sustainability: Sustainable aquaculture production as defined by certification schemes. *Global Environmental Change*, 60: e102025.
- Parkes, G., Young, J. A., Walmsley, S. F., Abel, R., Harman, J., Horvat, P., Lem, A., MacFarlane, A., Mens, M., Nolan, C., 2010. Behind the Signs—A Global Review of Fish Sustainability Information Schemes. *Reviews in Fisheries Science*, 18(4): 344-356.
- Pedrazzani, A.S., Tavares, C.P.S., Quintiliano, M., Cozer, N., Ostrensky, A. 2022. New indices for the diagnosis of fish welfare and their application to the grass carp (*Ctenopharyngodon idella*) reared in earthen ponds. *Aquaculture Research*. 53(17):5825-5845.
- Pereira, S.A., Kimpara, JM., Valenti, W.C. 2021. Sustainability of the seaweed *Hypnea pseudomusciformis* farming in the tropical Southwestern Atlantic. *Ecological Indicators*, 121, e107101. p. 1-9.

- Pereira, S.A.; Kimpara, J.M.; Valenti, W.C. 2020. A bioeconomic analysis of the potential of seaweed *Hypnea pseudomusciformis* farming to different targeted markets. *Aquaculture Economics & Management*, 24(4): 507-525.
- Pigou, A.C., 2005. *The Economics of Welfare: Volume I*. Cosimo, New York, London.
- Purvis, B, Mao, Y., Robinson, D. 2019. Three pillars of sustainability: in search of conceptual origins. *Sustainability Science* 14:681-695.
- R Core Team (2021). *A language and environment for statistical computing*. R Foundation for Statistical Computing. Vienna. <https://www.R-project.org/>.
- Rees, B., Campbell, L., & Williamson, P. 2002. The economic value of mussel aquaculture in New Zealand. *Aquaculture Economics & Management*, 6: 225-239.
- Rees, W., Wackernagel, M., 1996. *Our Ecological Footprint: Reducing Human Impact on the Earth*. New Society Publishers, Gabriola Island, BC. New Society Publishers.
- Schepers, J., van Wijnen, H., & van den Burg, E. 2010. Economic value of mussel aquaculture in the Netherlands. *Aquaculture Economics & Management*, 14: 303-316.
- Sheppard, V. 2021. *Research Methods for the Social Sciences: An Introduction*. Vancouver/Vitoria. BC Campus, 415p.
- Silva, T. H., Joana Mesquita-Guimarães, J., Henriques, B., Silva, F.S., Fredel, M.C. 2019. The Potential Use of Oyster Shell Waste in New Value-Added By-Product. *Resources* 2019, 8(1), 13;
- Soares, C.E. & Henry-Silva, G.G. 2019. Emission and absorption of greenhouse gases generated from marine shrimp production (*Litopenaeus vannamei*) in high salinity. *Journal of Cleaner Production* 218, 367-376.
- Sokal, R. R., & Rohlf, F. J. 1995. *Biometry: The principles and practice of statistics in biological research*, 3rd ed. W.H. Freeman, New York. 887p.
- Soto D, Aguilar-Manjarrez J, Hishamunda N, eds. (2008) *Building an ecosystem approach to aquaculture*. FAO/Universitat de les Illes Balears Expert Workshop. 7–11 May 2007, Palma de Mallorca, Spain. FAO Fisheries and Aquaculture Proceedings. No. 14. FAO, Rome.
- Steffen et al. 2015. Planetary Boundaries: Guiding human development on a changing planet. *Science* Vol. 347 no. 6223
- Stockholm Resilience Center, 2022. What is resilience? Available at: <https://www.stockholmresilience.org/research/research-news/2015-02-19-what-is-resilience.html>, assessed on March 15th, 2022.
- Strand Å, Rydstedt A, Lindblom E, 2022. Mapping existing and emerging LTS aquaculture in the Atlantic Region, AquaVitae, Tromsø, 18 pp.
- Sverdrup, H., Koca, D., & Ragnarsdottir, K. V. 2013. Peak Metals, Minerals, Energy, Wealth, Food and Population: Urgent Policy Considerations for a Sustainable Society. *Journal of Environmental Science and Engineering B2*, (2013), 189-222.
- Troell, M., B. Costa-Pierce, S. Stead, R.S. Cottrell, C. Brugere, A. Farmery, D. Little, Å. Strand, D. Soto, R. Pullin, M. Beveridge, K. Salie, R. Yossa, P. Moraes-Valenti, J. Blanchard, J. Dresdner, P. James, E. Allison, C. Devaney and U. Barg. 2023. Perspectives on aquaculture's contribution to the SDGs for improved human and planetary health. Background paper for FAO Shanghai Symposium - "Aquaculture and the SDGs". Paper published during the Global Conference on Aquaculture Millennium +20.
- UN (United Nations), 1992. Agenda 21. In: *United Nations Sustainable Development, United Nations Conference on Environment & Development*. United Nations, New York.
- UN (United Nations), 2007. *Indicators of Sustainable Development: Guidelines and Methodologies*, 3rd ed. United Nations, New York.
- UN (United Nations), 2015. *Transforming Our World: The 2030 Agenda for Sustainable Development*. United Nations, Department of Economic and Social Affairs.
- UN (United Nations), 2022. *Sustainable Development Goals*. Available at: <https://sdgs.un.org/goals>, accessed March 27th 2022.
- Valenti, W.C., Kimpara, J.M., Preto, B.L., 2011. Measuring aquaculture sustainability. *World Aquaculture* 42 (3), 26–30.

- Valenti, W.C.; Kimpara, J.M.; Preto, B.L. & Moraes-Valenti, P. 2018. Indicators of sustainability to assess aquaculture systems. *Ecological Indicators*, 88:402-4013.
- Walton, M.E.M., Vilas C., Cañavate J.P., Gonzalez-Ortegon E., Prietob, A., van Bergeijk S.A., A.J. Greenc, S.A., Librero M., Mazuelos N., Le Vay L. 2015. A model for the future: Ecosystem services provided by the aquaculture activities of Veta la Palma, Southern Spain. *Aquaculture* 448: 382–390.
- World Bank (2021) Carbon Pricing Dashboard. Gold Standard mechanism. Available at <[https://carbonpricingdashboard.worldbank.org/carbon\\_crediting](https://carbonpricingdashboard.worldbank.org/carbon_crediting)>. Accessed in December 2022.
- WWF. 2020. Living Planet Report 2020 - Bending the curve of biodiversity loss. Almond, R.E.A., Grooten M. and Petersen, T. (Eds). WWF, Gland, Switzerland.
- Yuan, J., Xiang, J., Liu, D.,.....et al. 2019. Rapid growth in greenhouse gas emissions from the adoption of industrial-scale aquaculture. *Nature Climate Change*, 9:318–322.
- Ziegler, F., Langeland, M., Guillen, J. & Druon, J.N. 2022. Scientific, Technical and Economic Committee for Fisheries (STECF) – Marketing standards: review of proposed sustainability criteria/indicators for aquaculture (STECF-22-13). Publications Office of the European Union, Luxembourg, 2022.

