AZA4ICE

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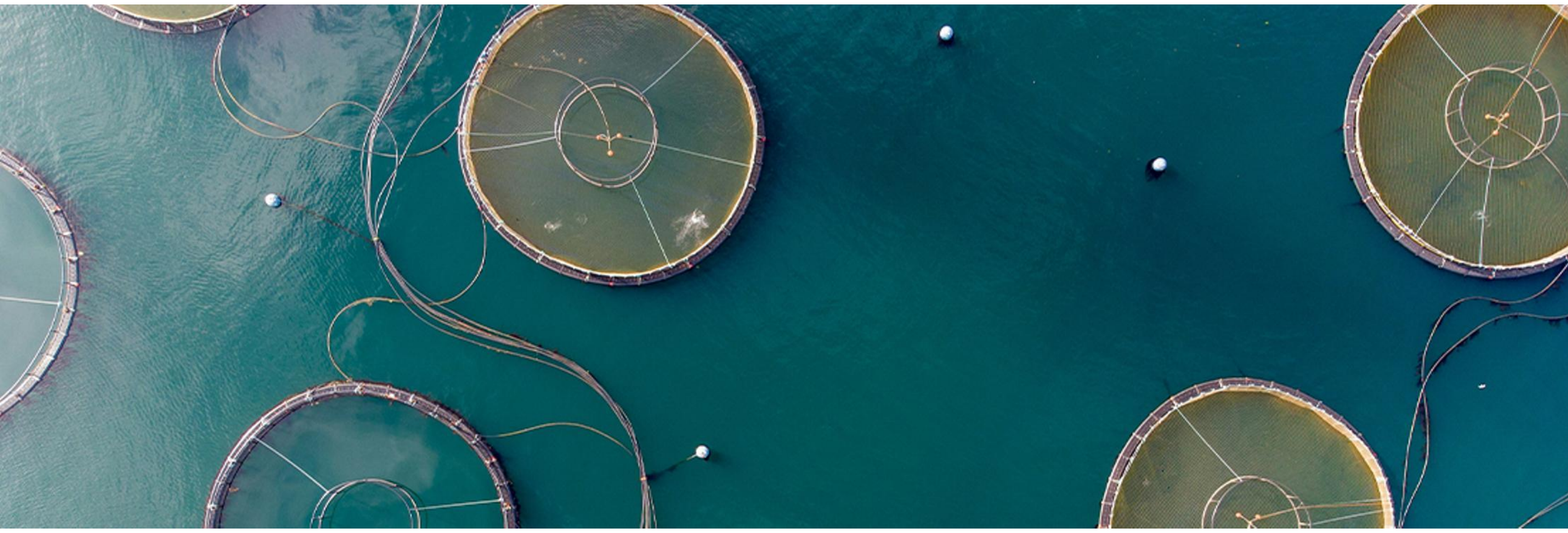

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Output 1.1 AZA4ICE methodology for circular aquaculture spatial planning embedded with innovative circular production systems

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Output ID

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Table of contents

Abbreviations

AHP Analytical Hierarchy Process

AZA Allocated Zones for Aquaculture

C-AZA Allocated Zones for Circular Aquaculture

FMF Fuzzy Membership Function

IMTA Integrated Multi-Trophic Aquaculture

ICI IMTA circularity index

IES Inorganic extractive species

IPI IMTA performance Index

MCDA Multi-Criteria Decision Analysis

MLD Monotonically Linearly Decreasing

MLI Monotonically Linearly Increasing

MSFD Marine Strategy Framework Directive

OES Organic extractive species

POM Particulate organic matter

PPs Project Partners

RAS Recirculating Aquaculture Systems

SI Suitability Index

SiSI Site Suitability Index

SNA Social Network Analysis

SSI Species Suitability Index

TAN Total Ammonium Nitrogen

TRZ Trapezoidal

TSS Total Suspended Solid

WFD Water Framework Directive

WLC Weighted Linear Combination

Executive Summary

This document aims to detail the testing methodology to guide the Project Partners (PPs) in defining the Allocated Zones for Circular Aquaculture (C-AZA) in the eight identified pilot sites throughout the Mediterranean and Black Sea basins. In particular, the steps outlined in this document encompass data collection, assessment of site suitability and species suitability, evaluation of suitable IMTA/RAS models and circular practices, presentation and evaluation of the results, and data evaluation through the stakeholders' involvement.

The methodological framework to be implemented in C-AZA is depicted in **Figure 1**. The number of steps to be applied varies depending on the type and main features of aquaculture activities developed in each pilot case study area. Specifically, the "*site suitability*" is the initial step of the C-AZA methodology when aquaculture activities are either underdeveloped or even absent, while it can be skipped if the sector is consolidated, and it represents a well-established activity in the area. This step is followed by the "*species suitability*", based mainly on the physiological tolerance range, technological culture development, the environmental characteristics of the water body considered, the market demand, regulatory requirements, and on the economic feasibility. The species suitability represents the baseline for the final step of the C-AZA methodology, the "*circularity suitability*" assessment.

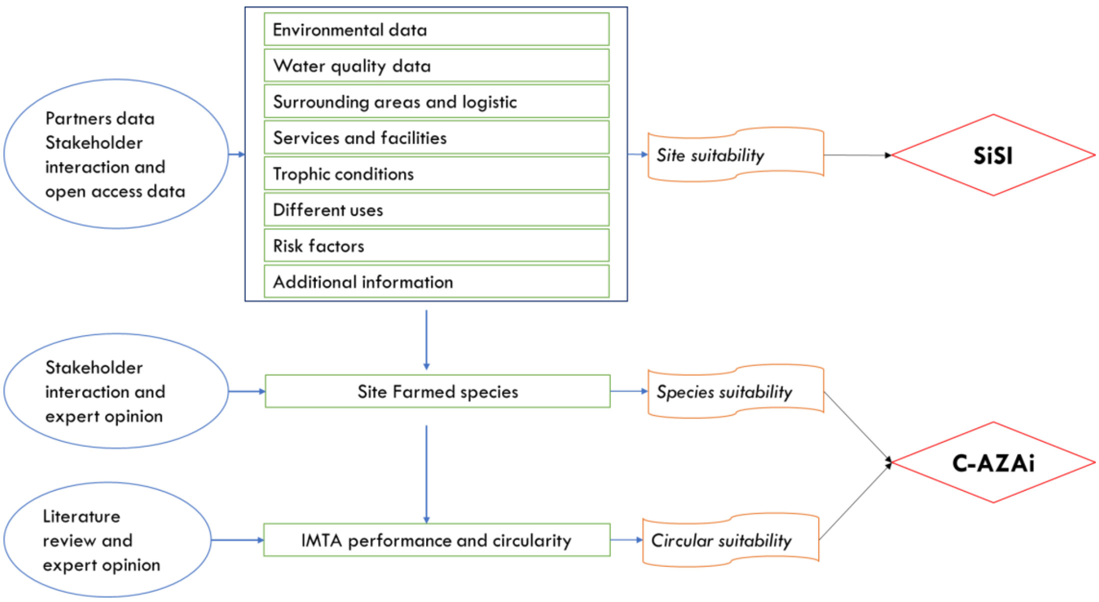

Figure 1. Methodological framework for C-AZA

By following the C-AZA methodology, PPs can systematically define Allocated Zones for Circular Aquaculture in the targeted pilot case study areas, ensuring alignment with project objectives, stakeholder needs, and sustainability goals. The outcomes obtained from the implementation of the C-AZA methodology can assist decision-makers for efficient planning of aquaculture activities in close-to-coast and inland waters based on an ecosystem-based approach aligned with European policies, including the European Common Fisheries Policy, the Farm to Fork Strategy, the Sustainable Blue Economy, and the European Green Deal.

1.1 Introduction

1.1.1 Spatial planning for aquaculture, an essential tool for sustainable aquaculture

An *Allocated Zone for Aquaculture* (AZA; **Figure 2**) is a designated coastal or marine area specifically intended for the development of aquaculture (*Sanchez-Jerez et al., 2016; Macias et al., 2019*). This means that aquaculture in considered the top priority activity in these geographical spaces over other uses. AZAs are established through a *spatial planning* process that takes into account a variety of factors including environmental, social, and economic components. The establishment of AZAs is an important tool for promoting sustainable aquaculture by minimizing conflicts between aquaculture and other aquatic activities, reducing the environmental impact, and optimizing the use of space.

Figure 2. Allocated Zone for Aquaculture located in a coastal area and in a lagoon together with other uses of the area.

Within a European Maritime, Fisheries and Aquaculture Fund (EMFAF) project, the AZA Sardegna Project, has developed a methodology for identifying AZA both at sea, in coastal areas, and in brackish lagoons, marshes, ponds, and lakes. While the specific steps for establishing an AZA may differ based on local conditions, the methodology developed in Sardinia can be transferred, compared, adapted, and tested for use in different regions. Aquaculture environments covered by PPs are diverse at different level of operational activities requiring site-specific aquaculture planning. This adaptation is the primary objective of Activity 1.1 within the AZA4ICE project, which involves refining the AZA instrument embedding circularity for application in eight pilot case studies.

1.1.2 Sustainable aquaculture models: Integrated Multi-Trophic Aquaculture (IMTA) and Recirculating Aquaculture Systems (RAS)

In line with the European Green Deal and Farm-to-Fork Strategy, the European Commission issued the EU Blue Growth Strategy and the "*Strategic Guidelines for a More Sustainable and Competitive EU Aquaculture (2021-2030)*" (European Commission, 2021). This communication encourages the enhancement of environmental performance of the EU aquaculture sector by ensuring the enforcement of environmental laws, mitigating aquaculture's impact, and promoting practices with lower environmental impact that also provide ecosystem services. Within the sustainable production models, implementing and optimizing the energy-efficient RAS and IMTA production systems emerge as target objectives. These developments should offer ecosystem services, including ponds, lagoons and marshes in brackish waters, and coastal waters, and support the maintenance and improvement of aquatic genetic resources and the use of selective breeding for aquaculture stocks.

According to FAO, IMTA can be defined as “a practice in which by-products from one species are recycled to become inputs for another” (*FAO, 2014*). IMTA is not a mere polyculture in the same body of water, but it requires that the co-cultivated species are trophically connected species creating an ecosystem in which one species feeds on the waste of another. Thus, the biggest challenges for IMTA are to create a balanced system of aquatic organisms, as it requires knowledge of each species’ life cycle, feeding habits, oxygen requirements, environmental tolerance and other specific requirements that vary from species to species (*Nissar et al., 2023*).

IMTA setup deals with the trophic connectivity of **four functional groups** within three main categories (***Figure 3***):

1) _*Fed aquaculture species*_ that are normally finfish or shrimps supplied of artificial pellets as a breeding practice during the production cycles. They would be situated in the upper trophic level releasing metabolic wastes such as faeces, pseudo faeces, excreta, and uneaten food suitable to feed a wide range of extractive species.

2) *Organic extractive species (OES)* that are those species that feed on particulate organic matter (POM) (faeces, pseudo faeces, and uneaten food). They are classified into two categories based on their position in the water column:

a) *Deposit OES*

b) Suspension OES

Deposit OES feed large POM at the bottom and include mainly species of echinodermata and polychaeta. In contrast, the suspension feeders filter the small organic particles covering mainly molluscs and sponges even non-feed herbivorous fish

2) *Inorganic extractive species (IES)* that are mainly photosynthetic organisms that absorb the dissolved inorganic matter originating from other trophic levels metabolism [ammonium ($NH4^+$), nitrate (NO3-), phosphate (PO_4^{3-}) and carbon dioxide (CO_2)]. This group include several species of aquatic plants, seaweeds, microalgae, seagrass, and halophytes able to use nutrients wasted in water (C, N, and P) to form new biomass and coupled to other trophic levels.

