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AlgaePro BANOS

MONITORING AND EVALUATION SUSTAINABILITY ASSESSMENT FRAMEWORK OF MICRO- AND MACROALGAL VALUE CHAINS

D1.1

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LIST OF ABBREVIATIONS

Abbreviation	Description
APB	AlgaeProBANOS
ASC-MSC	Aquaculture Stewardship Council and Marine Stewardship Council
CICES	Common International Classification of Ecosystem Services
CIRCALGAE	CIRCular valorisation of industrial ALGAE waste streams into high-value products to foster future sustainable blue biorefineries in Europe
CML	Center for Environmental Studies Method
D	Deliverable
EABA	European Algae Biomass Association
EC	European Commission
EcIAs	Economic Impact Assessments
Eco-LCA	Economic Life Cycle Assessment
EDIP	Environmental Development of Industrial Products
EEA	European Environment Agency
EFSA	European Food Safety Authority
EIAs	Environmental Impact Assessments
EU	European Union
FAO	The Food and Agriculture Organization
GRASS	Growing algae sustainably in the Baltic Sea
iCEA	Integrated Cumulative Effects Assessment
ICES	International Council for the Exploration of the Sea
IT	Information technology
LCA	Life Cycle Assessment
LCC	Life Cyle Costing
LCSA	Life Cycle Sustainability Assessment
LOCALITY	Nature-positive aLgae-based fOod, agriCulture, AquacuLture and textIle producTs made in North and Baltic Sea ecosYstems
LTA	Low Trophic Aquaculture
MSFD	Marine Strategy Framework Directive
ODSS	Operational Decision Support System
OWF	Offshore Wind Farms
PBs	Planetary Boundaries

PCRs	Product Category Rules
REALM	Reusing Effluents from Agriculture to unLock the potential of Microalgae
PEF	The Product Environmental Footprint
PEFCRs	Product Environmental Footprint Category Rules
RAs	Regulatory Assessments
SAFA	Sustainability Assessment of Food and Agriculture Systems
SDGs	Sustainable Development Goals
S-LCA	Social LCA
SMEs	Small and medium-sized enterprises
SEAs	Socio-Economic Assessments
SSBD	Safe and sustainable by design
TEAs	Techno-Economic Assessments
TETRAS	Technology transfer for thriving recirculating aquaculture systems in the Baltic Sea Region
UN	United Nations
WFD	Water Framework Directive

SUMMARY

This report presents the AlgaeProBANOS (APB) interdisciplinary multi-level sustainability assessment framework for the micro- and macroalgal value chains in the Baltic and North Sea region. The framework brings together insights from previous initiatives, a number of existing frameworks and academic articles, with a strong emphasis on sustainable development across environmental, economic, social and governance dimensions. It provides a methodological basis for assessing the sustainability of micro- and macroalgal value chains from these perspectives. This includes a detailed exploration of potential indicators, as well as methodologies for establishing baselines and targets. The framework emphasises the critical importance of environmental limits and constraints imposed by nature, and includes performance indicators across all dimensions - environmental, social, economic and governance. Importantly, the framework integrates multi-dimensional tools, in particular Life Cycle Assessment (LCA) tailored to micro- and macro-algal value chains. The LCA is complemented by a core set of socio-economic and governance indicators, enabling a comprehensive performance analysis across the four dimensions. This assessment is accompanied by a methodology to measure the uncertainties inherent in sustainability assessments. The framework is intended to inform key stakeholders and the public and to assist industry participants, environmental managers, and policy makers in making informed decisions about sustainable development and resilience in the algae sector.

Synopsis APB. APB is a research and innovation project, co-funded by the European Union through the Horizon Europe programme under project number 101112943. APB brings together 26 expert and industry partners, affiliated entities from the Baltic and North Sea area, to accelerate product development and market access for sustainable algae solutions. All this is in line with the objectives of Mission Ocean. Partners include start-ups, SMEs, research organisations and innovation experts. The overarching objective of APB is to demonstrate market accessibility and presence of sustainable solutions and innovative algae products in the Baltic and North Seas. It is geared towards the development of innovative and sustainable algae-based products, with a keen focus on meeting the growing market demands in this sector. The project is set to run from April 2023 to March 2027, with a total budget of €12,027,291. The core mission of APB is to support the development and market accessibility of algae-based products, aiming to position the EU as a global leader in this domain. This initiative strives to not only foster industry growth but also support coastal societies and stimulate local economies. It is part of the broader Blue Mission BANOS lighthouse initiative, which is dedicated to fostering a carbon-neutral and circular blue economy across the Baltic and North Seas. APB is supporting the launch of six business pilots, aiding SMEs and startups to introduce eight innovative algae-based products into the market. These products span various sectors including food, feed, nutraceuticals, textiles, cosmetics, and plant biostimulants. The project places a significant emphasis on sustainability, with the algae used in these products sourced from the Baltic and North Sea or from recycled resources. The development process involves iterative circular loops, ensuring the products meet high standards of quality, efficiency, and sustainability. APB is not just about product development; it is about creating an ecosystem that supports the entire value chain, from biomass producers to consumers. The project will develop digital tools and platforms to support industry needs, create market strategies tailored to each pilot, and construct a comprehensive Algae Accelerator to aggregate knowledge, develop solutions, and provide guidelines and training to industry stakeholders.

1. BUILDING A SUSTAINABLE FRAMEWORK FOR THE MICRO- AND MACRO-ALGAE SECTOR

Environmental, socio-economic and governance analyses for the micro and macroalgal sectors are often conducted in isolation. This approach can lead to a narrow view rather than a holistic understanding of the issue. There is, therefore, an urgent need for an integrated, practical and simple (though not simplistic) framework to enable a wide range of stakeholders to carry out comprehensive sustainability analyses.

Sustainability assessments can focus on organisations, examining their internal processes and impacts, or extend to value chains and products, analysing the environmental, economic, and social effects throughout the lifecycle of goods or services. While organisational assessments provide insights into the sustainable practices of a single entity, value chain or product assessments offer a broader view of sustainability impacts across different stages of production and consumption. In the APB project we are therefore focusing on assessing the sustainability of algae value chains and products. This involves identifying and reducing their environmental impacts, enhancing their positive contributions (or 'footprints') and optimising their socio-economic benefits. This perspective involves assessing and harnessing the regenerative potential of algae-derived products, such as their role in absorbing carbon dioxide during the production phase, their biodegradability, which helps to reduce waste in ecosystems, and their use in creating environmentally friendly alternatives to traditional materials. By focusing on the lifecycle benefits of algae products, APB aims not only to minimise environmental impact but also to actively contribute to ecological health and resilience, promoting a product-based approach that supports regenerative sustainability.

The aim of this report is to propose a theoretical basis for a balanced framework that assesses the sustainability of micro- and macroalgal value chains along environmental, economic, social and governance dimensions, and that is applicable to different use cases in the Baltic and North Sea regions. The target audience for the framework is broad, encompassing industry participants seeking to demonstrate their commitment to sustainability, environmental managers pursuing to synthesise scattered evidence, policymakers in search of formulating effective policies to support growth of the European algae sector, and the general public who will benefit from being better informed.