## Appendix 1 – Sustainability aspects and indicators

*Desired state: Specific sustainability aspects and associated indicators (D6.1, Lindblom et al., 2021) and whether they were used in the evaluation of sustainability in the Brazilian LTS aquaculture systems (environmental, social, economic), and in governance (all-Atlantic scope). Please observe that there may be some inconsistencies in terminology between D6.1 and the tables presented below.*

### Environmental sustainability

Desired state: Specific sustainability aspects	Indicator	Used in calculations in D6.3	Category in the analysis (section 3.2.1 and 4.2.1)
<b>Low use of natural resources</b>	Use of Space	Yes	a
	Use of Energy	Yes	a
	Dependence of water	Yes	a
	Use of Nitrogen	Yes	a
	Use of Phosphorus	Yes	a
<b>Use renewable energy and materials</b>	Proportion of Renewable Energy	Yes	a
<b>Releases little to no greenhouse gases</b>	Potential of Global Warming	Yes	c
<b>Use natural resources efficiently</b>	Efficiency in the Use of Energy	Yes	b
	Efficiency in the Use of Nitrogen	Yes	b
	Efficiency in the Use of Phosphorus	Yes	b
<b>Generate low quantity of pollutants and unused by-products</b>	Potential of Organic Pollution	Yes	c
	General Chemical Pollution	Yes	c
	Pollution by Hormones	Yes	c
	Pollution by Heavy Metals	Yes	c
	Production Actually Used	Yes	b
<b>Shows little to no intrinsic pollution and accumulation of by-products</b>	Production Actually Used	Yes	b
	Accumulation of Phosphorus	Yes	d
	Accumulation of Organic Matter	Yes	d
	Accumulation of Particulate Material	Yes	d
<b>Shows capacity of recycling and reusing materials</b>	Rate of circularity (used in economic domain – number of circular processes)	Yes	(f in economic domain)
<b>Produce little changes in the surrounding environment, including biotic communities</b>	Changes in water flow	No	-
	Shading	No	-
	Risk of Farmed Species	yes	e
	Change in alpha-biodiversity	No	-
	Potential to change water environment	No	-
	Impacts of seed acquisition	Yes	e

Desired state: Specific sustainability aspects	Indicator	Used in calculations in D6.3	Category in the analysis (section 3.2.1 and 4.2.1)
	Potential to change the gene pool of the native community	Yes	(e, included in the Risk of farmed species indicator)
<b>Shows low risk of damaging genetic diversity and biodiversity</b>	Risk of farmed species	Yes	e
	Change in alpha-biodiversity	No	-
	Potential to change water environment	No	-
	Impacts of seed acquisition	Yes	e
	Potential to change the gene pool of the native community	Yes	(e, included in the Risk of farmed species indicator)
<b>Mitigates environmental degradation</b>	Eutrophication (Potential of eutrophication of nitrogen and Potential of eutrophication of phosphorous)	Yes	c
	Oxygen depletion	No	-
	Potential of Organic Pollution	Yes	c
	Potential of Siltation	Yes	c
	Potential of Global Warming	Yes	c
	General Chemical Pollution	Yes	c
	Pollution by Heavy Metals	Yes	c
	Change in alpha-biodiversity	No	-
<b>Complies with principles of animal welfare</b>	Environmental comfort	Yes	f
	Animal Health	No	-

## Economic sustainability

Desired state: Specific sustainability aspects	Indicator	Used in calculations in D6.3	Category in the analysis (section 3.2.1 and 4.2.3)
<b>Shows capacity to keep a skilled staff</b>	Workforce capacitation	No	-
<b>Shows capacity to maintain family farmers in the activity</b>	Earning family ratio	No	-
	Annual income	Yes	d
	Annual earnings	No	-
<b>Shows efficient use of financial resources</b>	Ratio net income and initial investment	Yes	a
<b>Shows economic feasibility</b>	Internal rate of return	No	-
	Payback Period	No	-

Desired state: Specific sustainability aspects	Indicator	Used in calculations in D6.3	Category in the analysis (section 3.2.1 and 4.2.3)
<b>(They were replaced by the next block of indicators – including externalities)</b>	Cost-benefit ratio	No	-
	Net Profit	No	-
	Profitability	No	-
<b>Shows capacity to absorb negative externality costs (They also show economic feasibility under the perspective of economic sustainability)</b>	Internal rate of return (including externalities)	Yes	a
	Payback Period (including externalities)	Yes	b
	Cost-benefit ratio (including externalities)	Yes	b
	Net Profit (including externalities)	Yes	d
	Profitability (including externalities)	Yes	
<b>Shows resilience in changing scenarios</b>	Diversity of products	Yes	e
	Diversity of markets	Yes	e
	Potential of economic resilience (including externalities)	Yes	e
<b>Use the circular economy approach</b>	Rate of Circularity	Yes	f?
<b>Shows capacity to attract investors</b>	Risk Rate	Yes	e
	Ratio net income and initial investment (including externalities)	Yes	a
	Internal rate of return (including externalities)	Yes	a
	Payback Period (including externalities)	Yes	b
	Cost-benefit ratio (including externalities)	Yes	b
	Net Profit (including externalities)	Yes	d
	Potential of economic resilience (including externalities)	Yes	e
	Profitability (including externalities)	Yes	
	Annual Earnings (including externalities)	Yes	
	Strength of Value Chain	No	-
<b>Shows capacity to generate capital for reinvestment</b>	Invested Capital Generated in the Activity	Yes	d?

## Social sustainability – Social development

Desired state: Specific sustainability aspects	Indicator	Used in calculations in D6.3	Category in the analysis (section 3.2.1 and 4.2.2)
<b>Shows capacity to generate benefits to local communities</b>	Development of Local Economy	Yes	b
	Use of Local Workers	Yes	b

Desired state: Specific sustainability aspects	Indicator	Used in calculations in D6.3	Category in the analysis (section 3.2.1 and 4.2.2)
	Local Consumption of Production	Yes	b
	Access to Health-Insurance Programs	Yes	d
<b>Contribute to food security of local and global populations</b>	Local Consumption of Production	Yes	b
<b>Respect local culture and use of social capital of local communities</b>	Use of Local Workers	Yes	b
	Participation in Outside Community Activities	Yes	d
<b>Allow families to have socioeconomic conditions according to the local standards</b>	Earning family ratio	Yes	a
	Investment to Create Direct Employment	Yes	c
	Investment to Create Total Employment	No	-
	Proportion of Self-Employments	Yes	c
<b>Promote social use of earth spaces (land and water surfaces)</b>	Use of Space	Yes	(a in the environmental domain)
	Dependence of water	Yes	(a in the environmental domain)
<b>Ensure full employment, safe and decent work conditions</b>	Safety at Workplace	Yes	d
	Workforce capacitation	No	-
	Investment to Create Direct Employment	Yes	c
	Investment to Create Total Employment	No	-
	Proportion of Self-Employments	Yes	c
<b>Ensure a plan of professional development</b>	Schooling	Yes	d
	Workforce capacitation	No	-
<b>Generate direct and indirect jobs as well as self-employment</b>	Investment to Create Direct Employment	Yes	c
	Investment to Create Total Employment	No	-
	Proportion of Self-Employments	Yes	c
<b>Generate equitable income distribution</b>	Pay Equality	Yes	e
	Income Distribution	Yes	e
<b>Generate equality of opportunities</b>	Gender Inclusion	Yes	f
	Racial Inclusion	Yes	f
	Age Inclusion	Yes	f
<b>Promote inclusion of gender, age and different ethnic groups</b>	Gender Inclusion	Yes	f
	Racial Inclusion	Yes	f
	Age Inclusion	Yes	f
	Earning family ratio	No	a?
	Access to Health-Insurance Programs	Yes	d