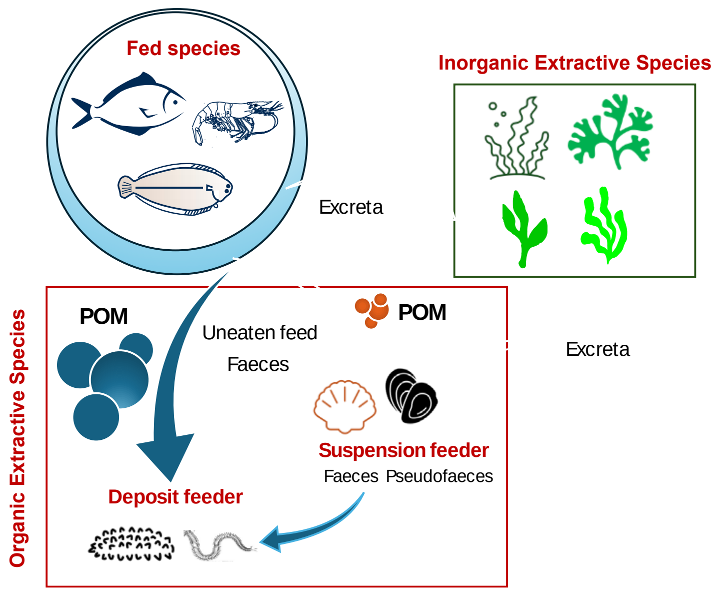

Figure 3. IMTA connectivity.

The highest level is represented by fed species (fish and shrimps) that release organic and inorganic nutrients in the form of faeces, uneaten feed and excreta. The large particulate organic matter (POM) is consumed by deposit feeders and the small POM by suspension feeders. Dissolved inorganic nutrients (excreta) are used by photosynthetic organisms.

The concept of IMTA is extremely flexible and it can be used for all aquaculture production models in open sea and land-based facilities, in marine, brackish, and freshwater or in cold and warm-waters. Hence, some criteria need to be considered IMTA in order to design species combinations into specific production models.

A previous project dealing with IMTA, the INTEGRATE consortium (*Dunbar et al., 2020*), agreed as minimum criteria to set a suitable IMTA model the following:

1. Species must be principally aquatic. This means that primary product must be aquatic. Although terrestrial plants could be integrated in IMTA such as halophytes, the core activity should be aquatic. Thus, marine aquaponics integrating fish and halophytes fulfil this criterion.

2. There should exist a demonstrated flow of nutrients. Mere polyculture cannot be considered IMTA. This means that species from different functional groups should be trophically connected.

3. IMTA should include at least 2 managed, functional groups (fed, *deposit OES, suspension OES* or IES). The most complex IMTAs include fish, seaweeds, oysters/mussels, sponges and cucumbers to increase production efficiency and decrease waste. However, easier models integrating two levels such as fish/halophytes, fish/seaweeds or mussels/seaweeds are also suitable IMTA depending on the AZA. The degree of trophic connectivity between compartments should be not a limitation.

4. IMTA should be considered as a productive model, not only as a bioremediation method and the secondary (tertiary etc.) species must be harvested. During this process, part of the biomass in the system is removed by harvesting creating a balanced system.

According to this criteria IMTA should be as an "***Enhanced production of aquatic organisms (with or without terrestrial organisms) of two or more functional groups, that are trophically connected by demonstrated nutrient flows and whose biomass is fully or partially removed by harvesting to facilitate ecological balance***."

1.2 Stakeholder involvement in C-AZA methodology

Effectively engaging stakeholders is crucial for the process of defining Allocated Zone for Circular Aquaculture (C-AZA). The coexistence of multiple uses and conflicting interests within a targeted study area can pose different challenges, underscoring the importance of gathering stakeholders' feedback. This feedback enables the identification of potential interaction (conflicts, synergies) or limiting factors that could hinder the transition toward a sustainable and circular aquaculture sector in the area. Different aspects must be considered, including competition for spaces, social acceptance, potential risks related to pathogens and pollution, invasive species or climatic changes.

Stakeholders' involvement in the C-AZA process is not an one-time activity but an ongoing effort. Indeed, depending on the stage of the C-AZA process, stakeholder engagement serves specific purposes, including identifying issues, gathering evidence and data collection, building consensus, monitoring and evaluation.

The exchange with stakeholders for C-AZA evaluation will be facilitated in the framework of LiRRIEs (WP2), where involved stakeholders representing the quintuple-helix (5-H) will be informed about C-AZA results and the implementation of the AZA4ICE methodology by PPs. This exchange will allow for cross-fertilisation of ideas and responses to targeted surveys identifying the potential impact of C-AZA. The stakeholder involvement process will include disseminating information to various target groups representing the 5-H, such as producers, relevant local, regional and national competent authorities, farmer organizations, and non-governmental organizations (NGOs), via workshops, meetings, and expert panels. The goal of these activities is to develop social acceptance and obtain a social license to effectively address the C-AZA mission.

Furthermore, the open access C-AZA geospatial platform will serve as a multi-stakeholder platform for convening and addressing common issues and challenges. Participation in such platforms will greatly help in fostering and building social acceptance.

1.3 Data collection

The accuracy and robustness of spatial aquaculture suitability assessment is highly dependent on the spatio-temporal coverage, quality, and reliability of the input dataset. Thus, this kind of analysis requires a comprehensive data collection to ensure accurate evaluation of environmental, social, and economic aspects. The C-AZA methodology offers a structured approach for integrating various factors throughout the evaluation of site suitability, species selection, and circularity principles.

Both satellite and/or *in situ* data can be used for aquaculture suitability assessment. The choice between them depends upon several factors such as the spatial scale, the specific project objectives, and the data availability. Satellite data offer numerous advantages including a broad spatial and temporal coverage, facilitating large-scale assessments across extensive areas. However, some coastal areas and shallow water bodies, like lagoons, are often inadequately covered by satellite data. Furthermore, some environmental variables, such as water quality parameters, may necessitate ground validation to ensure accuracy.

Continuous spatial data can be used for a spatially explicit suitability assessment, aiding in the identification of the most suitable areas across a wide territory. Conversely, *in situ* data can be used to evaluate the aquaculture suitability at specific points and, depending on the spatial coverage and extent of the water body, may inform spatial planning of aquaculture activities. These data have limited spatial coverage compared to satellite data, typically representing specific sampling locations or study sites, and may require extensive fieldwork or data collection efforts to obtain relevant information for site assessment. Nevertheless, *in situ* data can provide detailed and localised information on specific environmental parameters useful for a precise characterization of the site conditions. Moreover, they can be used for validating and supplementing satellite-derived data with ground-truth measurements. While daily data captures environmental fluctuations more comprehensively and provides a more accurate indication of the *site suitability*, weekly or monthly data can also offer valuable insights for this assessment.

The evaluation of aquaculture suitability model outputs must consider all these aspects. This ensures that decision-makers receive precise and informed suggestions and indications regarding aquaculture development in specific areas.

To carry out the *species* and *circularity suitability* it is required a holistic analysis of biological, environmental, aquaculture sector and technological development in the pilot sites and surrounding areas. Some criteria to setting IMTA models were outlined in section 1.1.2. However, the circularity suitability for IMTA nourishes from *in situ* information about geographical distribution of native species, environmental and requirements, life-cycle aspects, market value, and aquaculture information.

The data required for implementing C-AZA methodology are detailed in the following paragraphs, specifying *site suitability*, *species suitability*, and *IMTA circular suitability* assessment.

1.3.1 Data needed to run the AZA site suitability assessment

Conducting a *site aquaculture suitability* assessment requires a systematic process that integrates various types of data, with varying spatial and temporal resolutions. The data required to conduct this AZA assessment are outlined in the following paragraphs and tables, and they can be categorized into several key groups, including environmental data, water quality data, presence of facilities, trophic conditions, use of the water body and the surrounding land, risks associated with the aquaculture development, additional data and information, and the presence of native species in the water body under consideration.

Data collection for all these parameters may involve manual samplings, automated monitoring systems, and stakeholders' involvement, depending on available resources and the specific characteristics of the study area. Additionally, the appropriate sampling locations, methods, and equipment must be selected based on the site's characteristics.

All data must be collected and stored in a spreadsheet format, such as Excel or CSV, as indicated in the tables below (**Table 1** - **Table 9**). Moreover, it is essential to ensure that numerical values adhere to the English format, with a period used as the decimal separator and a comma used to separate thousands. This will ensure uniform and consistent datasets for subsequent upload to the C-AZA geospatial platform developed in Activity 1.4.

1.3.1.1 Description of the pilot site and environmental data collection

In order to provide an overview of the context and ensure accurate data collection and analysis, a synthetic description of each pilot site with the most relevant information is required. The description should include details of the site location, its geographical features indicating the extension and boundaries of the area, the identified sampling points, main activities carried out in the area, and details of the aquaculture activities if applicable.

For each pilot site and selected sampling points, environmental data can be obtained from various reliable sources including *in situ analysis*, from open-access databases (*e.g.* EMODnet, Copernicus, etc.), government databases, local environmental agencies, research institutions, or previously published reports, grey literature, and scientific publications. References to the original work must be provided if data are extracted from previous reports or datasets.

For *in situ* data, latitude and longitude of each sampling site must be recorded. All environmental data measured, along with the corresponding methods and/or instruments used must be reported in the template (Deliverable 1.2.1). Up to date, there exist very well-established methodologies for the parameters considered. Below are non-exhaustive lists of examples on how to report the monitoring of various environmental data (**Table 1**).

Physico-chemical parameters such as water temperature, dissolved oxygen, pH and salinity can be monitored using multiparametric probes, and turbidity through a turbidimeter. Chlorophyll-a can be directly monitored using a probe or calculated analysing water samples in the laboratory using one of the standard methods (*i.e. Jeffrey et al., 1997, Walsham et al., 2022*). Details on the environmental parameters, including units of measurement and suitable temporal framework needed to run the C-AZA methodology are depicted in **Table 1**. Water temperature, dissolved oxygen, salinity, turbidity, chlorophyll-a, depth, and pH will be used as first step to evaluate the *site suitability* for the aquaculture activities. These parameters are also crucial to drive life cycles, survival and range of distribution of cultivated species and thus useful for *species suitability* assessment.

For IMTA, some parameters related with nutrients body mass are required including the total suspended solids (TSS), total particulate organic matter in water and sediments, total dissolved inorganic nitrogen (DIN), their different fractions including total ammonium nitrogen (TAN), nitrite and nitrate and total phosphate (**Table 1**). TSS is a gravimetric parameter, POM is determined by a thermo-gravimetric analysis, and nutrients can be measured by spectrophotometric tests. In the case of DIN, measures of different fractions including total ammonium nitrogen (TAN), nitrite and nitrate are also useful to understand the main source of nitrogen as depicted in **Table 3**. They will be used to run the *species suitability* and *circularity suitability* assessment.

Table 1. Environmental data*. Variables, unit and recommended timelines are shown.*

Variables	Unit	Timeline
Water temperature	°C	daily, weekly, or monthly
Dissolved Oxygen	mg L^{-1}	daily, weekly, or monthly
Salinity	PSU	daily, weekly, or monthly
Turbidity	NTU	daily, weekly, or monthly
Chlorophyll-a	mg m^{-3}	daily, weekly, or monthly
Depth	m	mean, min and max
pH		daily, weekly, or monthly
Total Suspended Solids	mg L^{-1}	monthly
Total Organic Matter	mg L^{-1}	monthly
Dissolved inorganic nitrogen (DIN), NO_3, NO2 and $NH4_+$	mg L^{-1}	monthly
Total Phosphate	mg L^{-1}	monthly
Total organic matter in sediments at different distances from source (fed species)	mg L^{-1}	quarterly

1.3.1.2 Water quality and trophic conditions

For assessing water quality data and trophic conditions (**Table 2**) it is highly recommended to follow the guidance provided by the Water Framework Directive (*WFD*). This directive can be accessed online in various European languages at *http://data.europa.eu/eli/dir/2000/60/oj*.

EU members are responsible for monitoring water bodies ensuring they reach a good status within their territory. To access data related to this task, PPs should collaborate with local, regional or national authorities or environmental agencies involved in monitoring water bodies to access data relevant to this mission.

The ecological status will be determined for each water body, considering the biological quality, and supported by physico-chemical and hydromorphological data. Additionally, the chemical status is assessed by monitoring and analysing specific pollutants and priority substances such as heavy metals, pesticides, and certain organic pollutants that could pose significant risks to the aquatic environment and human health. The WFD also identifies other pollutants that may affect water quality, such as nutrients (*e.g.*, nitrogen, phosphorus), organic matter, and emerging contaminants.

Microbiological water classification is a system used to assess water quality in areas where shellfish are farmed. If available at the pilot site, the microbiological water classification (A, B, or C) for shellfish farming must be reported. National laws may have different standards for each type of water, however the European Union has set particular rules for categorizing shellfish farming waters based on microbiological criteria (Regulation (EC) No 854/2004).