Our framework is hierarchical, designed to provide core elements at each level of hierarchy that need to be assessed. To this end, the report first defines the key themes or 'building blocks' that underpin environmental, economic, social, and governance issues. At the lower level of the hierarchy, the framework defines a critical selection of indicator categories (or 'sub-themes') and a selection of indicators to be assessed within these building blocks. The specific indicators will be defined in case studies based on local specificities. In defining these broader indicator themes, sub-themes and indicators, we have drawn, where possible, on the concepts and indicators embedded in existing frameworks (e.g. FAO, 2013; EC, 2021c; European Parliament and Council, 2000); European Parliament and Council, 2008) descriptors for the environmental theme Common International Classification of Ecosystem Services (CICES, Haines-Young and Potschin, 2018) for the socio-economic theme, business examples (e.g. Fermentalg, 2022), and scientific publications (e.g. Husgafvel et al. 2017; Valenti et al. 2018; Havardi-Burger et al. 2021). Subsequently, we present several tools that integrate indicators from different dimensions to provide a comprehensive and comparative evaluation of the sustainability of micro- and macroalgal value chains. In this context, we refer to methodologies such as Environmental Impact Assessments (EIAs) and Life Cycle Assessments (LCAs), Regulatory Assessments (RAs), Socio- and Techno-Economic Assessments (SEAs, TEAs) and Economic Impact Assessments (EcIAs) for SME pilots that had not yet developed similar appraisals. We then propose to provide basic calculation rules to determine the level of sustainability of a given value chain and product. The conceptual framework developed has the potential to consolidate both quantitative and qualitative data from environmental, social, economic and governance analyses. By adopting this approach, we can ensure that the assessments cover a comprehensive set of issues across multiple dimensions, ensuring that the carrying capacity and sustainability of micro- and macroalgal value chains are thoroughly assessed and tailored to the unique characteristics of the region.

The refinement and exploration of these components will take place in Task 1.2, where the conceptual framework will be applied in various case studies to assess the sustainability of micro- and macroalgal value chains. This task also suggests appropriate data collection strategies, which will be shared with the case study leaders, who will then take responsibility for data collection using site-specific environmental and socio-economic indicators, production yield and cultivation technology designs, and the like. Ultimately, we bring this framework into practical use through the Operational Decision Support System (ODSS) portal (https://gis.sea.ee/bluebiosites/), which facilitates access for a wide range of stakeholders. This will enable them to use the conceptual framework and results of the value chain and product sustainability assessments carried out throughout the AlgaeProBANOS project.

2. OVERVIEW OF THE SUSTAINABILITY FRAMEWORK

2.1. Interactions between sustainable development, natural resource valuation and environmental impacts of production

Addressing sustainability challenges requires navigating a multifaceted landscape that intertwines environmental, economic, social and governance dimensions. These challenges stem primarily from the complex interactions between human and societal behaviour and the natural world. They are exacerbated by the ongoing struggle to reconcile human activities with the principles of nature. Responsibility for environmental problems is clearly collective, but paradoxically it is often not acknowledged by anyone. This suggests a governance gap that needs to be addressed. Furthermore, environmental change should be fully understood not only as a biogeophysical event, but as a complex socio-environmental phenomenon deeply embedded in economic systems and governance structures. This perspective is supported by the scholarly insights of Lipschutz and Mayer (1996) and Evans (2012), who emphasise the need for an integrated approach that considers the interplay of ecological, economic and political factors.

The intersection of economics and the natural sciences in the context of sustainable development often shows a marked divergence, resulting in a weakened interface for informed decision-making. This gap feeds into the rigid policy positions that are entrenched, undermining evidence-based decisions and jeopardising the critical pursuit of the 2030 Agenda's Sustainable Development Goals. Historically, traditional economic perspectives have often ignored the origin of ecosystem services from ecological systems. Instead, the focus has predominantly been on societal or consumer choices, neglecting to consider what the system can optimally provide. This means meeting human needs while maintaining ecological functions for present and future generations. This detachment has further emphasised the notion of 'human needs' as subjective and negotiable, separate from basic, non-negotiable human necessities. In addition, the extent to which resources and services are extracted from the natural environment has become increasingly influenced by the political process, leading to a significant decoupling between humans and the nature's potential to provide.

Life Cycle Assessment and related methodologies play an essential role in sustainable development by providing a comprehensive framework for assessing the environmental impacts associated with all stages of a product's life from “cradle to grave” (i.e. from raw material extraction, through material processing, manufacturing, distribution, use, repair and maintenance, to disposal or recycling). These tools are invaluable in identifying areas where a product or process is particularly resource intensive or damaging to the environment, and in highlighting potential improvements. However, the application of these methodologies is far from consistent, with different approaches being used even within a single sector or value chain. This inconsistency often results in a lack of harmonised assessments, which makes comparisons difficult and hinders the development of industry-wide or cross-sector best practices. It also leaves room for methodological biases that can distort results and undermine their reliability and credibility.

While LCA and similar tools provide a valuable perspective on the environmental impacts of a product or process, by assessing energy and material system inputs and outputs, they tend to be less adept at accounting for ecosystem services and other local effects. Ecosystem services are the various benefits that humans derive from the natural environment and well-functioning ecosystems, such as clean air and water, pollination of crops and climate regulation, i.e. benefits that help make human life both possible and worth living (Costanza et al., 1997; Millennium Ecosystem Assessment MA, 2003; Gómez-Baggethun et al., 2010). These include provisioning services such as food and water; regulating services that affect climate, floods, disease, waste and water quality; cultural services that provide recreational, aesthetic and spiritual benefits; and supporting services such as soil formation, photosynthesis and nutrient cycling. Combining LCA with ecosystem service assessments can provide a more holistic view of sustainability. It can enable us to consider not only the environmental impact of a product or process, but also its dependence on, and impact on, critical ecosystem services. This linkage could help align LCA more closely with the broader goal of sustainability - ensuring that we meet our needs in the present without compromising the ability of future generations to meet their own needs. Although different scientists interpret ecosystem services differently, many see ecosystem services as the conditions and processes through which natural ecosystems sustain and fulfil human life (Daily, 1997). These conditions are seen as essential for maintaining biodiversity, the cornerstone of all the goods that humans produce and consume and on which our economy is based. When attempting to value natural assets and regulate their use, different methods - whether economic or non-economic, monetary or non-monetary - produce divergent results, often depending on the intended use.

The Baltic and North Seas are highly complex and interconnected ecological systems, characterised by significant vulnerability and fundamental importance for both human societies and the health of the environment. While these waters are subject to international agreements and delimitations (e.g. ICES), they transcend individual national jurisdictions, resulting in environmental impacts that are cumulative, often have transboundary regional impacts, and involve a variety of uncoordinated decision-makers, stakeholders and societal structures. While several EU directives promote ecosystem-based management, the practical implementation and collaborative efforts to apply these principles are still evolving in the Baltic and North Sea area. Moreover, this challenge is partly due to the lack of comprehensive tools to capture and integrate knowledge from different fields such as environment, economy, society and governance. As human activities intensify and diversify the use of the oceans, most of the resulting environmental impacts are negative. These can only be effectively mitigated through harmonised, trans-boundary and trans-disciplinary strategies covering the entire sea area.

The need for informed decisions on sustainability is twofold: to ensure the sustainable use of marine resources and to maintain the regulating services vital to the survival of our ecosystems - aspects that have often been overlooked, particularly in such complex and interconnected environments. However, national decision-makers face a dilemma: they can neither extend their authority beyond their borders nor bear sole responsibility for the health of the oceans. The methodologies on which countries rely to manage their territories and assess environmental impacts vary widely, posing challenges when comparing different management measures or blue growth initiatives, and when calculating the cumulative environmental impacts of collective human activities in the Baltic and North Seas. The main obstacle lies in our limited understanding of the linkages between ecosystems, ecosystem functions and ecosystem services that benefit people, and hence the management of these ecosystems. This underlines the need for more harmonised approaches to assess and manage regional cumulative impacts across different dimensions - environmental, economic, social and governance.