Desired state: Specific sustainability aspects	Indicator	Used in calculations in D6.3	Category in the analysis (section 3.2.1 and 4.2.2)
Promote well-being, fulfillment and life-style according to the local standards	Schooling	Yes	d
Promote access to health programs, schooling and capacitation of the workforce.	Schooling	Yes	d
	Access to Health-Insurance Programs	Yes	d
	Workforce capacitation	No	

## Social sustainability – Policy and Governance

Desired state: Specific sustainability aspects	Indicator	Replaced or Merged to:	Used in calculations in D6.3	Category in the analysis (section 3.2.1 and 4.2.2)
Intergeneration equity (Consciousness to conserve the availability and abundance of natural resources for use by future generations)	Potential to change the gene pool of the native community	Risk of Farmed species	Yes	(e in environmental domain)
	Potential to change water environment	Potential of Eutrophication of Phosphorous	Yes	(c in environmental domain)
		Potential of Eutrophication of Nitrogen	Yes	(c in environmental domain)
	Potential of Organic Pollution	Potential of Organic Pollution	Yes	(c in environmental domain)
	General Chemical Pollution	General Chemical Pollution	Yes	(c in environmental domain)
	Pollution by Hormones	Pollution by Hormones	Yes	(c in environmental domain)
	Pollution by Heavy Metals	Pollution by Heavy Metals	Yes	(c in environmental domain)
	Potential of Global Warming	Potential of Global Warming	Yes	(c in environmental domain)
	Existence of a national monitoring programme to monitor chemicals	Removed	No	-
	Existence in national regulations of specific provisions on aquaculture site selection to preserve biodiversity and sensitive habitats	Inclusion in territorial management planning	Yes	b

Desired state: Specific sustainability aspects	Indicator	Replaced or Merged to:	Used in calculations in D6.3	Category in the analysis (section 3.2.1 and 4.2.2)
Ensure easy access to technical capacitation	Schooling	Schooling	Yes	(d in the social domain)
	Workforce capacitation	Access to workforce training	Yes	c
	Existence of training program for sector employees on financial aspects of activity			
	Existence of training program for sector on environmental aspects of activity			
Ensure a positive perception of aquaculture by the local population	Noise, light and odor originating from the farm are minimized in areas where it may impact others (if applicable to growing area)	Local population perception	Yes	i
Ensure a positive perception of aquaculture products by the consumers	Documented complaints response protocol that includes, at a minimum, a register of complaints and appropriate responses	Consumer perception	Yes	i
Effectiveness and efficiency of governments (e.g. in promoting decentralized and inexpensive regulations)	Legislation reviewed and streamlined	Clear rules and regulations	Yes	b
Accessible, broad, fair legislation with incentives	Evidence of compliance with all applicable legal requirements and regulations where the farming operation is located (e.g., permits, licenses, evidence of lease, concessions and rights to land and/or water use)	Clear rules and regulations	Yes	b
	Existence of research funds	Public financial transparency	Yes	e
Ensure easy and rapid obtaining of permits	Number of new licenses and authorized production volume	Obtention of permits	Yes	b
	Number of concessions and license for aquaculture			
Ensure a cost-effective tax policy	Subsidies in relation to production value	Tax policy	Yes	b
	Number and type of alternative incentive mechanisms implemented			
Ensure easy access to capital	Lack or inadequate access to financial resources by (prospective capture fisheries or) aquaculture entrepreneurs	Access to credit and loans	Yes	g
	Structural fund expenditure			

Desired state: Specific sustainability aspects	Indicator	Replaced or Merged to:	Used in calculations in D6.3	Category in the analysis (section 3.2.1 and 4.2.2)
Inclusion of aquaculture in the government development plans and the use of territory	Size of allocated zones for aquaculture	Inclusion in land/water use planning	Yes	b
Inclusion of aquaculture in plans of coastal and territorial management (e.g. coastal zoning)	Existence of national legislation for zoning	Inclusion in public planning	Yes	b
	Existence of allocated zones for aquaculture	Inclusion in land/water use planning	Yes	b
Accountability of all stakeholders with transparency and integrity in all actions	A mechanism (e.g., insurance or an industry agreement to collect derelict gear) is in place for the decommissioning of abandoned farms	Transparency of stakeholders	Yes	a
	Global partnership producing information for the world and avoiding proprietary	Removed	No	-
	Existence of participatory mechanisms in decision-making processes	Interaction between public & private sectors	Yes	a
Co-management of aquaculture sector by industry, government and community representatives (Participatory and shared decisions between all stakeholder, coordinating the interests of all actors)	Effective participation to decision making process	Sharing power	Yes	a
		Collaboration among stakeholders	Yes	a
	Mechanisms for participation established and reviewed periodically	Coordination of collective interest	Yes	a
Effective management of conflicts among stakeholders	Conflict resolution protocol, including publicly available registry of complaints and evidence of due diligence to resolve them	Managing conflicts	Yes	a
Support organization of cooperatives and farmer associations	Existence of unions and specific collective agreements for the aquaculture sector	Cooperatives and Associations	Yes	a
	Existence of producer's organizations or cooperatives for sales			
	Existence of stakeholder groups for conflict resolution	Managing conflicts	Yes	a
Ensure easy access to extension and specialized services	Strength of value (production) chain	Access to Extension services	Yes	c
	Existence of a professional status			

Desired state: Specific sustainability aspects	Indicator	Replaced or Merged to:	Used in calculations in D6.3	Category in the analysis (section 3.2.1 and 4.2.2)
Ensure suitable logistics for transporting supplies and production	Strength of value (production) chain	Access to Transport	Yes	f
	Unequal distribution of human and infrastructure capacity between and among (AU) Member state			
Ensure access to low cost and good quality energy (preferable renewable) and web communication	Strength of value (production) chain	Access to Energy	Yes	f
	Access to water and electricity			
	Proportion of Renewable Energy	Proportion of Renewable Energy	Yes	(a in the environmental domain)
Ensure easy access to obtain equipment, maintenance services, and supplies at a cost-effective price (preferable close to the farms)	Strength of value (production) chain	Access to Equipment	Yes	d
		Access to equipment maintenance	Yes	c
	Existence of equipment, maintenance and services close to the production sites	Access to equipment maintenance	Yes	c
Ensure access to new technologies and innovation programs	Existence of national mechanism supporting start-ups (tax-break, subsidies, financing)	Access to new technologies	Yes	g
	Existence of research funds			
	Existence of Government and private investments in technological innovations in the area			
Community use and maintenance of the more expensive equipment	Agreements of community use of equipment	Share of costly equipment and services	Yes	d
	Number of partnership contracts			
Economic and political stability, and predictability of the rule of law	Existence of solid and commercially stable government policies	Interaction between public & private sectors	Yes	a
Open to interaction between public, private and third-party institutions	Evidence of outreach (e.g., meeting records, newsletters, consultation with communities and indigenous groups, or membership in association with documented outreach program)			
		Existence of participatory mechanisms in decision making processes	Collaboration among stakeholders	Yes