Table 2. Water quality data*. Variables as defined in Water Frame Directive 2000/60 and scale description.*

Water quality data	Description
Ecological status	bad, poor, moderate, good, high
Chemical contamination of water	not good/good
Chemical contamination of sediment	not good/good
Chemical status	not good/good
Oxygen conditions	anoxia, hypoxia, normal
Microbiological water classification for shellfish farming	class A, B, C

Nitrate concentration ranges and scales used to define the trophic condition of each pilot site are presented in **Table 3**. This parameter serves as an indicator of trophic status, reflecting its overall organic productivity level and potential nutrient overload of water bodies.

Table 3. Water trophic conditions. *Scale and concentration ranges are shown.*

Trophic condition (select one)	Nitrate Concentration (mg L^{-1})
Fish	Oligotrophic (<0.5), Mesotrophic (0.5 - 2), Eutrophic (>2)
Shellfish	Oligotrophic (<0.5), Mesotrophic (0.5 - 2), Eutrophic (>2)
Algae, Aquatic plants and halophytes	Oligotrophic (<0.5), Mesotrophic (0.5 - 2), Eutrophic (>2)

1.3.1.3 Services, facilities and area use

In order to gather information regarding the availability of services and facilities, such as buildings and refrigerators for storing equipment and organisms (**Table 4**), as well as the intensity of the water body uses (**Table 5**), and surrounding land (**Table 6**) near the considered area, engagement with stakeholders and leveraging expert knowledge is indispensable.

Table 4. Services and facilities available in the area. *Expected description is indicated.*

Services and facilities	Description
Freshwater/Brackish aquaculture facilities	Absence/Presence of farmed species
Aquaponics facilities	Absence/Presence of farmed species
Marine Pond aquaculture facilities	Absence/Presence of farmed species
RAS aquaculture facilities	Absence/Presence of farmed species
Electricity	Presence/absence
Office/storage	Presence/absence
Refrigerator	Presence/absence
Fish traps	Presence/absence
Landing place	Presence/absence
Suitable building for aquaculture	Presence/absence
Unsuitable building for aquaculture	Presence/absence
Space availability for new facilities	Type

Table 5. Quantification of the potential uses of water bodies. *Expected description is indicated. Very low (VL), low (L), medium (M), high (H) and very high (VH) presence and intensity of the listed activities.*

Use of the water body	Description
Tourism	VL, L, M, H, VH
Sport	VL, L, M, H, VH
Hunt	VL, L, M, H, VH
Boat shelter	VL, L, M, H, VH
Sport fishing	VL, L, M, H, VH

Military areas	VL, L, M, H, VH
Salt factories	VL, L, M, H, VH
Naval building	VL, L, M, H, VH
Environmental services	VL, L, M, H, VH
Other (please specify)	VL, L, M, H, VH

Table 6. Uses of surrounding land. *Expected description is indicated. Very low (VL), low (L), medium (M), high (H) and very high (VH) presence and intensity of these uses.*

Use of the surrounding land	Description
Uncultivated/wild pasture	VL, L, M, H, VH
Agriculture	VL, L, M, H, VH
Bathing	VL, L, M, H, VH
Urban area	VL, L, M, H, VH
Tourist settlements	VL, L, M, H, VH
Environmental services	VL, L, M, H, VH

1.3.1.4 Risk analysis

Data concerning risk factors for aquaculture including information on the presence of invasive species, toxic algal blooms, eutrophication, disease outbreaks, marine pollution, water temperature rise, summer heat waves, and damage caused by ichthyophagous birds, must be collected following the **Table 7**. The risk perceived during the last twenty years is associated with the perception of farmers/users and clustered into five classes:

1. I've never had this problem (VL)
2. I have had this problem a few times in the last 20 years (<30%) (L)
3. I have had this problem several times over the last 20 years (30% - 50%) (M)
4. I have had this problem at least 10 times in the last 20 years (50% - 80%) (H)
5. I have had this problem almost every year for the last 20 years (>80%) (VH)

Table 7. Risks analysis for farming activities*. Expected description is indicated. very low (VL), low (L), medium (M), high (H) and very high (VH).*

Risk analysis	Description
Invasive species	VL, L, M, H, VH
Toxic algae blooms	VL, L, M, H, VH
Eutrophication phenomena	VL, L, M, H, VH
Disease outbreaks	VL, L, M, H, VH
Marine pollution	VL, L, M, H, VH
Water temperature rise	VL, L, M, H, VH
Summer heat waves	VL, L, M, H, VH
Fish theft	VL, L, M, H, VH
Damage from fish-eating birds (cormorants)	VL, L, M, H, VH

1.3.1.5 List of farmed aquaculture species and additional information

Information about the farmed species present in the pilot site can be collected through interaction with farmers or from scientific or grey literature publications. The list should only include native species indicating the vernacular and scientific names and the taxonomic group (**Table 8**). It should be important to identify the maturity degree in the activity indicating if operational procedures are at experimental scale or a consolidated activity. Also, if one species is farmed in closer or similar areas but not exploited in the pilot site, please, indicate a probable cause.

Table 8. Farmed aquaculture species*. Indicate the vernacular and scientific names, along with the taxonomic group (such as fish, mollusc, polychaeta, crustacean, echinoderm, sponge, seaweed, or microalgae), and the maturity level for aquaculture activities (Experimental, Consolidated or possible when the species exists but not exploited in the pilot site indicating the main reason if identified).*

Vernacular name	Scientific name	Group	Maturity level
Species 1			
Species 2			
Etc.			

Additionally, various supplementary data and information are required to characterise the study area and assess *site suitability* for aquaculture activities (**Table 9**).

Table 9. Additional data and information. *Expected description is indicated.*

Additional data and information	Description
Latitude and longitude	Decimal degrees WGS-84
Study area	Shapefile format
Land Use	shapefile or raster format
Aquaculture production	tonnes per month or year grouped by fish, shellfish, algae and others.
Faecal bacteria presence data	CFU 100 ml^{-1}
Area	km^2
Usable area	%
Urban waste	Presence/absence
Industrial waste	Presence/absence
Agricultural and livestock waste	Presence/absence
Other waste presence	specify
River	Presence/absence
Water pump	Presence/absence
Protected area (e.g. Natura 2000) limitation	Presence/absence
Protected species	Presence/absence

1.3.2 Data needed to run the AZA analysis for species suitability assessment

The aquaculture *species suitability* assessment is a process that assists in determining the optimal locations and species for successful farming. It involves a comprehensive analysis of environmental and biological factors to pinpoint areas with the highest potential for the growth, survival, and economic viability of the selected species.

The first step in the *species suitability* assessment entails identifying the species to be farmed, either alone or in combination with other species of different trophic levels (IMTA). *Environmental compatibility* as determined by the specific tolerance range is the first step in this assessment. Other aspects such as biological characteristics, national regulations, infrastructure and technology, market demand, and economic viability will be considered in point 1.3.3.

To conduct the aquaculture *species suitability* assessment, various types of data mainly related to environmental conditions and habitat requirements, influencing the growth and health of the target species are required. Main environmental requirements that influence species suitability are primarily related to water temperature, pH, dissolved oxygen, turbidity, chlorophyll-a, and salinity. Species-specific physiological requirements covering environmental tolerance, critical, and optimal ranges are key aspects to identify suitable species and to prioritize in IMTA and aquaculture operations. For example, while a water temperature of 20°C may be considered optimal for a fish species, temperature of 19°C or 21°C might still be suitable, albeit to a slightly lesser degree. An example are the sympatric true soles, *Solea solea* and *Solea senegalensis*. While tolerance range for the former is between 5 and 27°C, the latter is above 10-26°C defining the quite distinct distribution range and aquaculture practices (*Schram et al., 2013; Vinagre et al., 2006*). Fuzzy membership functions can represent these gradual transitions in suitability. The environmental data collected in the previous section 1.3.1 will be compared with species requirements in the species suitability assessment.

The variables should be compiled in separate tables by functional groups Fed aquaculture species (**Table 10**), Deposit and suspension organic extractive species (**Table 11** and **Table 12**) and *inorganic extractive species* (**Table 13**). Specifically, environmental criteria, critical minimum and maximum, optimal range, and the shape of the membership function (e.g. trapezoidal or monotonically linearly increasing) must be reported. The latter will be used to depict the relationship between environmental conditions and species performance.

Table 10. Environmental requirements of fed aquaculture species. *Optimal and tolerance range, the fuzzy membership function (FMF) and the reference are indicated. Trapezoidal (TRZ); Monotonically linearly increasing (MLI); Monotonically linearly decreasing (MLD).*

Species	Environmental criteria	Critical min	Optimal range	Critical max	FMF	Reference
Species 1	Temperature				TRZ	
	Oxygen				MLI	
	Turbidity or TSS				MLD	
	Salinity				TRZ	
	pH				MLD	

Table 11. Environmental requirements of suspension organic extractive species*. Optimal and tolerance range, the fuzzy membership function (FMF) and the reference are indicated. Trapezoidal (TRZ); Monotonically linearly increasing (MLI); Monotonically linearly decreasing (MLD).*

Species	Environmental criteria	Critical min	Optimal range	Critical max	FMF	Reference
Species 1	Temperature				TRZ	
	Oxygen				MLI	
	Turbidity or TSS				MLD	
	Salinity				TRZ	
	pH				MLD	
	Chlorophyll-a/POM				MLD/TRZ	

Table 12. Environmental requirements of deposit organic extractive species*. Optimal and tolerance range, the fuzzy membership function (FMF) and the reference are indicated. Trapezoidal (TRZ); Monotonically linearly increasing (MLI); Monotonically linearly decreasing (MLD).*

Species	Environmental criteria	Critical min	Optimal range	Critical max	FMF	Reference
Species 1	Temperature				TRZ	
	Oxygen				MLI	
	Turbidity or TSS				MLD	
	Salinity				TRZ	
	pH				MLD	

Table 13. Environmental requirements of Inorganic extractive species. *Optimal and tolerance range, the fuzzy membership function (FMF) and the reference are indicated. Trapezoidal (TRZ); Monotonically linearly increasing (MLI); Monotonically linearly decreasing (MLD).*

Species	Environmental criteria	Critical min	Optimal range	Critical max	FMF	Reference
Species 1	Temperature				TRZ	
	Turbidity or TSS				MLD	
	Salinity				TRZ	
	pH				MLI	
	DIN				MLI	
	Total phosphate				MLI	

Main output in this analysis will be the set of **suitable species by functional trophic groups** as function of environmental requirements in pilot sites and across the Mediterranean to assess the circular suitability.

1.3.3 Data needed to run the AZA analysis for IMTA circularity

Once *site* and *species suitability* according to environmental requirements are defined, final step is to prioritize IMTA performance and circularity as defined in section 1.1.2.

Essential aspects that should be considered for modelling IMTA and circular suitability were revised in *Nissar et al., 2023* and *Rossi et al., 2021* establishing six IMTA performance criteria:

1. Use of **native species** preventing introduction or creation of niches for invasive species. Geographical distribution is a key aspect although aquaculture operations are absent in a specific site.

2. Prioritize **complementarity** between co-cultured species capable of consuming nutrients from wastewater but also boosting economic output.

3. Consider the **type and consistency of waste materials** present in the selected farm site.

4. Prioritize extractive species with a **high growth potential** for periodic harvesting or high value compensating for lower biomass growth.

5. Prioritize species with an **established market value** and avoid species that may encounter obstacles to commercialization.

6. Ensure **socio-ecological and political acceptance** in the IMTA design of the setup.

According to these criteria, it is required to compile information about geographical distribution, breeding techniques, feeding requirements, growth performance, market value and social acceptance for each functional group. The variables to be considered are detailed in separate tables for *fed aquaculture species* (**Table 14**), *organic extractive species* (**Table 15**) and *inorganic extractive species* (**Table 16**). Information can be obtained from scientific publications, grey literature or stakeholder interactions.

Table 14. Aquaculture performance indicators of fed species.