2.2. Micro- and macroalgal value chains and their current sustainability assessments

In 2009, the establishment of the European Algae Biomass Association (EABA) marked a significant step towards fostering the algae sector, aiming to create strong connections among academic circles, industry players, and policymakers (Mendes et al., 2022). Nowadays, sustainable use of micro- and macroalgae has become a focal point in the environmental policy discourse within the European Union (EU), as evidenced by initiatives such as the EU Algae Initiative of the EC[1] (2022) and its first implementation action, the EU4Algae Stakeholder Forum[2]. In EU, the emerging algal industry, part of the EU's Blue Bioeconomy, is characterised by a diverse range of species and production methods, with macroalgae production led by Spain, France and Ireland, and microalgae production dominated by Germany, France and Spain. The European algal industry, including both microalgae and seaweed, is relatively small but growing, with approximately 420 companies distributed across 23 countries. These companies are primarily focused on producing *Spirulina* (46%) and seaweed (36%), with the remainder producing other microalgae (10%) and both *Spirulina* and other microalgae (8%). The industry is geared towards food and food-related applications, highlighting the nutritional value and sustainability of algae as a food source (Mendes et al.,

[1] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12780-Blue-bioeconomy-towards-a-strong-and-sustainable-EU-algae-sector_en
[2] https://webgate.ec.europa.eu/maritimeforum/en/frontpage/1727

2022). Despite its growth and technological advances, the industry, which relies predominantly on wild harvesting for macroalgae (68%) and photobioreactors for microalgae (71%), faces challenges and data gaps, highlighting the need for further research and development (Araújo et al., 2021; Mendes et al., 2022). The European microalgae industry also faces challenges such as competition from Asian producers who benefit from lower production costs. However, higher environmental standards and the demand for sustainable products in Europe provide a competitive advantage for European producers, who are increasingly focusing on high-quality, sustainable algae-based products. The potential of the industry is further underlined by its applications in the nutraceutical market, where microalgae-derived compounds are valued for their nutritional benefits (Mendes et al., 2022). Furthermore, the European Food Safety Authority (EFSA) has only authorised a limited number of microalgae species for human consumption, demonstrating the stringent safety and regulatory framework within which the industry operates. This regulatory environment ensures the safety of microalgae products, but also represents a barrier to the introduction of new species to the market (EABA, 2021). Overall, the European microalgae industry is on the verge of growth, driven by technological advances and a shift towards more sustainable and environmentally friendly products. However, the industry needs to overcome regulatory barriers, production challenges and the need for greater consumer acceptance to fully realise its potential.

Similarly, the cultivation of micro- and macroalgae in the Baltic and North Sea region is still at a relatively early stage, with a limited number of small and medium-sized enterprises (SMEs) involved. Advances in algal farming in the North Sea require a trial-and-error approach to better understand algal biology and physiology and to develop effective farming systems (Kerrison et al., 2018, 2019). There has been some focus on the economics of individual cultivation systems of the brown macroalga *Saccharina latissima* (Buck and Buchholz, 2004; van den Burg et al., 2013; Hasselström et al., 2020), and extensive research has been undertaken the past ten years to establish cultivation practices and to map out their effects on biochemical composition and resulting product suitability (Handå et al. 2013; Mols-Mortensen et al. 2017; Sharma et al. 2018; Forbord et al. 2020; Thomas et al. 2022b). However, in terms of wild harvesting potential (Bruhn et al., 2016; Araújo et al., 2021; Maar et al., 2023, Figure 1), it offers significant opportunities to help restore the environment and promote a circular economy (Araújo et al., 2021; Fernandez et al., 2021; Duarte et al., 2022; Thomas et al., 2022a).

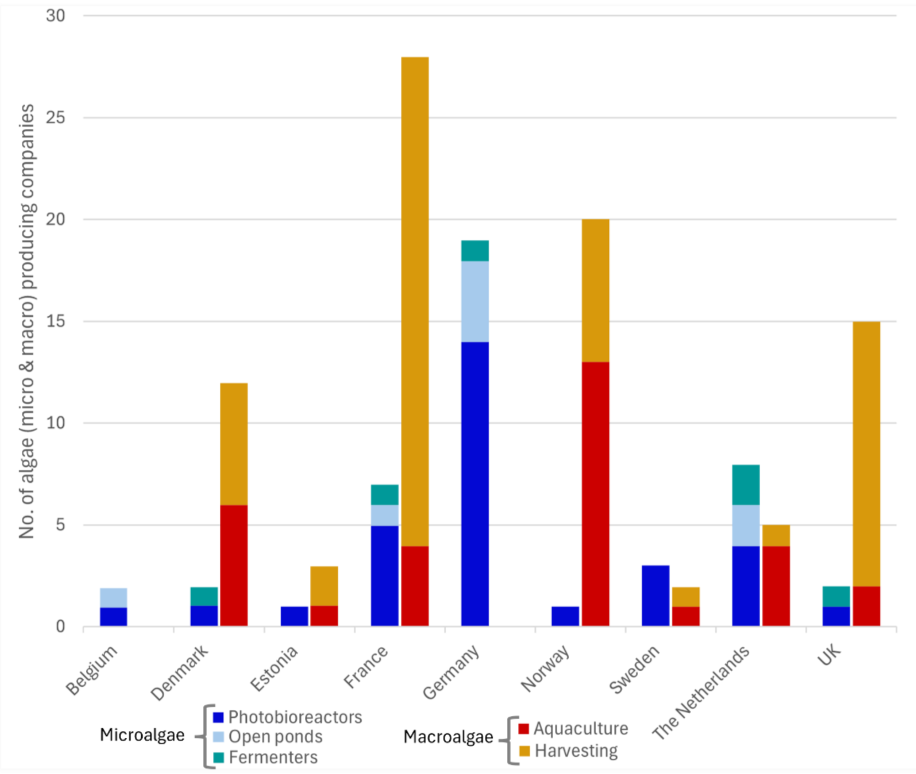

Figure 1. *Number of macro- and microalgae producing companies in Europe by production technology and country (adapted from Araújo et al., 2021). Only countries bordering the Baltic and North Seas are shown.*

In Norway, for example, seaweed farmers harvested only approximately 525 tonnes of brown seaweed (kelp) in 2022, despite a significant increase in commercial value in recent years (Hermans, 2022). This trend is mirrored in other Scandinavian countries, reflecting a growing interest in macroalgal biomass for various applications (Bruhn et al., 2016; Visch et al., 2020a, 2020b). Seaweed cultivation in the Baltic Sea region is gaining momentum. To date, the main focus of cultivation activities has been on *Saccharina latissima*. Notably, this is the only species that is currently cultivated commercially in the westernmost regions of the Baltic Sea (van Oirschot et al., 2017; Campbell et al., 2019; Weinberger et al., 2019). There are no viable macroalgal farms in other parts of the Baltic Sea region because low salinity in the Baltic Sea region leads to reduced growth rates of macroalgae (Kotta et al., 2022). But Est-Agar in Estonia is promoting the cultivation of the red alga *Furcellaria lumbricalis* as a source of a unique texturiser, Furcellaran. This substance provides an alternative to traditional gums, texturizers and oil-based, non-sustainable ingredients in a variety of industries. In addition, this alga serves as a source of other valuable products, including phycoerythrin (Saluri et al., 2019). Nordic SeaFarm, emerging from Swedish academic research, is revolutionizing *Ulva* (sea lettuce) production by transitioning to cost-effective, large-scale offshore cultivation. Their innovative efforts aim to increase the availability of *Ulva* as a nutritious alternative in the food industry, overcoming the limitations of land-based cultivation methods (Steinhagen et al., 2021). However, there is a growing interest in the cultivation of other species of algae in the Baltic Sea, underlined by several pilot projects (Brzeska-Roszczyk et al., 2017; Suutari et al., 2017; Christiansen, 2018; Meichssner et al., 2020; 2021a,b). Similarly, the AlgaeProBANOS project is evaluating the cultivation efficiency of the brown seaweed *Fucus vesiculosus* in the low salinity areas of the Baltic Sea. Innovative multi-use projects, such as the combination of low trophic aquaculture (LTA) with offshore wind farms (OWF), have been investigated in northern Europe (Buck et al., 2018; UNITED project, 2022). These studies suggest the feasibility of co-culturing species such as blue mussels (*Mytilus* spp.) and sugar kelp (*Saccharina latissima*) in the North Sea. When shellfish consumption exceeds local production, the transition to a diet with higher seaweed consumption is essential for market expansion (van den Burg et al., 2016, 2020; Maar et al., 2023).