Desired state: Specific sustainability aspects	Indicator	Replaced or Merged to:	Used in calculations in D6.3	Category in the analysis (section 3.2.1 and 4.2.2)
	Existence of regular public hearings to guarantee the participation of the population in decision-making	Sharing power	Yes	a
Financial and social accountability	Accountability mechanisms (reporting arrangements) met	Public social transparency	Yes	e
	Existence of economic policies to encourage aquaculture with social benefits	Public social transparency	Yes	e
Financial accounting, transparency and traceability	Accountability mechanisms (reporting arrangements) met	Public financial transparency	Yes	e
	Existence of transparent and reliable economic policies to encourage aquaculture			
Clear and effective rules and regulations (including environmental legislation)	Existence in national regulations of specific provisions on aquaculture site selection to preserve biodiversity and sensitive habitats	Public financial transparency	Yes	e
	Existence of legislation for monitoring of environmental parameters	Clear rules and regulations	Yes	b
	Existence of public policies with economic incentives for sustainable aquaculture production	Tax policy	Yes	b
	Existence of specific legislation governing the principles of the Code of Conduct for Responsible Fisheries (CCRF)	Tax policy	Yes	b
		Inclusion in public planning	Yes	b
Control of corruption and violence	International ranking of corrupt countries	Managing conflicts	Yes	a
	International ranking of violent countries			
Programs of sanitary inspection and biosecurity	Existence of quality certification schemes (independent bodies)	Sanitary and Biosecurity	Yes	h
		Product quality control	Yes	h
	Existence of biosecurity system	Sanitary and Biosecurity	Yes	h
	Existence of mechanisms of information with regard to the aquaculture production process and its compliance to regulations available and accessible to the public	Certification availability	Yes	h
	Existence of a traceability system	Product quality control	Yes	h

Desired state: Specific sustainability aspects	Indicator	Replaced or Merged to:	Used in calculations in D6.3	Category in the analysis (section 3.2.1 and 4.2.2)
<b>Programs of quality control of the seafood (broad sensus) production</b>	Existence of mechanisms of information with regard to the aquaculture production process and its compliance to regulations available and accessible to the public	Product quality control	Yes	h
<b>Programs of certification to aggregate value to the products</b>	Percentage of value-added products	Certification availability	Yes	h
	Existence of ecolabels and product specifications	Certification availability	Yes	h
	Price differential with respect to quality	Efficacy of certification	Yes	h
	Existence of sustainability certification companies (public or private)	Certification availability	Yes	h
		Efficacy of certification	Yes	h

## Appendix 2 – Governance questionnaire

### Work Package 6: Governance sustainability (please use one sheet for each system or location)

All data will be treated as confidential. No identified information will be disclosed. Please, feel free to skip the questions you are not comfortable answering

**Your name (optional):**  
**e-mail address (optional):**  
**Name of your institution (optional):**  
**Member of the AquaVitae consortium? ( ) Yes ( ) No**  
**If yes, cite the CS and WP you are enrolled:**  
 Production system (e.g., species, surface long-lines, etc.):  
 Location (Country, City, Region, etc.):  
 Mean annual production (tonnes):

Assess the following criteria considering the regional scenario for the production chain of your system.

<b>Rate each criterion below on a 1 to 5 scale, where: 1 = absent or poor, 2 = bad, 3 = medium, 4 = good, 5 = excellent.</b>	<b>Rate</b>	<b>Comment</b>
1. Is there any kind of coordination of the interests of all players?		
2. Are there suitable interactions between public (managed by governments in all levels) and private institutions?		
3. Are openness, transparency, and integrity characteristic of farms, other stakeholders and the regional management?		
4. Is there an effective system for managing conflicts		
5. Is there sharing of power among governing decision-makers and other stakeholders		
6. Is there effective collaboration among all stakeholders oriented to increasing performance?		
7. Is there a clear environmental legislation and other rules and regulations for this system?		
8. Is it easy and rapid to obtain permits?		
9. Are there organization of cooperatives and farmer associations?		
10. Is there a clear and realistic tax policy?		
11. Is it easy to get access to training of human resources?		
12. Is it easy to get access to extension services, such as, technical assistance?		
13. Is it easy to get access to specialized services, such as disease's identification, meat, water and diet analyses?		
14. Is it easy to get access to credit and loans?		
15. Are there suitable logistics for transporting supplies and production output?		
16. Is there access to low cost and good quality energy?		
17. How is the availability of equipment and supplies?		
18. How is the availability of equipment maintenance services close to the farms?		
19. Is there access to new technologies and innovation programs?		
20. Is it possible to get communitarian/shared use of the costly equipment, when needed?		
20. Is it possible to get communitarian/shared use of the costly equipment, when needed?		
21. Is there presence of supply providers in the same region of the farms?		
21. Is there presence of supply providers in the same region of the farms?		
22. Is there presence of consumers in the same region of the farms?		
22. Is there presence of consumers in the same region of the farms?		
23. Is aquaculture included in the government development plans (e.g. policies)?		
24. Is aquaculture included in plans of coastal management (e.g. land/water use)?		
25. Is aquaculture included in plans of territorial management (e.g. coastal zoning)?		
26. Is there transparent reporting on financial accounting provided by farmers?		

27. Is there transparent reporting on financial accounting provided by stakeholders other than farmers?		
28. Is there traceable financial accounting provided by local authorities?		
29. Is there social accounting provided by local authorities?		
30. Are there programs of sanitary inspection and biosecurity?		
31. Are there programs of certification to aggregate value to the products?		
32. If available, are the programs of certification effective?		
33. Are there programs to control the quality of the seafood production?		
34. Is there positive perception of the aquaculture by the local population?		
35. Is there positive perception of aquaculture products by the consumers?		