Variable	Description	Description
Species1	Scientific name	(only native species)
Distribution range and facilities **(criterion 1)**	Biogeography in the MED/Black Sea	Low, Medium (West or East MED/ Black Sea) or high=All MED/ Black Sea basin
	Aquaculture activity (number of facilities or licenses)	**Low** if not well-established activity, **medium** (1-5) or **high** >5
Domestication and breeding **(criterion 2)**	Production model[1]	**Extensive** <1 kg m-3, **semi-extensive** 1-2kg m^{-3}, **semi-**intensive 2-4 kg m^{-3}, **intensive** >4 kg m^{-3}
	Life cycle knowledge	**Low**, if limited knowledge about aquaculture operations, **medium** or **high** if very well studied
	Seed supply availability	**Low**, if the access to seeds is not easy by abundance or distances, **medium** or not available or **high**
Feeding requirements **(criterion 3)**	Feedstuff sustainability and knowledge	**Low**, if feedstuffs are based on marine meals and oils, **medium** or **high**
	Feeding efficiencies	**Low**: FCR>2; **medium** 1.5-2, **high**<1.5)
Growth and survival performance **(criterion 4)**	SGR Growth-out or Thermal growth coefficients (TGC)	SGR: **low** <1 %/day, **medium**, 1-2.5 or **high** >2.5/day TGC: **low** 0.5-1, **medium** 1-2; **high** >2
	Duration of production cycle	**Short** < 1 year, **medium** 1-2 y, **Long** >2 y)
	Survival	**Low**:<50%; **medium** 50-75%, **high** >75%
Market value **(criterion 5)**	Commercial value fresh product	**Low** <4€/kg; **medium** 4-8€ or **high** >8€)
	Commercial value by-products	**Low** (non-processed skin, viscera…), **medium** (processed fillets, Burger,) or **high** (premium products as caviar)
	Target market	**close** (local), **medium** (national), **far** (EU countries, non-EU countries
Social acceptance **(criterion 6)**	Consumer opinion	**Accepted** or **not accepted**
	Satisfaction	**Good**, if well accepted or **concerns** about quality, environment, or welfare

[1] Stocking densities of fish defined according to regulatory framework of Andalusian Region (Spain).

Table 15. Aquaculture performance indicators of organic extractive species.

Variable	Description	Description
Species1	Scientific name	Deposit or suspension or non-fed herbivorous fish
Distribution range and facilities **(Criterion 1)**	Biogeography in the MED/Black Sea	**Low**, **medium** (West or East MED/Black Sea) or **high**=All MED/ Black Sea basin
	Aquaculture activity (number of facilities or licenses)	**Low** if not well-established activity, **medium** (1-5) or **high** >5
Domestication and breeding **(Criterion 2)**	Production model feasibility and scalability in number and density	**Easy, medium or difficult** according to a reference (5*0 tones ha⁻1 for oysters;76 tones ha⁻1 for mussels*)[2]
	Life cycle knowledge	**Low,** if limited knowledge about aquaculture operations**, medium** or **high** if very well studied
	Seed supply availability	**Low**, if the access to seeds is not easy by abundance or distances or not available, **medium** or **high**
Extraction capabilities **(Criterion 3)**	Extraction efficiency	(N or P) (**Low**:<30%; **Medium** 30-70%, **High**>70%)
	Type of Production model. Exchange rate	Closed, semi open or open
Growth and survival performance **(Criterion 4)**	Duration of production cycle	Short (<6 months), **medium** (6-12m), **long** (>12m)
	growth rates[3] Mollusk shell mm day^{-1}	**Low**:<0.05; **medium** 0.05-0.20; **high** >0.20
	Survival	Low:<50%; **medium** 50-75%, **high** >75%
Market value **(Criterion 5)**	Commercial value fresh product	**Low** <1€/kg; **medium** 1-2€ or **high** >3€
	Commercial value by-products	**High** (alive, baits, food, agroindustry, biotechnology), **medium** (processed food, burger) **low** (meals,…)
	Target market	**close** (local), **medium** (national), **far** (EU countries, non-EU countries)
	Industrial uses	**High** (food, agroindustry, biotechnology), **medium** (feedstuff), **low** (energy and fertilizer)
Social acceptance **(Criterion 6)**	Consumer opinion	**Accepted** or **not accepted**
	Satisfaction	**Good**, if well accepted or **concerns** about quality, environment, or welfare

[2] *76 tones ha^{-1} for mussels*. Hughes AD, Black KD. Going beyond the search for solutions: understanding trade-offs in European integrated multi-trophic aquaculture development. Aquac Environ Interact. 2016; 8:191-199. doi:10.3354/aei00174

50 tones ha^{-1} for oysters. Cultured Aquatic Species Information Programme. *Crassostrea gigas*. FAO Fisheries and Aquaculture Department (online); 2005-2019.

10 tones ha^{-1} for sea cucumbers. Cultured Aquatic Species Information Programme. *Stichopus japonicus*. FAO Fisheries and Aquaculture Department (online); 2011-2019.

3 tones ha^{-1} *for polychaetas*. Brown N, Eddy S, Plaud S. Utilization of waste from a marine recirculating fish culture system as a feed source for the polychaeta worm, *Nereis virens*. Aquaculture. 2011;322–323:177-183.

[3] It would be defined better according to group of species identified.

Table 16. Aquaculture performance indicators of Inorganic extractive species.

Variable	Description	Description
Species1	Scientific name	seaweeds, microalgae, halophytes
Distribution range and facilities **(Criterion 1)**	Biogeography in the MED/Black Sea	**Low**, **medium** (West or East MED/Black Sea) or **high**=All MED/Black Sea basin
	Aquaculture activity (number of facilities or licenses)	**Low** if not well-established activity, **medium** (1-5) or **high** >5
Domestication and breeding **(Criterion 2)**	Production model feasibility and scalability in number and density	**Easy, medium or difficult according to a reference** : ~*95 tonnes ha^{-1} for seaweeds* [4]
	Life cycle knowledge	Low, if limited knowledge about aquaculture operations, **medium** or high
	Seed supply availability	**Low**, if the access to seeds is not easy by abundance or distances or not available, **medium** or **high**
Extraction capabilities **(Criterion 3)**	Extraction efficiency	(N or P) (**Low**:<30%; **medium** 30-70%, **high**>70%)
	Type of Production model. Exchange rate	Closed, semi open or open
Growth and survival performance **(Criterion 4)**	Duration of production cycle	**Short** (<6 months), **Medium** (6-12m), **long** (>12m)
	Productivity (~*95 tonnes ha^{-1} for seaweeds*, *3 t ha^{-1} for microalgae, 12 t ha^{-1} halophyte)*	**Low** <30 % estimated, **medium**: 30-70 % estimated, **high**: > 70 % estimated
	Survival	**Low**:<50%; **Medium** 50-75%, **high** >75%
Market value **(Criterion 5)**	Commercial value fresh product	**low** <1€/kg; **medium** 1-2€ or **high** >3€
	Commercial value by-products	**High** (food, agroindustry, biotechnology), **medium** (processed food, burger), **low** (meals)
	Target market	**close** (local), **medium** (national), **far** (EU countries, non-EU countries
	Industrial uses	**High** (food, agroindustry, biotechnology), **medium** (feedstuff), **low** (energy, fertilizer)
Social acceptance **(Criterion 6)**	Consumer opinion	**Accepted** or **not accepted**
	Satisfaction	**Good**, if well accepted or **concerns** about quality, environment, or welfare

Once the IMTA performance for each functional group is defined, the circularity of

[4] -*95 tonnes ha^{-1} for seaweeds*. Reid GK, Chopin T, Robinson SMC, Azevedo P, Quinton M, Belyea E. Weight ratios of the kelps, Alaria esculenta and *Saccharina latissima*, required to sequester dissolved inorganic nutrients and supply oxygen for Atlantic salmon, *Salmo salar*, in integrated multitrophic aquaculture systems. Aquaculture. 2013;408–409:34-46.
-*3 tonnes ha^{-1} for microalgae*. Brune D, Schwartz G, Eversole A, Collier J, Schwedler T. Intensification of pond aquaculture and high rate photosynthetic systems. Aquac Eng. 2003;28(1): pp. 65-86.

the whole system needs to be assessed using the indicators in Suitable species from different functional groups should be combined from easier to more complex IMTA and the circularity should be evaluated (**Table 17**).

Table 17. IMTA circularity indicators.

Indicator	Description	Description
1. Estimated food efficiency	% increase in newly harvested biomass for food and biotech	**Low** <20%, **medium** 20-50% or **high** >50%
2. Estimated nutrient recycling efficiency	% of nutrients recovered from water compared to a monoculture system. Nutrients emitted by higher trophic species absorbed by extractive species	**Low** <10%, **medium**, or **high** >50%
3. Estimated non-food resource efficiency	% increase in reuse services (sludge, by-products for compost, energy, feed, fertilizers)§	**Low** <40%, **medium** 40-70% or **high** >70%
4. Shared economy	% increase in connectivity between aquaculture producers and other actors (recycling)	**Low** <3, **medium** or **high** >10 new suppliers or producers
5. Energy efficiency (Entropy)	Use of highly efficient aquaculture methods and renewable energy	a) **Low**: Non-renewable; **Medium**; **High** >50% renewable energy b) **Low**: Reduction <10%; **Medium**; **High** >50%
6. Multi-species complexity index and biodiversity	Interaction and inclusion of wild biota	**Low** No change in biodiversity; **Medium**; **High** if >5 new species in the environment
7. Species complementarity	Number of functional trophic levels	**Low** if 2, **Medium** if 3, **High** if 4 new species in the environment
8. Integration of reused/recycled materials	Use of reused/recycled materials	**Low** <=1, **Medium** if 3, **High** if >4
9. Sustainable feeds (Only if fed species)	Use of ingredients from sustainable raw materials (for fish)	**Low** <30%, **medium** (50-70%) or **high** >80%
10. Water use efficiency	Recycled water (m^3) Water in the system (m^3) × 100	**Low**: Open, **Medium**: Semi-open, **High**: Closed

§Agroindustry and biotech uses should be considered in criteria 1

1.4 Modelling analyses

The assessment of aquaculture suitability frequently entails the consideration of multiple criteria that are complex and interrelated. Various methodologies, such as Multi-Criteria Decision Analysis (MCDA) and fuzzy logic classification, are commonly employed to evaluate suitability for aquaculture either individually or in combination. The selection of a methodology for assessing aquaculture suitability is contingent upon the objectives, data availability, stakeholder preferences, and the degree of uncertainty inherent in the decision-making process. Each methodology possesses distinct strengths and limitations, necessitating experts to tailor and modify approaches to align with the context of the specific case study under consideration.

MCDA encompasses the integration of multiple criteria or factors influencing aquaculture suitability to facilitate informed decision-making. This approach typically involves assigning weights to each criterion based on its relative importance and integrating them using mathematical or analytical techniques. MCDA process generally consists of three steps: (*i*) normalizing the criteria; (*ii*) assigning weights to each criterion; (*iii*) aggregating the criteria to estimate the Suitability Index (SI).

The following paragraphs delineate the methodologies to be employed in estimating the *site suitability* index for aquaculture activities in the eight pilot case studies. In the subsequent paragraphs, various tables containing specific values for this analysis are shown. Nonetheless, it is important to highlight that the normalization process as well as the scores and weights assigned in the suitability assessment must be tailored to the specific characteristics of the case study area.

1.4.1 Methodology to run the AZA site suitability assessment

The data collected in section *1.3 Data collection* can be used to evaluate the *site suitability* both qualitatively and quantitatively. The environmental data collected provides initially an overview of the feasibility of establishing an aquaculture activity in the pilot site and potentially identifies appropriate species for farming. For instance, while different salinity ranges may not directly correlate with aquaculture *site suitability* assessment, they can offer insights into the species that could be farmed. Indeed, the salinity requirements of aquaculture species can vary considerably from euryhaline organisms such as sole, seabream and seabass that tolerate from 2-5 to 45 ppt, to stenohaline organisms such as channel catfish and goldfish that necessitates low salinity levels (<15 ppt) or seagrass in the range 37-39 ppt.

1.4.1.1 Data normalization

The normalization is the first step in the analysis to ensure that all datasets are on an appropriate scale for data processing and comparisons. Criteria normalization can be conducted using various techniques, depending on the input data. Most suitable methods rely on the specific decision problem and the criteria characteristics. For instance, if a criterion has spatially explicit values (*e.g.*: temperature), normalisation between the minimum and maximum values is applied to identify the most suitable area relative to others (*Brigolin et al., 2017; Porporato et al., 2020*). This approach proves useful in comparing different spatial datasets with varying scales or units.

Another method involves ***assigning scores*** ranging from 0 (not suitable) to 1 (optimal) to different value ranges of a criterion to assess suitability (e.g.: *1=optimum, 0.75=intermediate high suitable, 0.5=good, 0.25 intermediate low suitable, 0= not suitable*) (*Graham et al., 2020*). This approach allows for a more nuanced evaluation of suitability based on the specific requirements of the analysis or decision-making process.