Previous (and ongoing) project initiatives in the Baltic and North Sea areas have addressed the technical, economic and environmental aspects of improving the sustainability of algal value chains. The SeaChem project evaluated the entire seaweed value chain through a life cycle comparison approach, aiming to improve the economic viability of each step while assessing environmental impacts in line with the UN SDGs and planetary boundaries. TANG.NU was a large Danish national project that examined seaweed harvesting for marine cleanliness and its biomass for food and feed, with a focus on sustainability. SeaMark (ongoing project) is contrasting the environmental footprint of algae-based products with their terrestrial counterparts. LOCALITY (ongoing project) aims to harness algae value chains to minimize waste from production industries, developing innovative and sustainable solutions within three regional ecosystems in the North and Baltic Seas. CIRCALGAE (ongoing project) sought to transform under-utilised algal biomass into valuable products that promote ecosystem health. REALM (ongoing project) develops a sustainable microalgae cultivation system using renewable energy and recycled water. KELP-EU, led by Oceanium, investigated the life cycle impacts and market potential of kelp. SeaFarm in Sweden proposed a bio-based system for seaweed as a resource, highlighting its environmental advantages over land-based biomass. The MacroFuels project aimed to advance technologies for producing liquid transportation biofuels from cultivated seaweed, offering a sustainable solution for transportation fuels in heavy goods transport and the aviation sector. The GRASS project aimed to raise awareness and build capacities among public authorities and stakeholders across the Baltic region on the cultivation, harvesting, and use of macroalgae, thereby facilitating the development of a blue bioeconomy and promoting blue growth. Together, these projects advanced our understanding of the role of seaweed in sustainable ecosystems and economies and demonstrated a shift towards more integrated and environmentally friendly practices in seaweed cultivation and use. The United and UltFarms projects broadened the scope and aimed to integrate wind energy with low trophic aquaculture, assessing environmental impacts using a framework based on EIA principles and Integrated Cumulative Effects Assessment (iCEA). This approach divides activities into specific actions related to environmental pressures, forming 'impact chains' that affect different ecosystem components. These chains are assessed both qualitatively and quantitatively to prioritise significant impacts, facilitating targeted assessment through an ecosystem services approach, thereby enhancing the sustainability of multi-use marine infrastructure including seaweed farming.

The research carried out in these projects has focused on the sustainability of algal value chains, emphasising the need for production systems that are in harmony with nature and based on the carrying capacity of the seas rather than large-scale production (van den Burg et al., 2021). The environmental benefits of seaweed farming, such as nutrient removal, biodiversity enhancement and carbon sequestration, are widely recognised. However, challenges such as disease outbreaks and environmental degradation from intensive farming highlight the complexity of scaling up seaweed farming sustainably. Despite the potential of seaweed cultivation and product valorisation, there are legitimate concerns about the safe scale-up of macroalgal value chains. In order to prevent unintended damage to the fragile and valuable habitats of the Baltic and North Sea, macroalgal cultivation must be subject to a comprehensive monitoring and control framework. Here, international experience in algal aquaculture provides valuable insights for the adoption of low-risk strategies in the Baltic and North Sea region (Campbell et al., 2019; Tonk et al., 2021; Banach et al., 2022).

The EU blue bioeconomy report emphasizes the importance of 'Aquaculture 4.0' technologies, such as Information Technology and automated monitoring, in managing large-scale microalgal and seaweed facilities. These advancements could standardize the production process, making it more efficient and sustainable (EC, 2023). There is, however, little information on how to effectively quantify the sustainability of algal value chains across environmental, economic, social and governance dimensions. There are significant uncertainties surrounding the environmental impacts of seaweed cultivation, with difficulties in comparing impacts and recognising benefits due to different cultivation and processing methods. Here, LCA has emerged as a key method for assessing these impacts throughout the life cycle of a product. Over the past decade, LCA has made significant progress in assessing seaweed value chains and has provided valuable insights. Many LCA studies have been carried out on *Saccharina latissima* products, with each study focusing on a specific cultivation system. This highlights the need for comprehensive research that encompasses the diversity of these systems and examines how infrastructure affects environmental outcomes (Alvarado-Morales et al., 2013; Taelman et al., 2015; Parsons et al., 2019; Thomas et al., 2020). These projects also integrated a new approach to incorporate ecosystem services into the life cycle sustainability assessment (LCSA) of seaweed farming and biorefinery systems, in line with the Sustainable Development Goals (SDGs) and Planetary Boundaries (PBs). Despite efforts to determine the climate benefits of seaweed cultivation, uncertainties and insufficient evidence of net negative emissions prevent seaweed value chains from being labelled as definitive climate solutions (e.g. Hasselström and Thomas, 2022). Future research directions include improving assessment frameworks to balance environmental, economic and social benefits, and addressing uncertainties in the climate change mitigation potential of seaweed cultivation and valorisation processes.

2.3. Structural overview and key building blocks of the sustainability framework

The APB project aims to enhance macro- and microalgal value chains by creating toolkits that cater to the requirements of algae innovators and entrepreneurs. An important element of this toolkit is a **sustainability assessment framework for algae products** that incorporates comprehensive data on energy and material flows, a broad set of indicators across environmental, social, economic and governance dimensions, and tools to integrate all these dimensions. The framework aims to identify and mitigate environmental impacts while promoting socio-economic benefits and supporting the growth of sustainable algal industries. The framework is founded on four pillars (Figure 2).