## Appendix 3 – Bar graphs of governance indicators

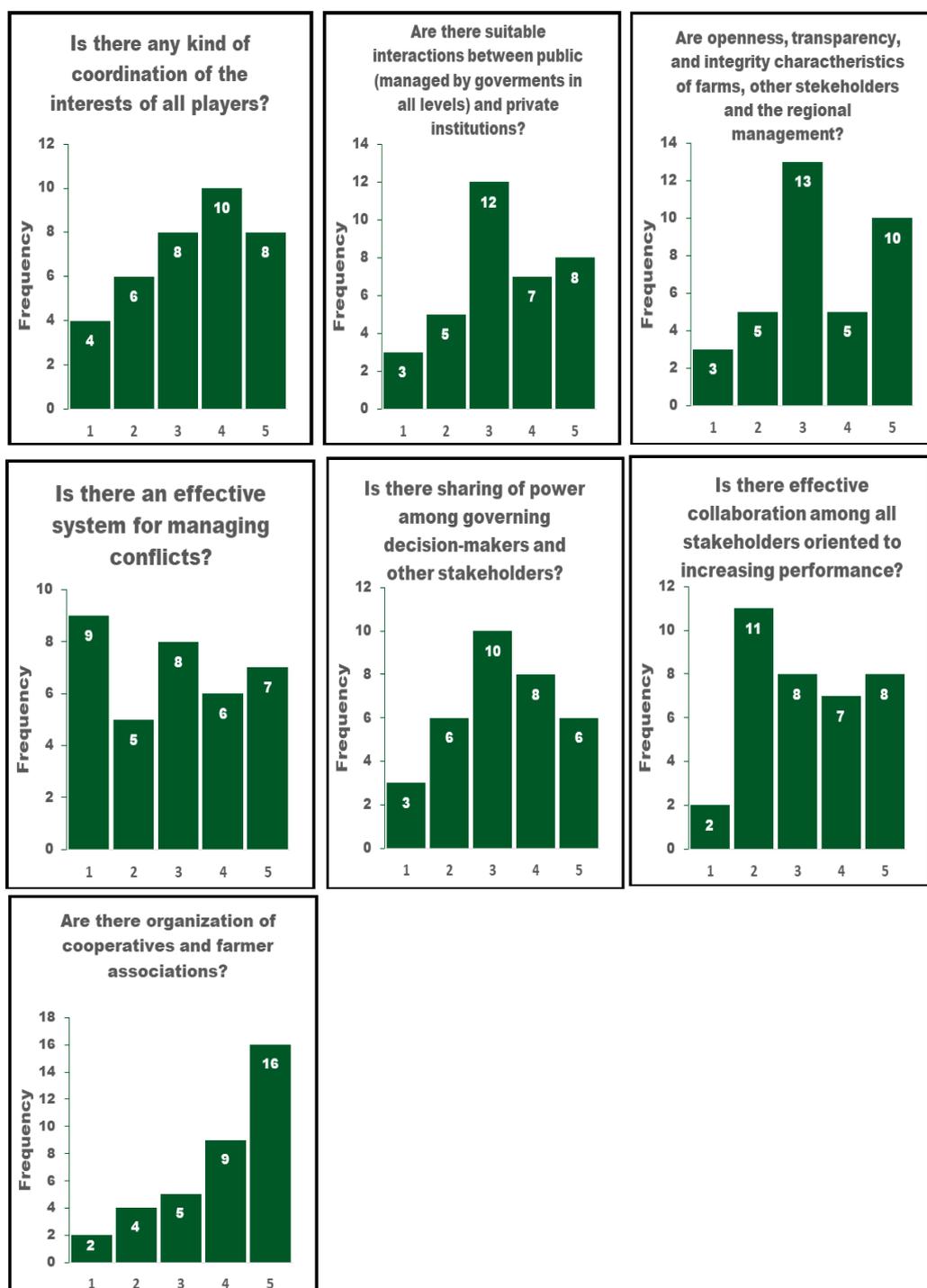


Figure A3.1. Level of sustainability of each feature of a desired governance for LTS aquaculture for the sub-topic relationship among stakeholders. Data were obtained from a survey with stakeholders spread to all Atlantic. Sustainability increases from 1 to 5. Figures inside the bars represent the times the relevant score was attributed to this topic.

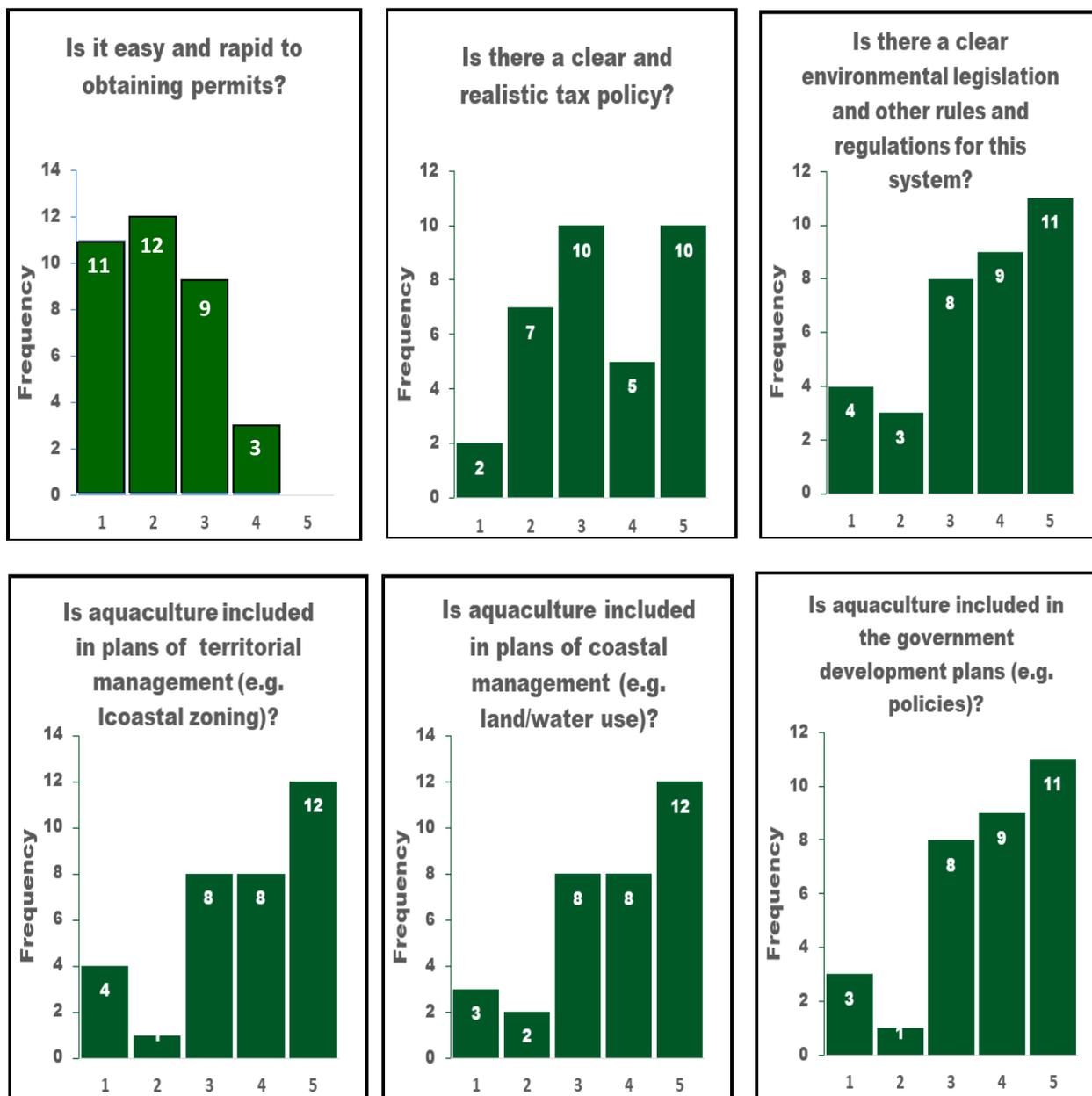


Figure A3.2. Level of sustainability of each feature of a desired governance for LTS aquaculture for the sub-topic planning, rules and regulations. Data were obtained from a survey with stakeholders spread to all Atlantic. Sustainability increases from 1 to 5. Figures inside the bars represent the times the relevant score was attributed to this topic.