Based on expert knowledge, stakeholder input, literature review, and the specific requirements of the pilot site, suitability scores must be assigned to each criterion. The following tables present the scores that could be assigned to the collected criteria, specifically for the water quality (**Table 18**), trophic conditions (**Table 19**), available services and facilities already in the area (**Table 20**), utilization of the surrounding areas (**Table 21**), and risk factors (**Table 22**).

Table 18. Water quality scores.

Variable	Score				
	Bad	**Poor**	**Moderate**	**Good**	**High**
Ecological status	0.2	0.4	0.6	0.8	1
	Not good	**Good**			
Chemical contamination of water	0.2	1.0			
Chemical contamination of sediment	0.2	1.0			
Chemical status	0.2	1.0			
	Anoxia	**Hypoxia**	**Normal**		
Oxygen conditions	0.2	0.4	1.0		
	A	**B**	**C**	**Absent**	
Microbiological water classification for shellfish farming	1	0.5	0	0.25	

Table 19. Trophic condition scores for fish, shellfish, and photosynthetic organisms

Variable	Score		
	Oligotrophic	Mesotrophic	Eutrophic
Fish	1	0.5	0.2
Shellfish	0.2	0.5	1
Algae, Aquatic plants and halophytes	0.2	0.5	1

Table 20. Services and facilities scores§.

Variable	Score
Freshwater/Brackish aquaculture facilities	0.05
Aquaponics facilities	0.1
Marine Pond aquaculture facilities	0.1
RAS aquaculture facilities	0.1
Electricity	0.1
Office/storage	
Refrigerator	0.1
Fish traps	0.1
Presence of a landing place (e.g. equipped with a pier)	0.15
Suitable building	0.15
Unsuitable building	0.05
Space availability for new facilities	0.05

§Sum of Scores should be 1

Table 21. Use of the area scores.

Variable	Score				
Use of the water body	**Very low**	**Low**	**Medium**	**High**	**Very high**
Tourism	1	0.8	0.6	0.4	0.2
Sport	1	0.8	0.6	0.4	0.2
Hunt	1	0.8	0.6	0.4	0.2
Boat shelter	1	0.8	0.6	0.4	0.2
Sport fishing	1	0.8	0.6	0.4	0.2
Military areas	1	0.8	0.6	0.4	0.2
Salt factories	1	0.8	0.6	0.4	0.2
Naval building	1	0.8	0.6	0.4	0.2
Environmental services	1	0.8	0.6	0.4	0.2
Other (please specify)	1	0.8	0.6	0.4	0.2
Use of the surrounding land					

Uncultivated/wild pasture	1	0.8	0.6	0.4	0.2
Agriculture	1	0.8	0.6	0.4	0.2
Bathing	1	0.8	0.6	0.4	0.2
Urban area	1	0.8	0.6	0.4	0.2
Tourist settlements	1	0.8	0.6	0.4	0.2
Environmental services	1	0.8	0.6	0.4	0.2

Table 22. Risk analysis scores. *Criteria defined in section 1.3.1.4. Very low (VL), low (L), medium (M), high (H) and very high (VH).*

Risk analysis	**Score**				
	VL	**L**	**M**	**H**	**VH**
Invasive species	1	0.8	0.6	0.4	0.2
Toxic algae blooms	1	0.8	0.6	0.4	0.2
Eutrophication phenomena	1	0.8	0.6	0.4	0.2
Disease outbreaks	1	0.8	0.6	0.4	0.2
Marine pollution	1	0.8	0.6	0.4	0.2
Water temperature rise	1	0.8	0.6	0.4	0.2
Summer heat waves	1	0.8	0.6	0.4	0.2
Fish thefts	1	0.8	0.6	0.4	0.2
Damage from fish-eating birds (cormorants)	1	0.8	0.6	0.4	0.2

1.4.1.2 Weights assignment

The weight assignment is carried out by employing the Analytic Hierarchy Process (AHP), a decision-making technique that decomposes a complex problem into a hierarchy of criteria and alternatives, enabling decision-makers to systematically assess and prioritise them. This process entails pairwise comparisons, wherein numerical values are assigned to the relative importance of criteria and alternatives and deriving a priority vector for decision-making. The pairwise comparison method of the AHP can be used to weight the standardised criteria by priority. In the context of aquaculture activities, the weighting of criteria is based on optimal growth conditions for farmed organisms.

The AHP consists of three fundamental steps: (1) *hierarchical structuring*, (2) *comparative judgement*, and (3) *synthesis of judgments*. In the first step, *hierarchical structuring*, the problem under evaluation is structured hierarchically, placing objectives at the highest level, followed by criteria and alternatives in successive levels. The second step, *comparative judgement*, involves pairwise comparisons of all elements within each level against each element of the immediately subsequent level. Finally, in the synthesis of judgments, the comparative judgments are synthesized in order to establish a ranking of the alternatives. The order of hierarchical structuring involves goals, criteria and alternatives which are arranged in ascending order according to the level of abstraction. In pairwise comparison, the preference of one element over another is never absolute but always relative, with reference to the element of the higher level.

Through pairwise comparison, the preference of one alternative over another is expressed and quantified, individually for each criterion. The synthesis of judgments occurs by retracing the hierarchy in ascending order: the overall scores assigned to each alternative resulting from pairwise comparison of that alternative with all others must be multiplied by the weight assigned to the criteria.

Assigning weights to the selected criteria is a crucial step in the *site suitability* assessment process, as it signifies the relative importance of each criterion in the decision-making process. The tables below present the weights of each intermediate criterion that could be applied in the pilot case study. It's important to note that the weights assigned to criteria can be adjusted based on the specific environmental, economic, and social characteristics of the area where aquaculture activities will occur, but the **sum of them must always be equal to 1**. For example, different species of aquaculture can have varying impacts on the environment, economy, and society. The selection of species can thus influence the relative importance of the chosen criteria. For instance, criteria related to water quality might be more critical for sensitive species or in areas with limited water resources. The perceptions and preferences of stakeholders involved in or affected by aquaculture activities can also influence criteria weighting. Moreover, experts from diverse fields such as ecology, economics, and social sciences may contribute to the weighting process. Stakeholders may prioritize differently based on their interests, values, and concerns, underscoring the importance of integrating their perspectives into the decision-making process.

Considering these factors engaging stakeholders and experts in the weighting process can lead to more informed and contextually appropriate decisions in aquaculture planning and management. Throughout the aquaculture *site suitability* assessment process, as well as in all spatial planning processes for human activities, maintaining transparency and open communication is crucial. This ensures that the assigned weights (**Tables 23-28**) accurately reflect the collective values and objectives of all relevant stakeholders.

Table 23. Weights of water quality variables.

Variable	Weights
Ecological status	0.25
Chemical status	0.25
Oxygen conditions	0.25
Microbiological water classification for shellfish farming	0.25

Table 24. Weights of trophic condition.

Variable	Weights
Fish	0.35
Shellfish	0.35
Algae, Plants	0.30

Table 25. Weights of services and facilities.

Services and facilities	Weights
sum the single score	

Table 26. Weights of the water body uses.

Use of the water body	Weights
Tourism	0.35
Sport	0.20
Hunt	0.10
Boat shelter	0.05
Sport fishing	0.05
Military areas	0.10
Salt factories	0.05
Naval building	0.05
Environmental services	0.05
Other (please specify)	

Table 27. Weights of the surrounding land uses.

Use of the surrounding land	Weights
Uncultivated/wild pasture	0.10
Agriculture	0.10
Bathing	0.20
Urban area	0.25
Tourist settlements	0.30
Environmental services	0.05

Table 28. Risk analysis weights.

Risk analysis	Weights
Invasive species	0.12
Toxic algae blooms	0.11
Eutrophication phenomena	0.11
Disease outbreaks	0.11
Marine pollution	0.11
Water temperature rise	0.11
Summer heat waves	0.11
Fish theft	0.11
Damage from fish-eating birds (cormorants)	0.11

In the MCDA process, macro criteria denote overarching categories or groups of criteria that encompass several related sub-criteria. Weighting these macro criteria is essential for aggregating all the sub-criteria, or intermediate criteria, to estimate the SI for the aquaculture activity. The table below reports the weights that can be assigned to the selected macro criteria (**Table 29**).

Table 29. Macro criteria weights.

Macro criteria	Weights
Water Quality	0.250
Trophic condition	0.250
Facilities	0.150
Use of the water body	0.125
Use of the surrounding land	0.125
Risk analysis	0.100

1.4.1.3 *Site Suitability* Index estimation

In order to aggregate the weighted criteria and derive an overall assessment of aquaculture suitability based on optimal growth conditions, the Weighted Linear Combination (WLC) methodology can be applied. This method involves multiplying each criterion's value by its weight and summing the weighted values to obtain an overall suitability score for each potential site.

The WLC method enables the integration of results obtained from fuzzy logic and weights derived from the Analytic Hierarchy Process (AHP) into a unified decision framework. Specifically, the WLC approach facilitates the aggregation of fuzzy information and AHP-derived priorities, thereby providing a quantitative measure of aquaculture suitability.

To estimate the *Site Suitability* Index (SiSI), each normalized criterion is multiplied by its corresponding weight to obtain the weighted score. Subsequently, the weighted scores across all criteria are summed to calculate the overall suitability index for each site.

SiSI for a given site can be expressed as (**Equation 1**):

$$SiSI = \sum_{i=1}^{n} (w_i * x_i)$$

Equation 1

where

SiSI = Suitability Index

w_i = weight assigned to the criterion i

x_i = the normalised value of the criterion i

If the weights reported in **Table 29** are applied, the following formula (**Equation 2**) can be used to estimate the site SiSI:

$$\text{SiSI} = (Water\ Quality * 0.250) + (Trophic\ condition * 0.250) + (Facilities * 0.150) + (Use\ of\ the\ water\ body * 0.125) + (Use\ of\ the\ surrounding\ land * 0.125) + (Risk\ analysis * 0.100)$$

Equation 2

The SiSI is a single numerical value that represents the overall suitability of a location for aquaculture. Higher SiSI values indicate locations with greater potential for successful and sustainable operations. The specific thresholds for interpreting suitability (*e.g.*: highly suitable, moderately suitable, unsuitable) depend on the specific context of the case study. As reported in *Porporato et al. 2020*, conducting a sensitivity analysis, can aid in evaluating how the suitability index fluctuates with variations in weight assignments or individual criterion scores. This process helps identify critical factors and provides valuable insights for decision-making.

Considering the scores, the final SiSI will oscillate between 0.2 and 1.0 as follows:

Range	Median Score	Assessment
0.2-0.4	L/VL	Poor
0.4-0.6	L/M	Fair
0.6-0.8	M/H	Acceptable
0.8-1.0	H/VH	Optimum

1.4.2 Methodology to run the AZA *species suitability* assessment

The assessment of the *species suitability* primarily depends on the data gathered in the previous step (refer to section *1.3.2 Data needed to run the AZA analysis for species suitability assessment*) and the methodology previously outlined for the *site suitability* assessment (*section 1.4.1 Methodology to run the AZA site suitability assessment*).

The criteria to be considered are primarily the species' tolerance ranges to specific environmental variables (*e.g.*: temperature, dissolved oxygen, chlorophyll-a, etc.). To establish a correlation between these variables and *species suitability*, fuzzy logic membership functions can be applied (*Gimpel et al., 2015*). Fuzzy logic is a mathematical framework that addresses reasoning and decision-making in the presence of uncertainty and imprecision, allowing for a more adaptable approach to modelling and decision-making process. Unlike classical logic, which relies on binary true/false values, fuzzy logic enables the representation of partial truth and degrees of membership between 0 and 1. Membership functions are used to define the shape and characteristics of fuzzy sets, indicating the extent to which an element belongs to a set. Membership functions illustrate the degree to which a species is associated with a specific environmental condition.

1.4.2.1 Data normalization

In *species suitability* assessment, standardizing criteria involves converting raw data into a common scale and then applying fuzzy membership functions to represent the degree of membership of each considered parameter. This process allows for the integration of expert knowledge and the management of uncertainties in the input criteria.

For each criterion raw data must be standardized to ensure all criteria on a common scale. Common methods include normalization (scaling to a 0-1 range). Membership functions encompass various shapes such as triangular, trapezoidal, Gaussian, sigmoidal, or any other shape that reflects the expert knowledge about the criterion's influence on farmed species suitability. These functions are typically represented by a graphical curve where the x-axis represents the environmental factor value (*e.g.* temperature) and the y-axis represents the degree of membership (ranging from 0 to 1). Starting, control, and endpoints must be selected depending on the criteria chosen. More precisely, the starting point of a membership function signifies the value at which the membership starts to increase from 0. This point is crucial in shaping the curve and defining the gradual increase in membership as the input variable's value changes.