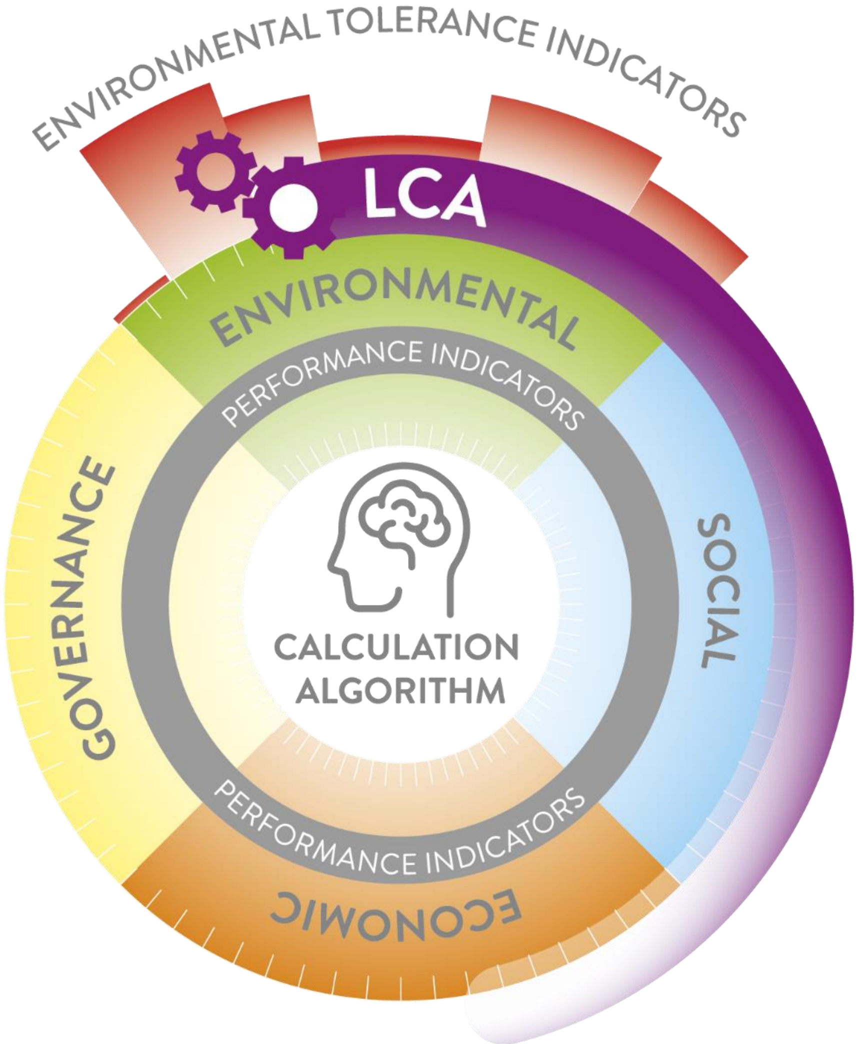

Figure 2. *Four pillars of the AlgaeProBANOS sustainability assessment framework. (1) Environmental Tolerance Indicators assess the sustainability of algal value chains against natural carrying capacities. These indicators prevent adverse environmental impacts by ensuring ecological thresholds are not exceeded. (2) Performance Indicators Across Dimensions evaluate environmental, economic, social, and governance aspects. This approach evaluates the sustainability of algal value chains by balancing ecological concerns with economic viability, social equity, and governance effectiveness. (3) Integrated Assessment Tools, such as Life Cycle Assessment (LCA), are used to facilitate holistic evaluations across various sustainability themes, including e.g. environmental and economic aspects. These tools are important for analysing the impacts and benefits of algal value chains, providing a detailed perspective on their sustainability performance. (4) The Holistic Sustainability Calculation Algorithm synthesises insights from various indicators and assessments into a unified sustainability score. This summary allows stakeholders to comprehensively assess sustainability performance, guiding informed decision-making and identification of sustainable practices within algal value chains.*

The **first pillar** of the framework is the recognition that natural environments have inherent limitations and needs that are critical to ecosystem functioning. This ensures the maintenance of vital conditions for the biosphere and its various subsystems (Röckstrom et al., 2009). Therefore, exceeding the sustainability thresholds of natural systems would make algae production impossible. These thresholds are non-negotiable and underline the urgent need for a vigorous discourse between and within different scientific disciplines to promote a more integrated approach to sustainability assessment. This integration would reduce uncertainty in scientific knowledge and strengthen evidence-based decision-making around sustainability. The framework deals with environmental limitations by using **environmental tolerance indicators** to evaluate whether any environmental aspect exceeds the sustainability limits for a particular value chain. If the limits are exceeded, it recommends seeking mitigation strategies to overcome these sustainability challenges (Figure 3).

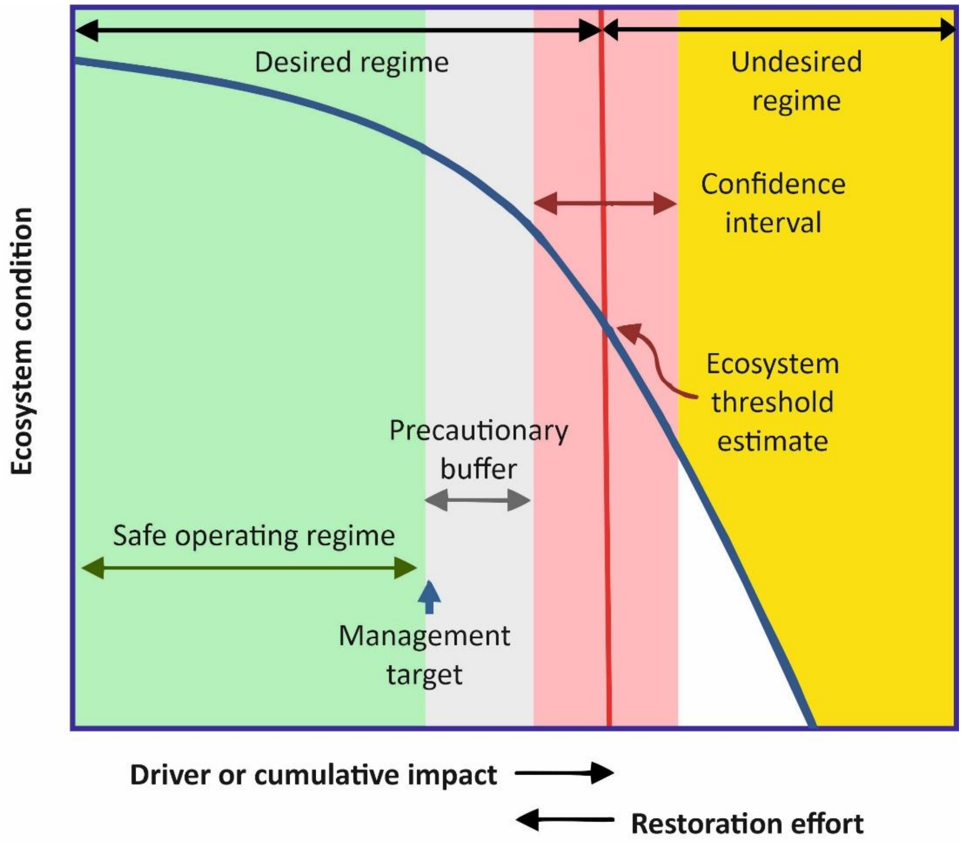

Figure 3. *Conceptual framework for sustaining natural systems in the face of multiple human pressures. Environmental tolerance indicators are used to ensure that the environmental system remains within the safe operating limits of its desired state. When the cumulative impact of human activities exceeds the critical threshold of environmental tolerance, the ecosystem reaches a tipping point, leading to a detrimental regime shift and the potential collapse of many ecosystem services.*

Figure 4. *A schematic representation of the dimensions of sustainability. This diagram illustrates the integrated nature of sustainability, where the environmental dimension is the core foundation, encompassing ecological and biological elements such as biodiversity, natural resources and environmental sinks. It sets the boundaries for all growth and emphasises that the economy is a subset of this larger ecological system. Nested within the environmental dimension is the social dimension, which emphasises the dependence of social systems on the Earth's ecosystems. The governance dimension, in turn, underpins the social layer, advocating decision-making based on wisdom and moral virtue in the face of uncertainty. At the innermost level, the economic dimension is shown to be interdependent with environmental, social and governance conditions, underlining the interconnectedness of economic activities with the broader sustainability framework.*

In contrast to the traditional view of the three foundations of sustainability (social, environmental and economic) as separate entities, a sustainable vision should consider the economy as one component embedded in a larger ecological system (Raworth, 2017) (Figure 4). The environmental dimension encompasses a broad range of ecological and biological elements, such as biodiversity, natural resources, and environmental sinks. The Earth's ecological system sets the ultimate limit, or true 'bottom line', for all growth and should therefore be the starting point for all subsequent economic analysis. Within this environmental dimension is the social dimension, which recognises the dependence of social systems on the Earth's ecosystems. Consisting of institutions, systems and networks, the social dimension represents a human-constructed system responsible for meeting human needs while preserving natural resources. Beneath the social dimension is the governance dimension, creating a hierarchy that ensures that governance is made with wisdom and moral virtue. Incomplete knowledge or high uncertainty should not be used as an excuse for distorting knowledge to serve stakeholder interests. Instead, these factors should lead to more cautious action, guided by practical wisdom and moral virtue, to ensure sustainable management of natural resources. The economic dimension is embedded in the other three dimensions mentioned above. It reinforces the understanding that economic activities depend on and impact on environmental, social and governance conditions.

This approach is in line with the objectives of the European Green Deal (EC, 2019), which aims to transform the EU into a fair and prosperous society, underpinned by a resource-efficient and competitive economy. This economy should be decoupled from intensive resource use and free of greenhouse gases. The Green Deal advocates a just and inclusive transition that puts people and local communities first, with particular attention to regions and industries facing the greatest challenges. In addition, active public participation is seen as essential for shared governance at all levels of government, highlighting the importance of the social dimension.