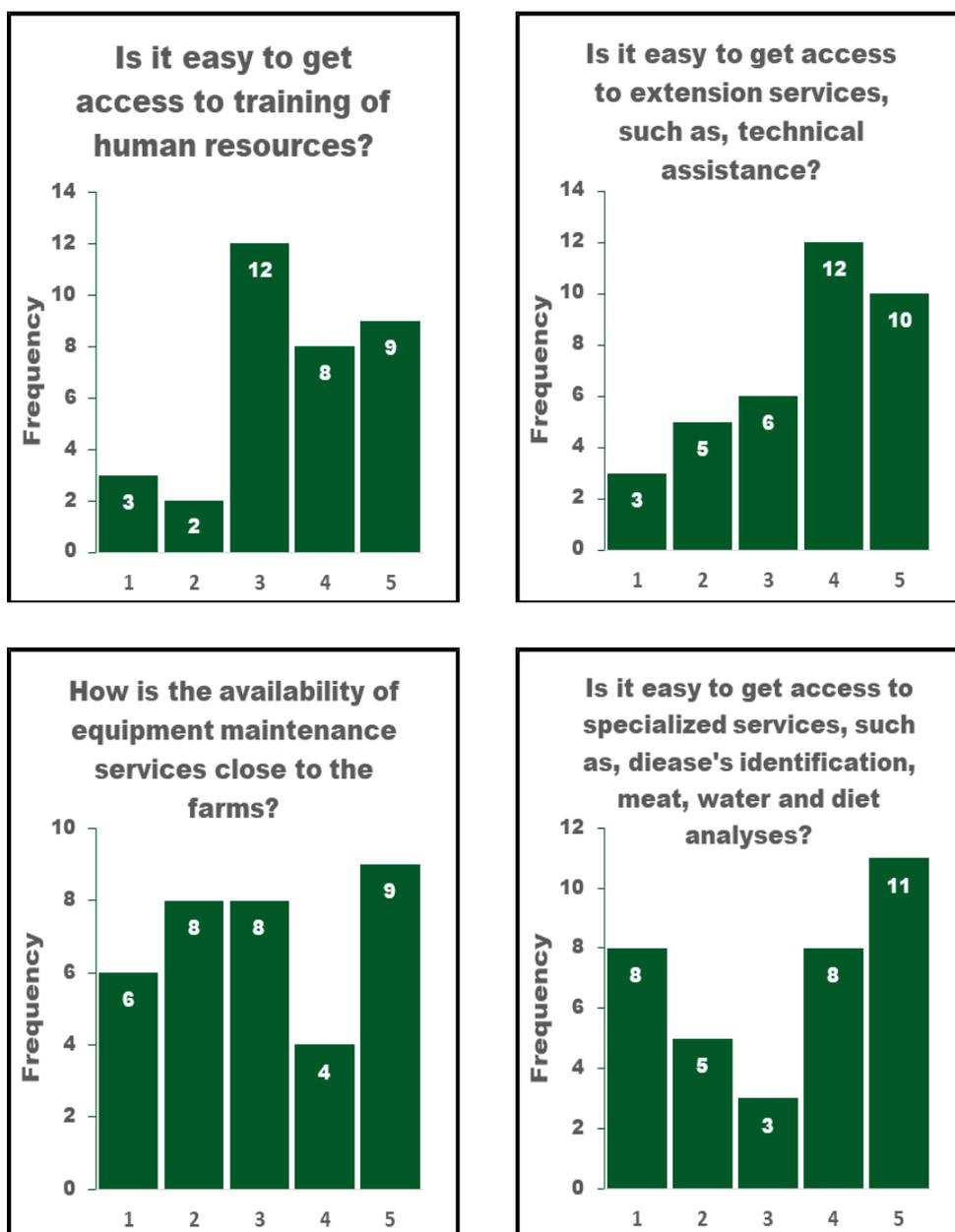


Figure A3.3. Level of sustainability of each feature of a desired governance for LTS aquaculture for the sub-topic access to specialised services. Data were obtained from a survey with stakeholders spread to all Atlantic. Sustainability increases from 1 to 5. Figures inside the bars represent the times the relevant score was attributed to this topic.

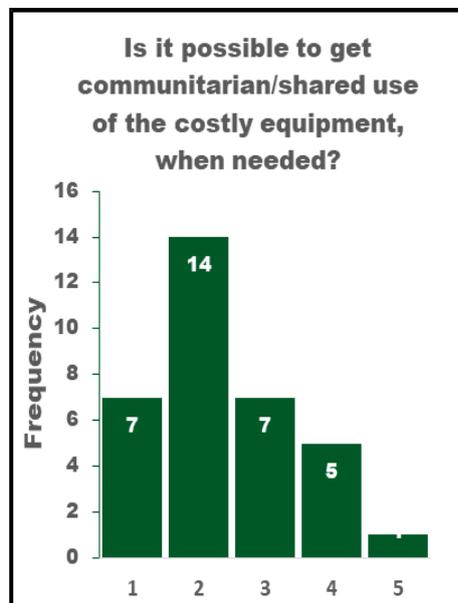
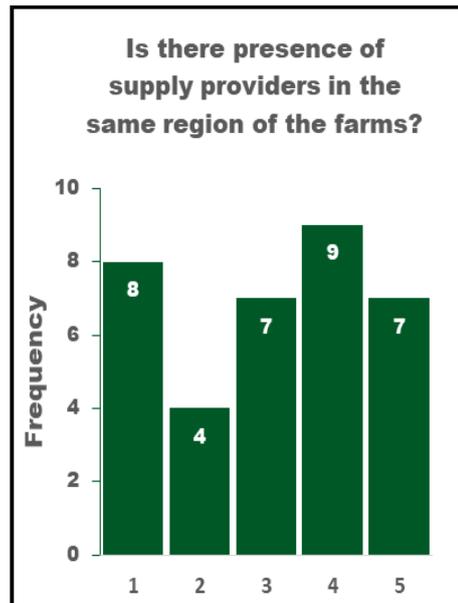
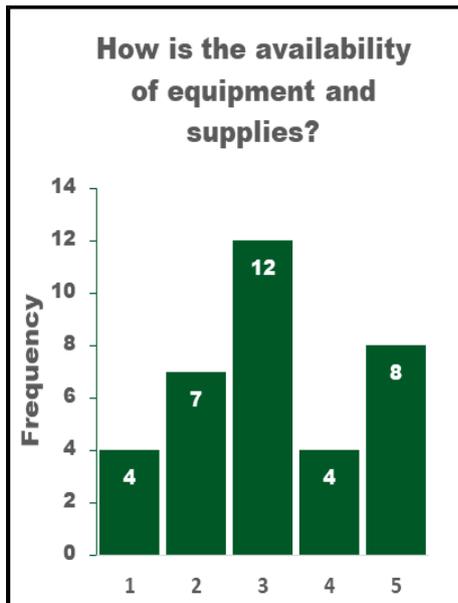


Figure A3.4. Level of sustainability of each feature of a desired governance for LTS aquaculture for the sub-topic access to supplies. Data were obtained from a survey with stakeholders spread to all Atlantic. Sustainability increases from 1 to 5. Figures inside the bars represent the times the relevant score was attributed to this topic.