In order to calculate the degree of membership for fuzzy sets using different types of membership functions, a specific formula tailored to each function should be applied. Below are reported the formulas for each type.

The trapezoidal membership function typically represents a fuzzy set with a trapezoidal shape, where the membership value increases linearly from the lower base to the peak and then decreases linearly to the upper base. Given the parameters a, b, c and d (where $a \leq b \leq c \leq d$), and an input value x, the degree of membership ($\mu(x)$) can be calculated applying the following **Equation 3**:

$$\mu(x) = \begin{cases} 0 & if\ \varkappa \leq a \text{ or } \varkappa \geq d \\ \dfrac{\varkappa - a}{b - a} & if\ \ a \leq x \leq b \\ 1 & if\ \ b \leq x \leq c \\ \dfrac{d - x}{d - c} & if\ \ c \leq x \leq d \end{cases}$$

Equation 3

For the trapezoidal membership function, *a* corresponds to the critical minimum, *b* and *c* represent the optimal range, and *d* denotes the critical maximum.

The excel formula (**Equation 4**) for the trapezoidal membership function is:

$$= IF(OR(A2 <= \$B\$2; A2 >= \$E\$2); 0;\ IF(AND(A2 >= \$B\$2; A2 < = \$C\$2); (A2 - \$B\$2)/(\$C\$2 - \$B\$2);\ IF(AND(A2 <= \$D\$2; A2 > = \$C\$2); 1;\ IF(AND(A2 >= \$D\$2; A2 < = \$E\$2); 1 - (A2 - \$D\$2)/(\$E\$2 - \$D\$2);\ 0))))$$

Equation 4

In this formula:

A2 represents the input value (e.g., temperature);

a, *b*, *c*, and *d* are the parameters defining the trapezoidal shape of the membership function;

The formula calculates the degree of membership (*μ(x)*) based on the input value A2 and the parameters *a*, *b*, *c*, and *d*.

To implement the trapezoidal membership function in Excel (**Figure 4**), you can follow these steps:

- In column A, enter the environmental variable values;
- In column B, enter the critical minimum value;
- In column C, enter the low value of the optimal range;
- In column D, enter the high value of the optimal range;
- In column E, enter the critical maximum value;
- In column F, input the formula for the trapezoidal membership function.