The **second pillar** of the framework outlines a core set of elements at different hierarchical levels, incorporating a wide range of indicators assessed across the environmental, economic, social and governance dimensions (Figure 5; for further information on the indicators, please refer to Annex 1.). In developing the indicators within our framework, we have drawn, where possible, on established concepts and metrics from existing frameworks. These include the FAO's SAFA (Sustainability Assessment of Food and Agriculture Systems; FAO, 2013), which provides a comprehensive approach to food and agriculture sustainability across four key dimensions: good governance, environmental integrity, economic resilience and social well-being. Key sources of information for the environmental theme in our framework include the Water Framework Directive (WFD) (European Parliament and Council, 2000) and the Maritime Strategy Framework Directive (MSFD) (European Parliament and Council, 2008), which provide indicators for environmental assessment, and the CICES (Haines-Young and Potschin, 2018) for the socio-economic theme. The Blue Economy Sustainability Criteria framework (EC, 2021c) guides sustainable marine and coastal development, balancing economic activities with maintaining the health of marine ecosystems and emphasising environmental, economic, social and governance factors. Our framework also incorporates insights from business examples, such as Fermentalg (2022), and relevant scientific literature, including works by Husgafvel et al. (2017), Valenti et al. (2018), and Havardi-Burger et al. (2021), to ensure alignment with 'best practice' and the most up-to-date data available. This synthesis of different sources supports a holistic approach to managing environmental and socio-economic sustainability in our assessment framework.

The European Green Deal outlines a blueprint for a sustainable economy, while the Circular Economy Action Plan is a legislative initiative to promote sustainable products. Together, they lay the foundations for achieving climate neutrality and circularity in EU policies. To measure progress towards the governance objectives, the AlgaeProBANOS assessment includes governance indicators. These indicators shed light on current regulatory requirements and identify any gaps, focusing in particular on elements of the circular bioeconomy that impact the local value chain assessed. The above policies, including the broader scope of the Ecodesign Directive and consumer empowerment initiatives, inform the governance indicators within the framework, reflecting sustainability standards and economic decoupling from environmental impacts (EC, 2020a). At the same time, the EU Algae Initiative and related policies, such as the 2021 Strategic Guidelines for Sustainable Aquaculture, the Sustainable Blue Economy Framework, the 2023 Framework of SSBD and EU taxonomy for sustainable activities underline the value of marine bioresources in promoting healthy ecosystems and a sustainable circular bioeconomy (EC, 2020b, 2021ab, 2023; Caldeira et al., 2023). However, current practices, such as setting harvesting quotas based mainly on the experience of local authorities, do not sufficiently consider the impacts of climate change, pollution and increasing demand for macroalgae. Challenges such as coastal water quality, underestimation of the benefits of macroalgae farming, lengthy environmental impact assessments and socio-economic barriers such as the transition to green energy, fair wages and the integration of advanced IT in rural areas will be addressed within the framework to ensure a comprehensive sustainability assessment (BlueBioClusters, 2023).

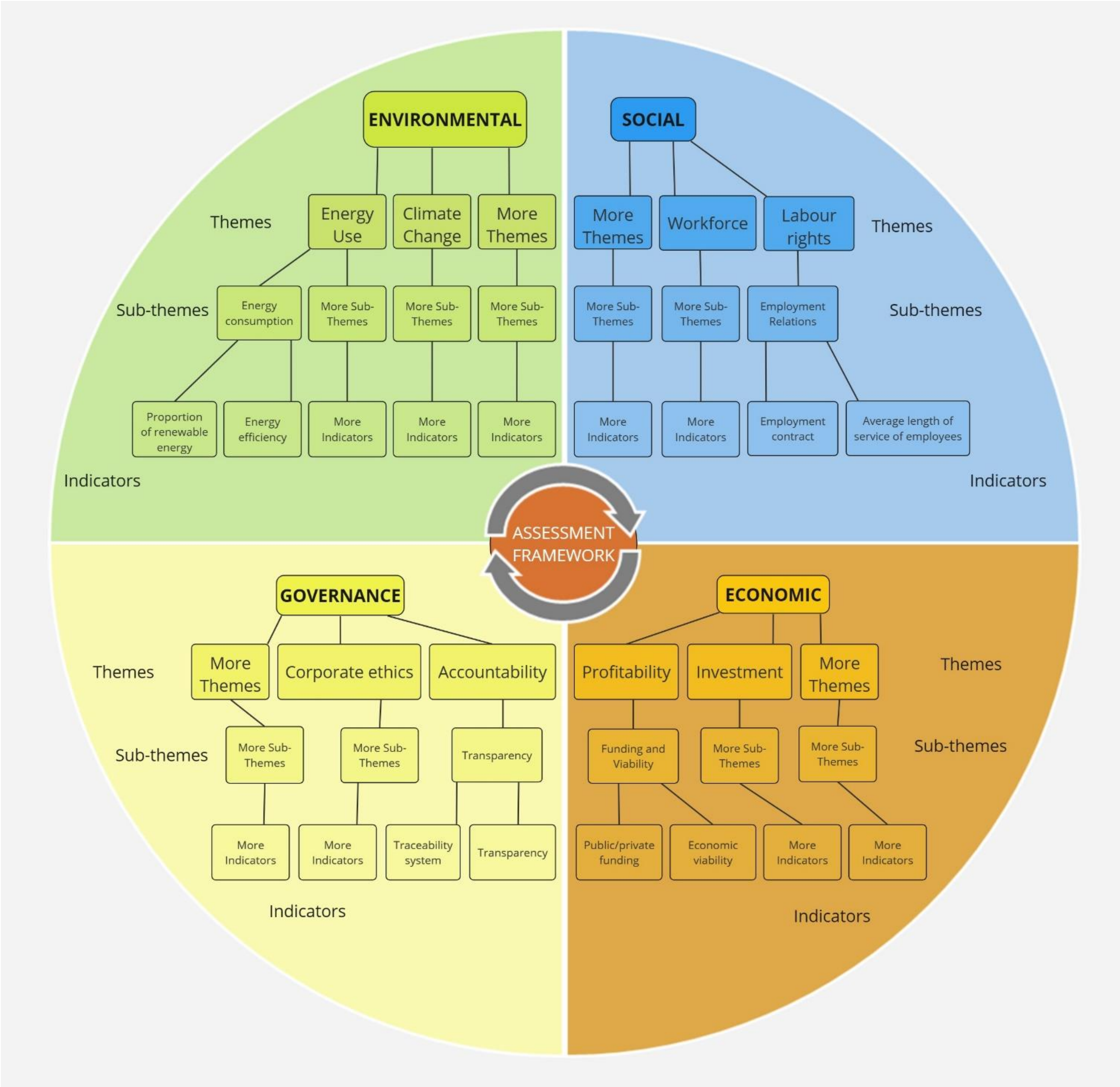

Figure 5. *The assessment hierarchy within the AlgaeProBANOS framework, which describes a core set of elements at different hierarchical levels. It shows how a wide range of indicators are integrated and assessed across four dimensions: environmental, economic, social and governance. Within each dimension, a core set of themes covers a wide range of issues (e.g. climate change, air pollution and the marine environment). These themes are further broken down into specific sub-themes (e.g. air quality, greenhouse gas emissions and biodiversity conservation), each of which is supported by a number of indicators. These indicators are essential for assessing a wide range of environmental impacts and sustainability performance.*

Environmental themes encompass a range of issues, including climate change, air pollution, marine environment, ecosystem and biodiversity protection, energy and materials usage, water quality and use and circularity. Each of these themes is supported by specific sub-themes, such as air quality, greenhouse gas emissions, biodiversity conservation, habitat conservation and harvesting practices and similar. Indicators within these sub-themes assess a range of impacts, including emission reductions, biodiversity conservation, energy efficiency, and sustainable sourcing, in line with the principles of a circular economy. Unlike environmental tolerance indicators, which set environmental thresholds for algal value chains, environmental performance indicators focus on the environmental contributions of the algal sector, such as decarbonisation and nutrient sequestration, and highlight the positive impact of algae farming on ecosystem health.

Social themes encompass issues such as capacity development, gender equality, health and safety, quality of life, ageing society, labour rights and local benefits, with the aim of creating a sustainable industry that values the well-being of its employees and communities. Key areas of focus include stable employment opportunities, inclusion of vulnerable groups, non-discrimination practices, access to benefits, ensuring a safe working environment, preventing overwork for a balanced quality of life, and supporting local economies through fair wages and investment in communities.