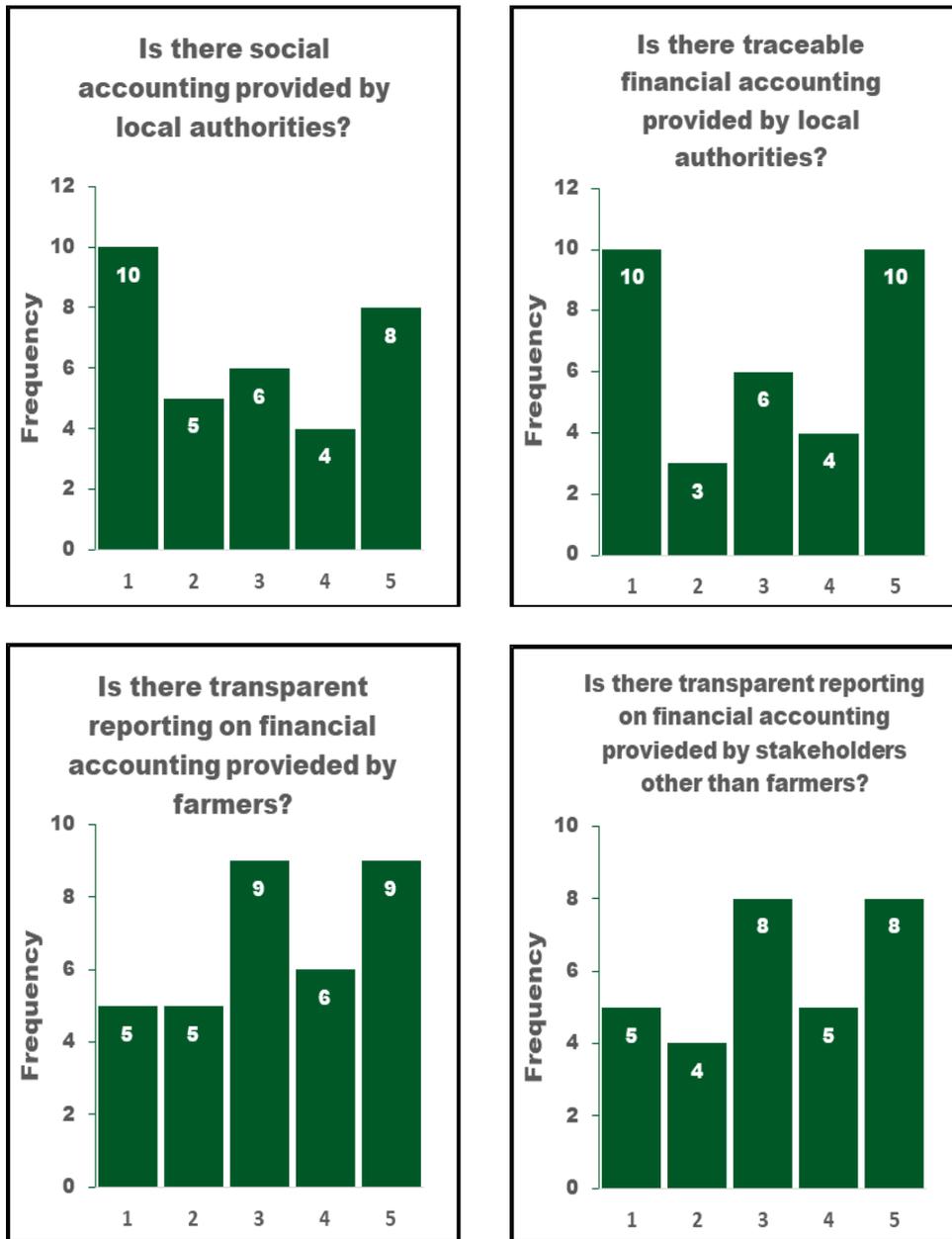


Figure A3.5. Level of sustainability of each feature of a desired governance for LTS aquaculture for the sub-topic accounting and transparency. Data were obtained from a survey with stakeholders spread to all Atlantic. Sustainability increases from 1 to 5. Figures inside the bars represent the times the relevant score was attributed to this topic.

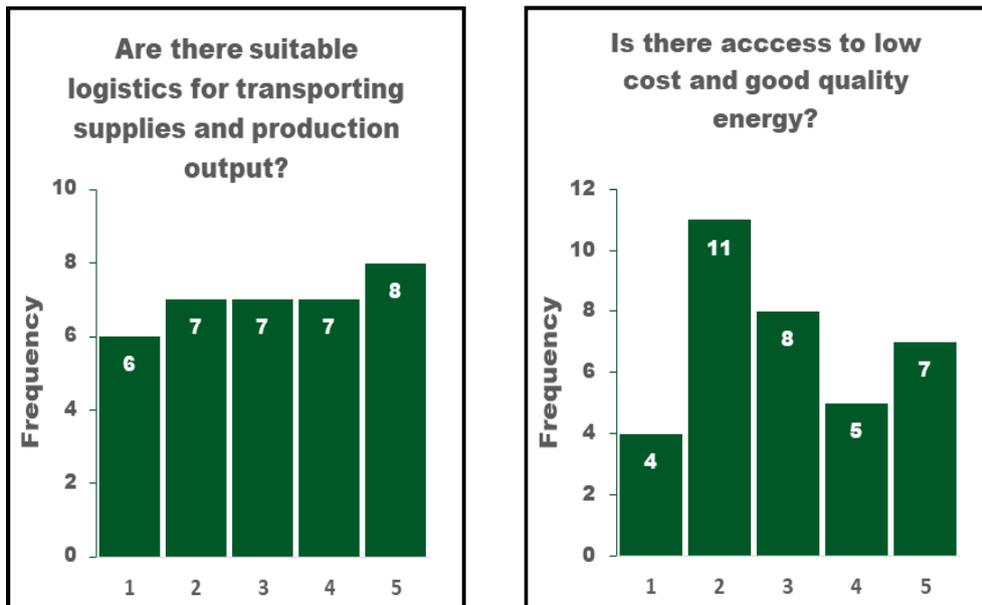


Figure A3.6. Level of sustainability of each feature of a desired governance for LTS aquaculture for the sub-topic infrastructure. Data were obtained from a survey with stakeholders spread to all Atlantic. Sustainability increases from 1 to 5. Figures inside the bars represent the times the relevant score was attributed to this topic.

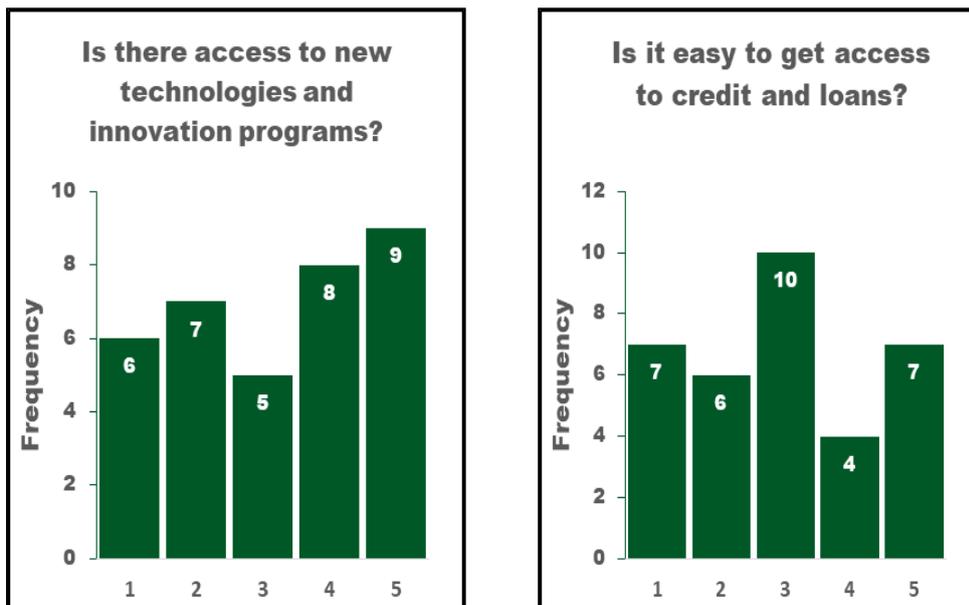


Figure A3.7. Level of sustainability of each feature of a desired governance for LTS aquaculture for the sub-topic access to innovations and credit. Data were obtained from a survey with stakeholders spread to all Atlantic. Sustainability increases from 1 to 5. Figures inside the bars represent the times the relevant score was attributed to this topic.