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```
=SE(O(A2<=$B$2;A2>=$E$2);0;
SE(E(A2>=$B$2;A2<=$C$2);(A2-$B$2)/($C$2-$B$2);
SE(E(A2<=$D$2;A2>=$C$2);1;
SE(E(A2>=$D$2;A2<=$E$2);1-(A2-$D$2)/($E$2-$D$2); 0))))
```

	A	B	C	D	E	F	G	H	I
1	Temperature	critical minimum	low value of optimal range	high value of optimal range	critical maximum	SI			
2	0	6	20	25	30	)			
3	0.1					0			
4	0.2					0			
5	0.3					0			
6	0.4					0			
7	0.5					0			
8	0.6					0			
9	0.7					0			
10	0.8					0			
11	0.9					0			
12	1					0			
13	1.1					0			
14	1.2					0			
15	1.3					0			
16	1.4					0			
17	1.5					0			
18	1.6					0			

Figure 4. Screenshot of the Excel table displaying the construction of the table and the fuzzy formula applied to assess the suitability of AZA species using the trapezoidal membership function.

Ensure to replace \$B\$2, \$C\$2, \$D\$2, and \$E\$2 with the cell references for the critical minimum, low value of the optimal range, high value of the optimal range, and critical maximum, respectively.

This formula will calculate the degree of membership for each environmental variable value based on the trapezoidal membership function parameters provided in columns B, C, D, and E.

For the linear increasing membership function, which represents a fuzzy set where the membership value increases linearly with the input value, the degree of membership ($\mu(x)$) can be calculated applying the following **Equation 5**:

$$\mu(\varkappa)=\begin{cases}0 & if\ x\leq a\\ \dfrac{\varkappa-a}{b-a} & \text{if } a\leq\varkappa\leq b\\ 1 & if\ \varkappa\geq b\end{cases}$$

Equation 5

In this formula:

a and *b* are the parameters defining the range of the membership function (where *a*≤*b*);

x is the input value for which the degree of membership is being calculated.

For the linear increasing membership function, where *a* correspond to the critical minimum and *b* to the optimal range, the excel formula (**Equation 6**) can be expressed as follows:

$$=IF(OR(A2<=\$B\$2);0;IF(AND(A2>=\$B\$2;A2<=\$C\$2);(A2-\$B\$2)/(\$C\$2-\$B\$2);IF(AND(A2>=\$B\$2);1)))$$

Equation 6

In this formula:

A2 represents the input value (*e.g.*, dissolved oxygen);

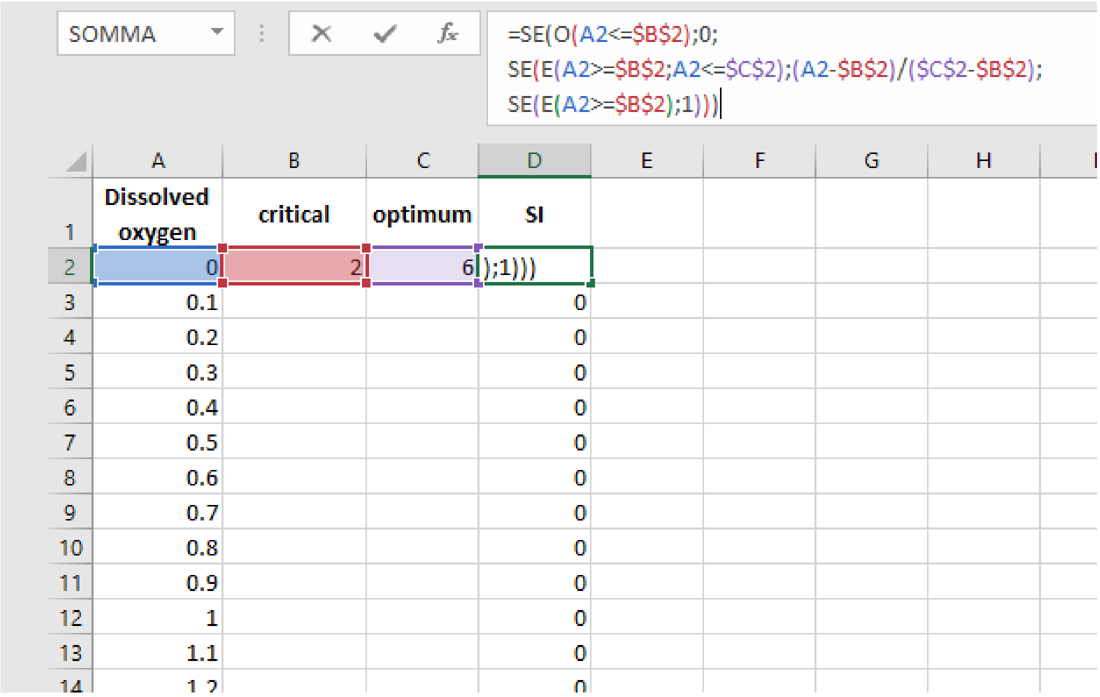
\$B\$2 represents the cell containing the critical minimum value;

\$C\$2 represents the cell containing the optimal range value.

This formula calculates the degree of membership (*μ(x)*) based on the input value A2, the critical minimum (*a*), and the optimal range (*b*).

To implement the linear increasing membership function in Excel (**Figure 5**), you can follow these steps:

- In column A, enter the environmental variable values;
- In column B, enter the critical minimum value;
- In column C, enter the optimal range value;
- In column D, input the formula for the linear increasing membership function.



	A	B	C	D
1	Dissolved oxygen	critical	optimum	SI
2	0	2	6	);1)))
3	0.1			0
4	0.2			0
5	0.3			0
6	0.4			0
7	0.5			0
8	0.6			0
9	0.7			0
10	0.8			0
11	0.9			0
12	1			0
13	1.1			0
14	1.2			0

Figure 5. Screenshot of the Excel table displaying the construction of the table and the fuzzy formula applied to assess the suitability of AZA species using the linear increasing membership function.

Ensure to replace B2with the cell reference for the critical minimum value in column B and $C$2 with the cell reference for the optimal range value in column C.

This formula will calculate the degree of membership for each environmental variable value based on the linear increasing membership function parameters provided in columns B and C.

For the linear decreasing membership function, which represents a fuzzy set where the membership value decreases linearly with the input value, the degree of membership (*μ(x)*) can be calculated as follows (**Equation 7**):

$$\mu(\varkappa) = \begin{cases} 1 & if\alpha \leq a \\ \frac{b-\varkappa}{b-a} & if a \leq x \leq b \\ 0 & if\varkappa \geq a \end{cases}$$

Equation 7

In this formula:

a and *b* are the parameters defining the range of the membership function (where *a*≥*b*);

x is the input value for which the degree of membership is being calculated.

For the linear decreasing membership function, where *a* corresponds to the critical minimum and *b* to the optimal range, the excel formula can be expressed as follows (Equation 8):

$$= IF(OR(A2 <= \$B\$2); 0; IF(AND(A2 >= \$B\$2; A2 <= \$C\$2); (A2 - \$B\$2)/(\$C\$2 - \$B\$2); IF(AND(A2 >= \$B\$2); 1)))$$

Equation 8

In this formula:

A2 represents the input value (*e.g.*, turbidity);

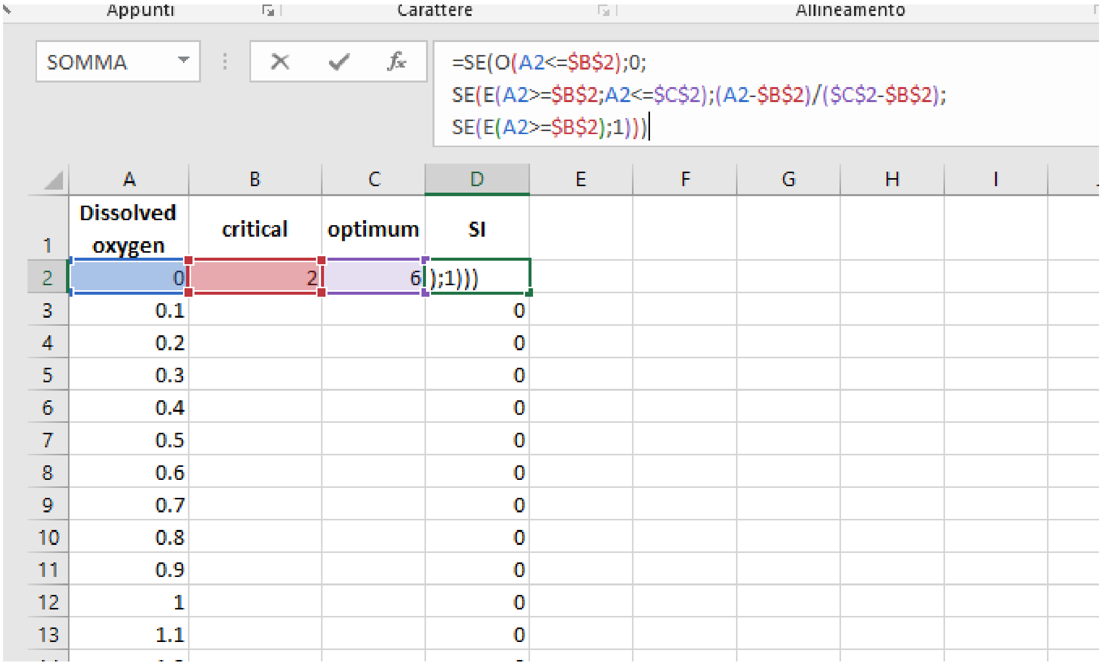
$B$2 represents the cell containing the critical minimum value;

$C$2 represents the cell containing the optimal range value.

This formula calculates the degree of membership (*μ(x)*) based on the input value A2, the critical minimum (*a*), and the optimal range (*b*).

To implement the linear decreasing membership function in Excel (**Figure 6**), you can follow these steps:

- In column A, enter the environmental variable values;
- In column B, enter the optimal range value;
- In column C, enter the critical minimum value;
- In column D, input the formula for the linear decreasing membership function.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=SE(O(A2<=$B$2);0;
SE(E(A2>=$B$2;A2<=$C$2);(A2-$B$2)/($C$2-$B$2);
SE(E(A2>=$B$2);1)))

	A	B	C	D
1	Dissolved oxygen	critical	optimum	SI
2	0	2	6	);1)))
3	0.1			0
4	0.2			0
5	0.3			0
6	0.4			0
7	0.5			0
8	0.6			0
9	0.7			0
10	0.8			0
11	0.9			0
12	1			0
13	1.1			0

Figure 6. Screenshot of the Excel table displaying the construction of the table and the fuzzy formula applied to assess the suitability of AZA species using the linear decreasing membership function.

Ensure to replace $B$2 with the cell reference for the optimal range value in column B and $C$2 with the cell reference for the critical minimum value in column C.

This formula will calculate the degree of membership for each environmental variable value based on the linear decreasing membership function parameters provided in columns B and C.

In the next figures are reported three examples of membership function relationship: trapezoidal to temperature (**Figure 7**), linear increasing to dissolved oxygen (**Figure 8**), and linear decreasing to turbidity (**Figure 9**).

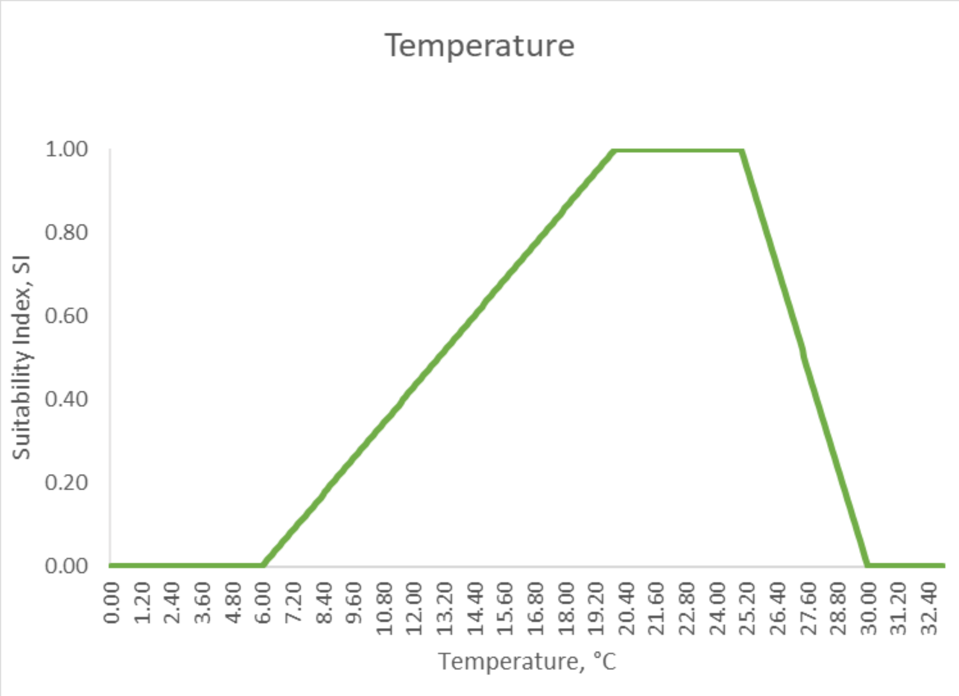

Figure 7. Temperature trapezoidal membership function.

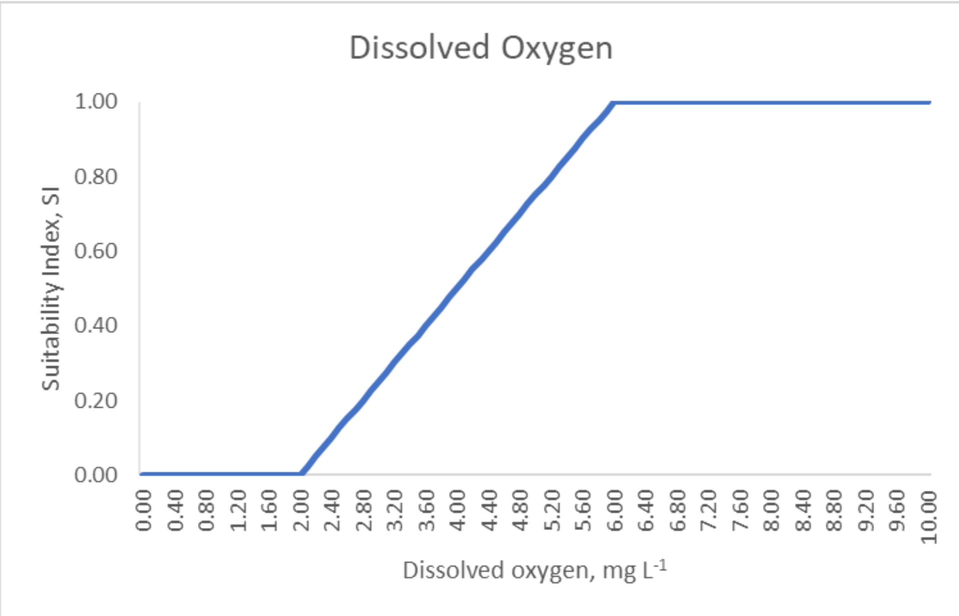

Figure 8. Dissolved oxygen linear increasing membership function.

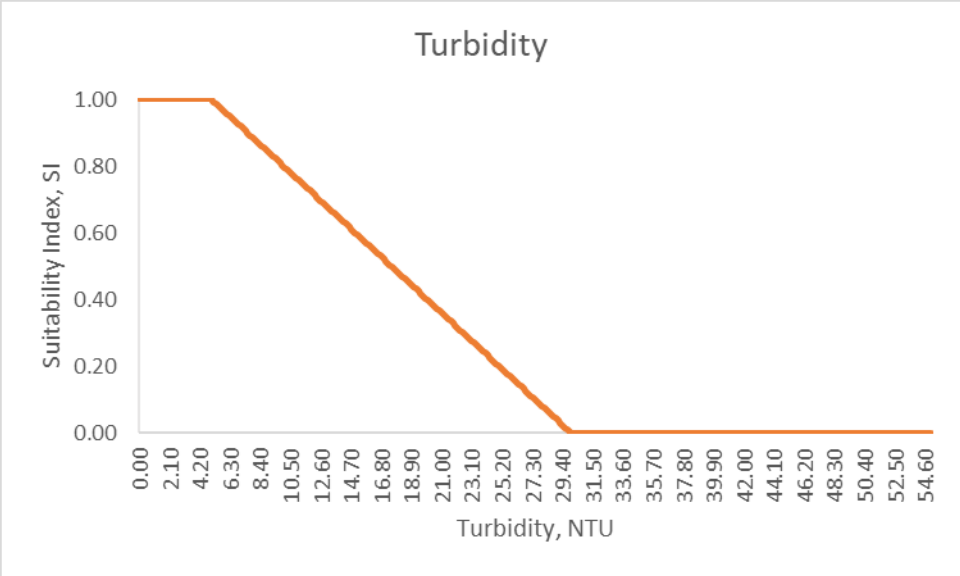

Figure 9. Turbidity linear decreasing membership function.

Noteworthy, ensuring that functions such as IF, AND, and OR are translated to match the language settings of the user's PC is crucial before running Excel functions. This guarantees that the Excel formulas are consistent with the user's language and that no error will be produced using these formulas.

1.4.2.2 Weights assignment

Understanding the varying degrees of tolerance that different farmed species exhibit towards environmental variables is crucial, as it depends on their physiological adaptations. This understanding is essential for accurately determining the weights to be assigned in the species suitability estimation process. For instance, Pacific oysters (*Crassostrea gigas*) are recognized for their high tolerance to salinity fluctuations, whereas they are more sensitive to chlorophyll-a concentration.

Identifying the correct tolerance limits helps avoid selecting sites with environmental conditions that could stress the species, potentially resulting in disease outbreaks, reduced growth rates, or even mortality events. By considering species-specific tolerances, aquaculture practitioners can make informed decisions to ensure the optimal growth and health of farmed species in their chosen environments.

In the table below, an example is provided of the weights that could be assigned to a hypothetical species for temperature, oxygen, turbidity, and salinity (**Table 30**).

Table 30. Example of weights to be assigned to environmental criteria for fed species suitability assessment.

Species	Environmental criteria	Weights
Species 1	Temperature	0.5
	Oxygen	0.2
	Turbidity	0.1
	Salinity	0.2

Table 31. Example of weights to be assigned to environmental criteria for suspension organic suitability assessment.

Species	Environmental criteria	Weights
Species 1	Temperature	0.35
	Oxygen	0.2
	Turbidity	0.1
	Salinity	0.2
	Chlorophyll-a	0.15

Table 32. Example of weights to be assigned to environmental criteria for deposit organic species suitability assessment.

Species	Environmental criteria	Weights
Species 1	Temperature	0.5
	Oxygen	0.15
	Salinity	0.35

Table 33. Example of weights to be assigned to environmental criteria for inorganic extractive species suitability assessment.

Species	Environmental criteria	Weights
Species 1	Temperature	0.35
	Turbidity	0.05
	Salinity	0.2
	DIN	0.2
	Total phosphate	0.2

1.4.2.3 Species Suitability Index estimation

Applying the methodology outlined for the *site suitability* assessment, once the criteria have been standardized and weights assigned, the overall suitability index for each considered species can be calculated using the WLC. The WLC formula (**Equation 9**) combines the standardized scores of each criterion, weighted by their respective weights, to derive a singular index representing the *species suitability*. For instance, in the case of a finfish species, the Species Suitability Index (SSI) can be computed applying the following formula:

Fed species

$$SSI = (Temperature * 0.5) + (Oxygen * 0.2) + (Turbidity * 0.1) + (Salinity * 0.2)$$

Suspension organic species

$$SSI = (Temperature * 0.35) + (Oxygen * 0.2) + (Turbidity * 0.1) + (Salinity * 0.2) + (ChlA * 0.15)$$

Suspension organic species

$$SSI = (Temperature * 0.5) + (Oxygen * 0.15) + (Salinity * 0.35)$$

Inorganic species

$$SSI = (Temperature * 0.35) + (Turbidity * 0.05) + (Salinity * 0.2) + (DIN * 0.2) + (TP * 0.2)$$

Equation 9

In **Equation 9**, all the environmental variables were normalized using the fuzzy membership function and then multiplied by their respective weights.

After calculating the SSI using the WLC method, sensitivity analysis and validation techniques can be applied to evaluate the robustness and reliability of the results. Sensitivity analysis provides insight into the effects of variations in weights or scores on the overall index, while validation entails comparing the estimated suitability indexes with empirical data, expert judgments, or known aquaculture practices to verify their accuracy.

1.4.3 Methodology to run the AZA analysis for IMTA and circularity

Data from section *1.3.3 Data needed to run AZA analysis for IMTA circularity* will be used for MCDA and social network analysis (SCA). The Species' Suitability Index (SSI), estimated as reported in section 1.4.2, will define the best trophic functional groups throughout the pilot sites. These data are essential to assess the IMTA and circularity suitability according to the six criteria defined in section 1.3.3.

1.4.3.1 Data normalization

Based on expert knowledge, stakeholders' input, literature review, and the specific requirements of the pilot site, suitability scores must be assigned to each criterion. The following tables present the performance scores for fed species (**Table 34**) and extractive species (**Table 35**) that can be assigned to each IMTA sub-criteria.

Table 34. IMTA sub-criteria scores for performance of fed species

Criteria		Scores			
		Low	**Medium**	**High**	
Distribution range and facilities **(Criterion 1)**	Biogeography in the MED and Black Sea	0.2	0.5	1.0	
	Aquaculture activity	0.2	0.5	1.0	
Domestication and culture **(Criterion 2)**		**EXT**	**SemiEXT**	**SemiINT**	**INT**
	Production model	0.2	0.5	0.7	1
		Low	**Medium**	**High**	
	life cycle knowledge	0.2	0.5	1.0	
	Seed supply	0.2	0.5	1.0	
Feeding requirements **(Criterion 3)**		**Low**	**Medium**	**High**	
	Feedstuff Sustainability and knowledge	0.2	0.5	1.0	
	Feeding efficiencies	0.2	0.5	1.0	
Growth and survival performance **(Criterion 4)**	Growth rates	0.2	0.5	1.0	
	Duration of production cycle	1.0	0.5	0.2	
	Survival	0.2	0.5	1.0	
Market value **(Criterion 5)**	Commercial value fresh product	0.2	0.5	1.0	
	Commercial value by-products	0.2	0.5	1.0	
		close	**medium**	**far**	
	Target market	1.0	0.5	0.2	
Social acceptance **(Criterion 6)**		**Accepted**	**Not accepted**		
	Consumer opinion	1.0	0		
	Satisfaction	1.0	0		