Economic themes include profitability, market development, investment and financing opportunities, cost effectiveness and economic resilience. It aims to promote a competitive algae industry that generates stable profits, attracts investment, creates jobs and contributes to the economy, while ensuring the sustainability of production practices. By focusing on economic sustainability, the framework seeks to balance financial growth with environmental stewardship and social responsibility, underpinning the development of a robust and resilient algae sector that supports long-term economic prosperity.

Governance themes navigate the complex landscape of national and European Union legislation, including the MSFD, the WFD and the Habitats Directive, which collectively aim to minimise ecological damage and promote sustainable management practices. Despite the existence of these directives, there's a notable lack of co-ordination and consistent application across different jurisdictions, highlighting the need for a consistent regulatory approach. In addition, the framework is aligned with global standards such as those set by the Aquaculture Stewardship Council in 2022 and its ASC-MSC Seaweed Standard, which advocate responsible aquaculture and environmental stewardship. This governance approach aims to ensure that macroalgae farming not only meets the highest standards of environmental and social responsibility, but also contributes to the regulatory coherence and sustainability of the sector.

The **third pillar** of the framework is a set of tools for sustainability assessment. Tools that cover multiple dimensions are ideal for integrating assessments across various disciplines, making them a natural choice for a holistic evaluation of sustainability. There are a wide range of tools available to assess the complexity of environmental, social, economic and governance performance. These tools can be organised according to their focus and the type of objects they assess, e.g. products, value chains, systems, projects and organisations (Finnveden and Måberg, 2005). Amongst these methods, LCA has emerged as one of the most commonly applied methods, and primarily serves to assess the impacts of a product or service delivering a specific function: inputs and outputs of a service or product system are inventoried and the impacts of these flows can be modelled across the whole life cycle of said product or service, i.e. from raw material extraction to end-of-life. Impacts are measured across a wide number of different impact categories and associated units, which are generally categorised as midpoint or endpoint indicators. Midpoint indicators in LCA quantify specific environmental stressors or emissions resulting from a product's life cycle stages, such as greenhouse gas emissions or acidification potential. They provide insight into direct environmental pressures. Endpoint indicators in LCA capture broader environmental impacts on human health, ecosystems, and resources, integrating multiple midpoint indicators into holistic measures. They assess consequences like respiratory diseases, biodiversity loss, and resource depletion, offering a comprehensive view of a product's environmental implications. Combined, midpoint and endpoint indicators give important insights about the environmental performance of a product, service or system, and follow well established calculation methods that have evolved over several decades of academic and commercial practice. The results of LCA studies provide insights not only about environmental burdens of a particular product or service, but also of potential trade-offs resulting from different changes to the systems, and insights about possible impact mitigation pathways or environmental optimisation strategies.

Understanding trade-offs within LCA is crucial for interpreting comparative results, as it helps to identify where one alternative outperforms or underperforms another in terms of the environmental consequences of particular decisions. Rather than providing an absolute description of each alternative individually, our framework suggests that the analysis should clarify the relative trade-offs between decision alternatives. This approach allows LCA practitioners to focus their analyses on the elements that are most critical to the decision-making process. It also helps to identify areas where data refinement would be most beneficial given the level of uncertainty, thereby improving existing analyses. Extending the trade-off analysis beyond LCA to other core issues and sub-themes requires the integration of LCA approaches with broader framework level considerations. This integrated approach allows for a comprehensive assessment of trade-offs across different dimensions, including environmental, economic, social and governance aspects. By applying the logic of trade-off analysis at the framework level, practitioners can identify linkages and potential conflicts between different sustainability objectives. This holistic view facilitates a more detailed understanding of the implications of decisions across the full range of sustainability dimensions. It promotes a balanced approach to decision making, where trade-offs between competing interests or priorities are explicitly recognised and addressed.

Though LCA is a valuable tool for assessing the environmental impacts of products or processes throughout their life cycles, the method tends to focus more on global and aggregated impacts, often overlooking specific local effects. Local impacts may require more detailed and site-specific data, which might not be readily available or might be challenging to obtain. LCA often relies on general data and assumptions due to the complexity of collecting precise local information. It also generally provides a snapshot of environmental impacts over the entire life cycle of a product or process, and thus may not capture short-term or dynamic local effects that can be associated with specific activities, such as the immediate impacts of seaweed farming on local biodiversity or pollution.

EIAs can be used to estimate or monitor such effects. EIAs typically serve in the planning stages of a project, notably as part of licensing procedures, to quantify the anticipated environmental impacts of a proposed action but likewise to assess the actual impacts. EIAs consider a wide range of impacts, most commonly associated with direct local or site-specific changes to the environment, such as pollution, noise, changes to biodiversity, and hydrological effects. The current permitting processes and criteria for EIAs are mainly centred around fish and shellfish farming (EC, 2016; Wood et al., 2017). Despite some initial progress, the adaptation and refinement of these criteria for the cultivation of macroalgae in the Baltic Sea region is ongoing and not yet finalised. (GRASS, 2021; BalticSeaSafe, 2022).

The **fourth pillar** of the framework is an advanced **calculation algorithm** that combines environmental tolerance indicators with performance metrics across environmental, economic, social and governance dimensions, using various tools for a holistic sustainability assessment. Essentially, this framework proposes to complement the proposed work of LCA, EIA and similar tools with a set of additional indicators to provide a holistic sustainability assessment. Rather than advocating trade-offs at the expense of natural assets, our framework provides a unified solution at a general level while allowing flexibility at the indicator level. This approach recognises that a single methodology may not be universally applicable. We therefore allow users to select the most appropriate methodologies from a range of options at a finer scale, depending on data availability and specific knowledge. This tailored approach aims to effectively achieve the Sustainable Development Goals and the European Green Deal. The framework draws on a wide range of scientific literature and current best practices. This approach promotes agreement on the common good and mitigates social conflict arising from unsupported and subjective interests. The framework serves as an interface between science, policy and society, facilitating processes of knowledge co-creation for more informed, evidence-based decision-making. It provides different functions for different societal actors, making it a versatile tool for promoting sustainable development.

2.4. Selection of indicators and setting of targets

2.4.1. Indicator development and selection within the AlgaProBANOS assessment framework

The APB assessment framework describes a hierarchically structured set of themes and sub-themes across multiple dimensions, including environmental, economic, social and governance considerations (Figure 5). Each sub-theme is composed of several indicators that industry users can select based on their relevance to specific use cases. A preliminary set of indicators has been developed. The full list of indicators and their detailed explanations can be found in Annex 1. While the current table presents a set of sample indicators, it is important to note that our ongoing work, particularly in the activities of Task 1.2, will involve further development of the hierarchy along with the expansion and refinement of this set of indicators. This expansion will take place as the framework is tested and adapted in practice to ensure its practical applicability and relevance.

The APB assessment framework advocates a participatory approach to identify and prioritise the key sustainability aspects for different algal cases within the APB sustainability framework. This method facilitates the selection of relevant indicators, ensuring a comprehensive and inclusive assessment process. This collaborative approach will help to enhance the relevance, legitimacy and credibility of the assessment process, and the practical applications of results in real-world scenarios (EEA and Eckley, 2001). The participatory approach is implemented through workshops, focus groups or interviews, depending on the complexity of the case in hand and nature of the problem/system being studied. Structured or simple problems are characterised by consensus on relevant norms, values, and known knowledge, facilitating agreement among stakeholders on defining and solving the problem. Conversely, unstructured, wicked, or complex problems arise when stakeholders strongly disagree on problem definition and solution approaches, accompanied by uncertainty and contention regarding the reliability of the relevant knowledge (Termeer et al., 2019). Hisschemöller and Hoppe's (1996) quadrant of four archetypal policy problems can inform degree of participation required to effectively address problems (Figure 6). Thus, depending on the nature of the product system and associated contested issues, varying degrees of stakeholder participation will be required to define an appropriate sustainability context and assessment approach (Potting et al., 2022).