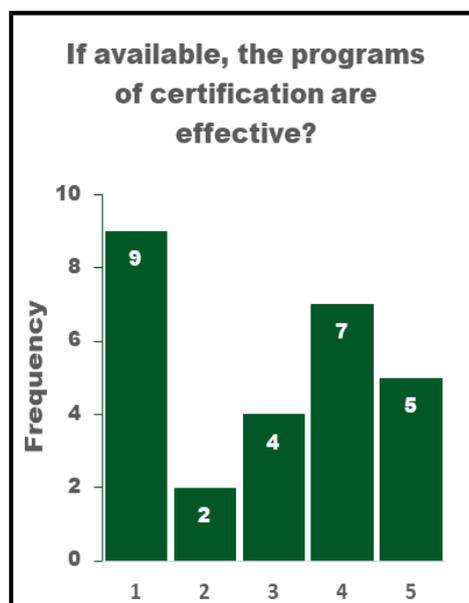
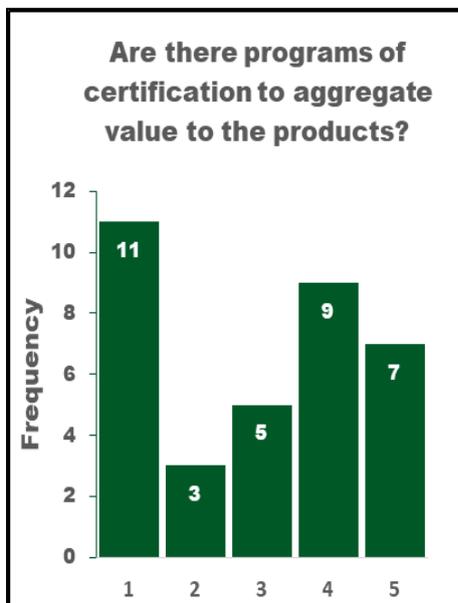
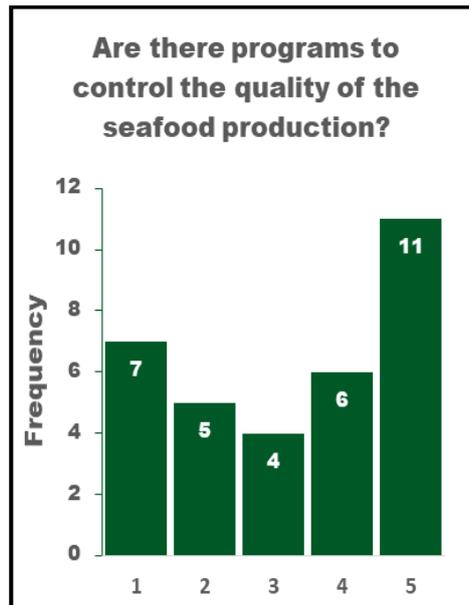
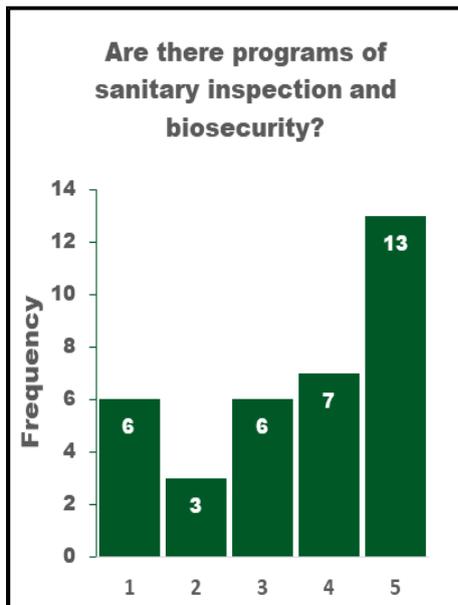


Figure A3.8. Level of sustainability of each feature of a desired governance for LTS aquaculture for the sub-topic product quality and certification. Data were obtained from a survey with stakeholders spread to all Atlantic. Sustainability increases from 1 to 5. Figures inside the bars represent the times the relevant score was attributed to this topic.

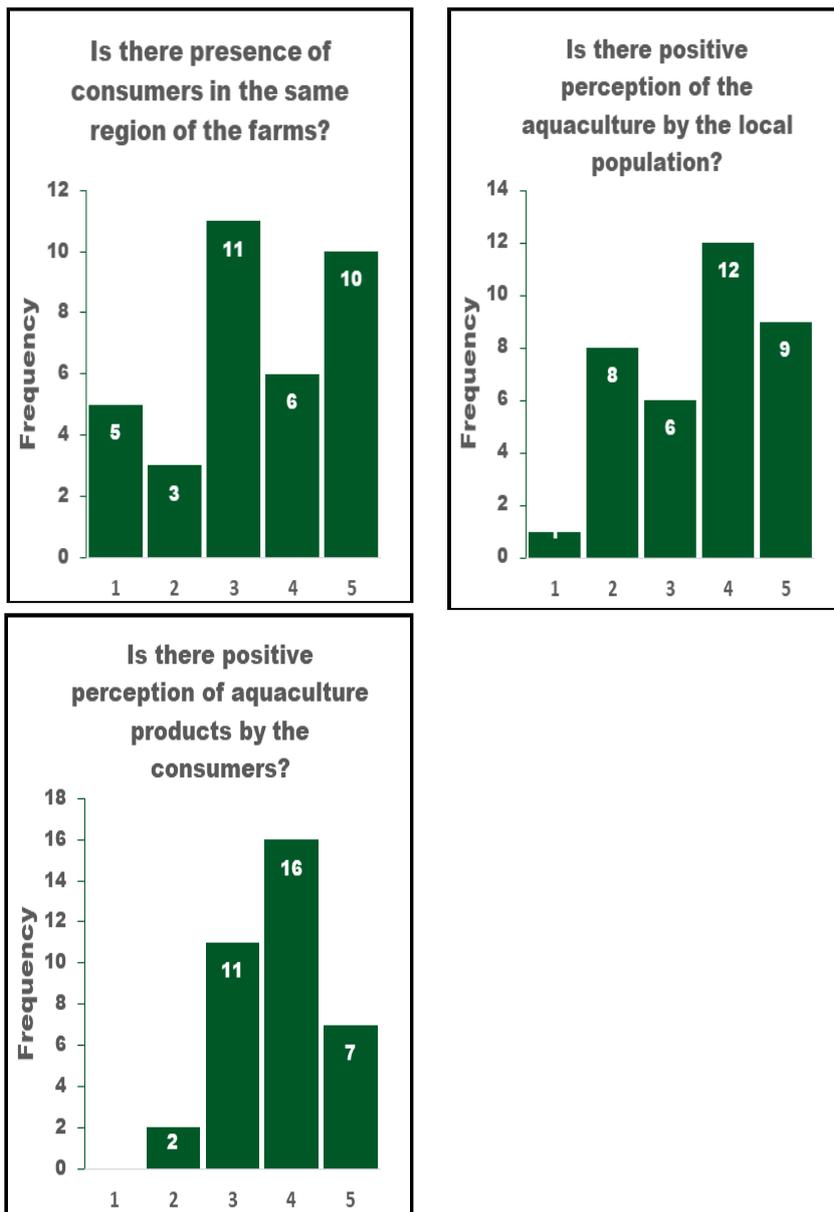


Figure A3.9. Level of sustainability of each feature of a desired governance for LTS aquaculture for the sub-topic consumers' proximity and perception. Data were obtained from a survey with stakeholders spread to all Atlantic. Sustainability increases from 1 to 5. Figures inside the bars represent the times the relevant score was attributed to this topic.