Table 35. IMTA sub-criteria scores performance of organic and inorganic extractive species

Criteria		Scores		
		Low	**Medium**	**High**
Distribution range and facilities **(Criterion 1)**	Biogeography in the MED and Black Sea	0.2	0.5	1.0
	Aquaculture activity	0.2	0.5	1.0
Domestication and culture **(Criterion 2)**		**Difficult**	**Medium**	**Easy**
	Scalability	0.2	0.5	1
	life cycle knowledge	0.2	0.5	1
	Seed supply	0.2	0.5	1
		Low	**Medium**	**High**
Feeding requirements **(Criterion 3)**	Extraction efficiency	0.2	0.5	1.0
		Closed	**Semi-open**	**Open**
	Type of Production model	1.0	0.5	0.2
Growth and survival performance **(Criterion 4)**	Growth rates	0.2	0.5	1.0
	Duration of production cycle	1.0	0.5	0.2
	Survival	0.2	0.5	1.0
Market value **(Criterion 5)**	Commercial value fresh product	0.2	0.5	1.0
	Commercial value by-products	0.2	0.5	1.0
		close	**medium**	**far**
	Target market	1.0	0.5	0.2
	Industrial uses	0.2	0.5	1.0
Social acceptance **(Criterion 6)**		**Accepted**	**Not accepted**	
	Consumer opinion	1	0	
	Satisfaction	1	0	

Once the performance indicators are established, the **circularity** of whole system need to be assessed considering the indicators shown in **Table 36**.

Table 36. IMTA circularity scores.

Criteria	Scores		
	Low	Medium	High
Estimated food efficiency	0.25	0.5	1.0
Estimated waste management efficiency	0.25	0.5	1.0
Estimated Resource efficiency	0.25	0.5	1.0
Sharing economy	0.25	0.5	1.0
Energy efficiency	0.25	0.5	1.0
Multi-species complexity and biodiversity index	0.25	0.5	1.0
Species complementarity	0.25	0.5	1.0

1.4.3.2 Weights assignment

Similarly to sections 1.4.1 and 1.4.2. it is required to set weights to the selected criteria for the IMTA/circularity suitability assessment process to properly guide the decision-making process. Each criterion and sub-criterion are allocated a percentage of relevance through a two-step process aimed at evaluating IMTA performance (**Table 37, Table 38**) and circularity (**Table 39**).

As indicated earlier, these weights must be tailored to the specific environmental, economic, and social dynamics of the aquaculture site. For instance, different aquaculture species can yield diverse impacts on the environment, economy, and society, thereby affecting the relative importance of selected criteria. Thus, involving stakeholders and experts in the weighting process can foster well-informed and contextually apt decisions in aquaculture planning and management.

Table 37. Weights of IMTA performance indicators for fed species

Criteria	Weight	Sub-criteria	Weight
Distribution range and facilities **(Criterion 1)**	**0.10**	Biogeography in the MED and Black Sea	0.40
		Aquaculture activity (number of facilities or licenses)	0.60
Domestication and breeding **(Criterion 2)**	**0.25**	Production model	0.20
		Know-how life cycle	0.20
		Seed supply availability	0.60
Feeding requirements **(Criterion 3)**	**0.15**	Feedstuff Sustainability and knowledge	0.40
		Feeding efficiencies	0.60
Growth and survival performance **(Criterion 4)**	**0.15**	Growth rates	0.40
		Duration of production cycle	0.20
		Survival	0.40
Market value **(Criterion 5)**	**0.15**	Commercial value fresh product	0.60
		Commercial value by-products	0.30
		Target market	0.10
Social acceptance **(Criterion 6)**	**0.20**	Consumer opinion	0.50
		Satisfaction	0.50

Table 38. Weights of IMTA performance indicators for organic and inorganic extractive species

Criteria	Weight	Sub-criteria	Weight
Distribution range and facilities **(Criterion 1)**	**0.10**	Biogeography in the MED and Black Sea	0.40
		Aquaculture activity (number of facilities or licenses)	0.60
Domestication and breeding **(Criterion 2)**	**0.25**	Production model	0.20
		Know-how life cycle	0.20
		Seed supply availability	0.60
Feeding requirements **(Criterion 3)**	**0.15**	Extraction efficiency	0.80
		Type of Production model. Exchange rate	0.20
Growth and survival performance **(Criterion 4)**	**0.15**	Growth rates	0.40
		Duration of production cycle	0.20
		Survival	0.40
Market value **(Criterion 5)**	**0.15**	Commercial value fresh product	0.50
		Commercial value by-products	0.20
		Target market	0.10
		Industrial uses	0.20
Social acceptance **(Criterion 6)**	**0.20**	Consumer opinion	0.50
		Consumer Satisfaction	0.50

Table 39. Weights of IMTA circularity indicators.

Indicator	Weight
Estimated food efficiency (FE)	0.15
Estimated waste management efficiency (WE)	0.20
Estimated non-food Resource efficiency (RE)	0.10
Sharing economy (SE)	0.05
Energy efficiency (EE)	0.15
Multi-species complexity and biodiversity index (BI)	0.10
Species complementarity (SC)	0.05
Integration of reused/recycled materials (RU)	0.10
Sustainable feeds (Only if fed species) (SF)	0.05
Water use efficiency (WE)	0.05

1.4.3.3 Suitability Index estimation

To determine the suitability of IMTA, the initial step involves estimating the IMTA performance index (IPI). Subsequently, this information undergoes transformation into an IMTA circularity index (ICI) which integrates various indicators along with the Species Suitability Index (SSI). This index serves as a measure of the holistic functioning of the system and provides insight into the anticipated impact of sustainable aquaculture practices.

To calculate the IPI, the WLC formula combines the SSI and the standardized scores of each performance weighted criterion using the following formula:

$$IPI = (criterion1 * 0.10) + (criterion2 * 0.25) + (criterion3 * 0.15) + (criterion4 * 0.15) + (criterion5 * 0.15) + (criterion6 * 0.20)$$

Equation 10

To calculate ICI for a specific IMTA, the formula is:

$$ICI = (FE * 0.15) + (WE * 0.20) + (RE * 0.10) + (SE * 0.05) + (EE * 0.15) + (BI * 0.1) + (SC * 0.05) + (RU * 0.10) + (SF * 0.05) + (WE * 0.05)$$

Equation 11

Finally, C-AZA index (C-AZAi) will be calculated as considering the mean performance in the species indexes SSI and IPI and the ICI for both species in the IMTA in a two-step procedure as follows:

(Step 1) calculate the weighted IMTA suitability (IS) as the mean SSI and IPI performance of species in the IMTA

$$IS= [(SSI_{s1} * 0.5) + IPI_{s1} * 0.5)] + [(SSI_{s2} * 0.5) + IPI_{s2} * 0.5)] + ... + [(SSI_{sn} * 0.5) + IPI_{sn} * 0.5)]/\sum n$$

Equation 12

where s1...sn are the different species in the IMTA and n the total number of species

Considering the weights, the final IS will oscillate between 0.2 and 1.0 as follows:

Range	Median Score	Assessment
0.2-0.4	L	Poor
0.4-0.6	L/M	Fair
0.6-0.8	M/H	Acceptable
0.8-1.0	M/H	Optimum

(Step 2) AZA circularity index (C-AZAi) combines the IS for a specific IMTA in **Equation 12** and the corresponding ICI as calculated in **Equation 11** using the following formula:

$$C\text{-}AZAi= IS*0.65+ ICI * 0.35$$

Equation 13

The final C-AZAi values will oscillate between 0.2 and 1.0 as follows:

Range	Assessment
0.2-0.4	Poor
0.4-0.6	Fair
0.6-0.8	Acceptable
0.8-1.0	Optimum

In addition to MCDA, *Social Network Analysis (SNA)* will be used to identify and target leverage points in IMTA. This methodology, also called Structural Analysis, analyse and rank relationships between sites, species, and circularity within a network, and set the social structures arising from these relationships. This network comprises two basic elements: the *nodes* that represent the sites/species/circularity and edges/lines that indicate the weight of forces or relationships between nodes. SNA is based on the mathematical language of graph theory, matrices, and relational algebra. Network connectivity is assessed by the average weight associated with survey scores as already defined in section 1.4. To determine connectivity between sites and species within each species, edge weights are estimated. SNA analysis can be carried out using Gephi 0.9.3 (https://gephi.org/) and Fruchterman Reingold distribution with gravity 5.0. This configuration allows us for minimizing crossings between edges, *i.e.*, nodes do not overlap links that do not affect them and maintain a uniform edge length.

1.5 Interpretation of the outcomes from AZA4ICE methodology application

The outcomes of the Site Suitability Index (SiSI) and the Allocated Zones for Circular Aquaculture Index (C-AZAi) can be used to assist decision makers in evaluating the development of aquaculture activities. Once the indices have been estimated, this can be interpreted as high suitability if the values are above 0.6 and low suitability if the values are below 0.6. As already outlined, the threshold can be modified depending on the specific context of the case study. The table below shows the four possible combinations of the two indices SiSI and C-AZAi (**Table 40**).

Table 40. SiSI and C-AZAi interpretation for decision makers. *High and low values refer to a threshold of 0.6 for both indices. Note: the thresholds can be modified.*

SiSI	C-AZAi	Interpretation of the combination of the outcomes
H	H	The outcomes derived from the application of the AZA4ICE methodology indicate that the studied area holds potential for the development of aquaculture activities.
L	L	The findings generated from the application of the AZA4ICE methodology indicate that the studied area is not suitable for the development of aquaculture activities.
H	L	The species and/or criteria contributing to low values of C-AZAi should be thoroughly assessed to gain a better understanding of how to intervene in the process effectively. Additionally, it may be beneficial to consider changing the species selected for analysis to obtain more comprehensive insights.
L	H	The criteria responsible for low values of SiSI should be scrutinized to ascertain the feasibility of aquaculture development in the area. For instance, actions aimed at mitigating certain impacts or modifying land uses in the surrounding areas could be implemented to address identified issues and potentially improve the suitability for aquaculture.

1.6 Key performance indicators

The effectiveness of the AZA4ICE methodology requires appropriate monitoring and evaluation. The IMC Foundation has established specific Key Performance Indicators (KPIs; **Table 41**) to gauge the implementation of the AZA4ICE methodology. These KPIs serve as metrics to assess various aspects of the methodology's performance and its impact.

Table 41. Key Performance Indicators for the AZA4ICE methodology.

Area	No.	Performance indicator name	Metric	Description of performance indicator
Pilot area and data collection	1	Number of data collected	number	The indicator measures the total number of collected for AZA4ICE methodology
	2	Number of variables collected in field	number	The indicator measures the number of variables per typology measured for AZA4ICE methodology.
	3	Number of variables collected by secondary sources	number	The indicator measures the number of variables per typology collected by secondary sources (*e.g.* scientific or grey literature, stakeholders' involvement, experts' knowledge) for AZA4ICE methodology.
	4	Number of sampling field points	number	The indicator measures the number of field sampling point identified within the pilot study areas for AZA4ICE methodology
	5	Number of stakeholders involved in data collection	number	The indicator measures the number of stakeholders involved in data collection for the implementation of AZA4ICE methodology
Site suitability	6	Number of areas suitable for aquaculture activities	number	The indicator measures the number of suitable areas identified within the pilot study area
	7	Extension of areas suitable for aquaculture activities	ha	The indicator measures the extension of suitable areas identified within the pilot study area
Site Species suitability	8	Number of species considered in species suitability assessment	number	The indicator measures the number of species identified for the species suitability assessment in the pilot case study
	9	Number of suitable species	number	The indicator measures the number of species identified as suitable (*e.g.* with a suitability index >0.6) for the pilot case study

Circular IMTA suitability	10	Number of ranked species by performance and trophic functional group	number	The indicator measures the number of species ranked by performance for the pilot case study
	11	Number of suitable IMTA circular models	number	The indicator measures the circularity performance of functional IMTAs identifying species combinations.

Tables and figures

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List of tables

List of figures

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