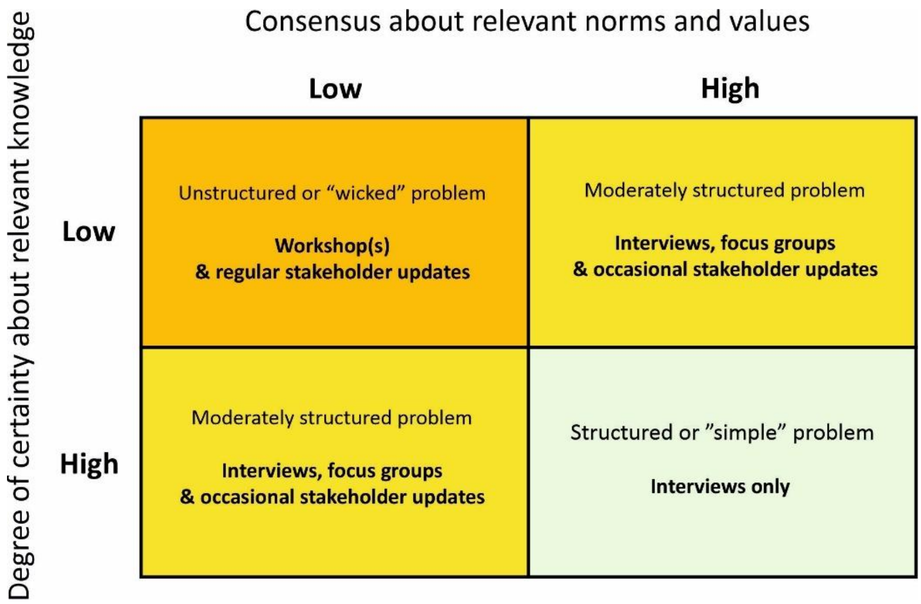

Figure 6. *Quadrant of four archetypal policy problems adapted from Hisschemöller and Hoppe (1996), highlighting the need for varying degrees of participation and information exchange with relevant stakeholders determined by the nature of the problem at hand.*

Within the indicator table, each sub-theme can potentially accommodate an unlimited number of specific indicators. However, industry users are encouraged to exercise discretion in selecting the most appropriate indicators for each sub-theme based on their specific use cases and objectives. This flexibility allows for a tailored approach to meet the specific needs and objectives of different stakeholders. Our overarching goal is to ensure that all dimensions, themes and sub-themes are covered when conducting sustainability assessments. The framework acknowledges that evaluating every aspect of sustainability demands considerable time and resources, which many industry participants may not have the capacity to implement comprehensively. Therefore, instead of attempting to address the full spectrum of sustainability, we suggest that the industry concentrate on a core set of essential indicators for algae value chains; for instance, 10 ReCiPe method indicators from the LCA, supplemented by select socio-economic and governance indicators. In addition, we provide a comprehensive list of recommended indicators for those who can engage more deeply. This approach enables us to effectively assess levels of sustainability both within and across dimensions. By maintaining a robust and adaptable set of indicators, the AlgaProBANOS assessment framework is ready to support informed decision-making and promote sustainability throughout the algae-based value chains in the Baltic and North Sea region.

The framework is designed to enable users to efficiently gather information on a critical number of issues that are representative of the broad range of sustainability considerations in value chains. It strikes a balance between ease of use and the complexity inherent in sustainability assessments. The aim is to provide a pragmatic tool that simplifies the assessment process without reducing the complexity of the sustainability challenges it seeks to address. This balance is crucial, as oversimplification could undermine the reliability of sustainability claims, particularly in a sector as emerging and variable as seaweed and microalgae. Given the nascent state of the sector and the high level of uncertainty, the framework does not rely solely on established methodologies. Instead, it requires a focus on complexity and a commitment to scientific rigour in assessing sustainability. There is explicit recognition of the need for thorough scientific evaluation to substantiate the sustainability claims of the seaweed and microalgae industry.

Regarding the choice of indicators, the framework suggests agreeing on a critical number of indicator types for assessment. However, we also recognised the importance of context specificity in the selection of indicators. Therefore, when focusing on specific case studies, it is appropriate to define geographically relevant and context-specific indicators, as guided by the framework. It advocates a focused approach in which fewer indicators are selected through a careful and participatory process that is relevant to the assessment under consideration. This ensures that the indicators selected are highly relevant and that the necessary expertise is available to explore them in depth. Pragmatism should be a key consideration throughout the study. Where several indicators are available within a group, priority should be given to those that are either easier to measure or for which data are readily available, minimising the need for expert judgement. In situations where key indicators are lacking, it is appropriate to develop new indicators based on available knowledge and data. These indicators should be specific enough to meet the practical needs or concrete objectives of an application, such as assessing the sustainability of a practice. It is equally important to ensure that these indicators are easily measurable, with expert judgement used only in rare and necessary cases.

The APB Sustainability Framework uses a structured set of indicators, each with unique attributes to ensure accurate and consistent assessment. Indicators are grouped into four dimensions - environmental, economic, social or governance - as outlined in a hierarchy of Themes and further subdivided into Sub-themes. Each indicator is defined by an indicator description that specifies what the indicator measures. The methodology for quantifying these indicators varies from laboratory analysis to financial analysis and interviews, as detailed in Calculation details. The unit of measurement is specified for each indicator, with spatial ('local', 'regional', 'global') and temporal ('short term', 'medium term', 'long term') scales identified to contextualise the data. Indicators are linked to relevant Sustainable Development Goals (SDGs) and contributions to the EU Green Deal, requiring thoughtful measurement approaches. Each indicator is also characterised by a baseline, set benchmark and target. Each indicator is anchored with references for validation and provides a standardised current value to facilitate comparability and track progress towards future targets.

When selecting indicators, it is important to take into account the specificity of the site (e.g. setting thresholds locally), recognising that there is no universal approach. For LCA, options include running scenarios tailored to specific sites or adopting more general ones, such as using local versus average European energy mixes. In addition, the scale of operations plays an important role. Small-scale projects are less likely to have significant environmental impacts, while larger projects warrant more detailed assessments due to their potential impacts on ecosystems, including shading, nutrient uptake, dispersal of propagules, and other factors (Tonk et al., 2021). Understanding the limits of upscaling is essential, with studies focusing on how much seaweed cultivation is possible without causing negative impacts or exceeding limits of unacceptable change (Kotta et al., 2022). Suitable locations can be analysed using the ODSS, which provides detailed information on macroalgae production potential in different regions of the Baltic Sea (Armoškaite et al., 2021; Kotta et al., 2022). The environmental compatibility of the site and its impact on other marine activities and ecosystems are of paramount importance, and this varies from site to site, as the requirements and impacts vary considerably from one site to another (Wood et al., 2017; Campbell et al., 2019; Tonk et al., 2021; Banach et al., 2022).

2.4.2. Indicators of sustainability in Life Cycle Assessment

LCA has evolved over several decades as a methodology to systematically evaluate the environmental impacts of products, processes, or services throughout their entire life cycle, from raw material extraction to end-of-life disposal or recycling. Originating in the 1960s and 1970s, LCA gained prominence as environmental concerns grew and industries sought ways to minimise their ecological footprint. There are several different schools of thought about how to conduct LCAs, of which the attributional and consequential approaches are most established. The focus of the former is to attribute environmental burdens to specific processes and inputs in the life cycle of a product or system. It answers the question: "What are the environmental impacts of this product or process as it is?". The latter, consequential approach, serves to analyse the broader system effects and impacts that may occur due to changes in demand, technology, or policy. It aims to answer the question: "What would be the environmental impacts if we changed the way we produce or consume?". The two methodological approaches are suited to different situations and result in a suite of alternative recommended practices (Ekvall, 2019; Schaubroeck et al., 2021). Beyond these two types of LCAs, others too have emerged with different niche aspects, for instance a suite of future oriented LCAs such as ex-ante or prospective LCAs (Arvidsson et al., 2023).

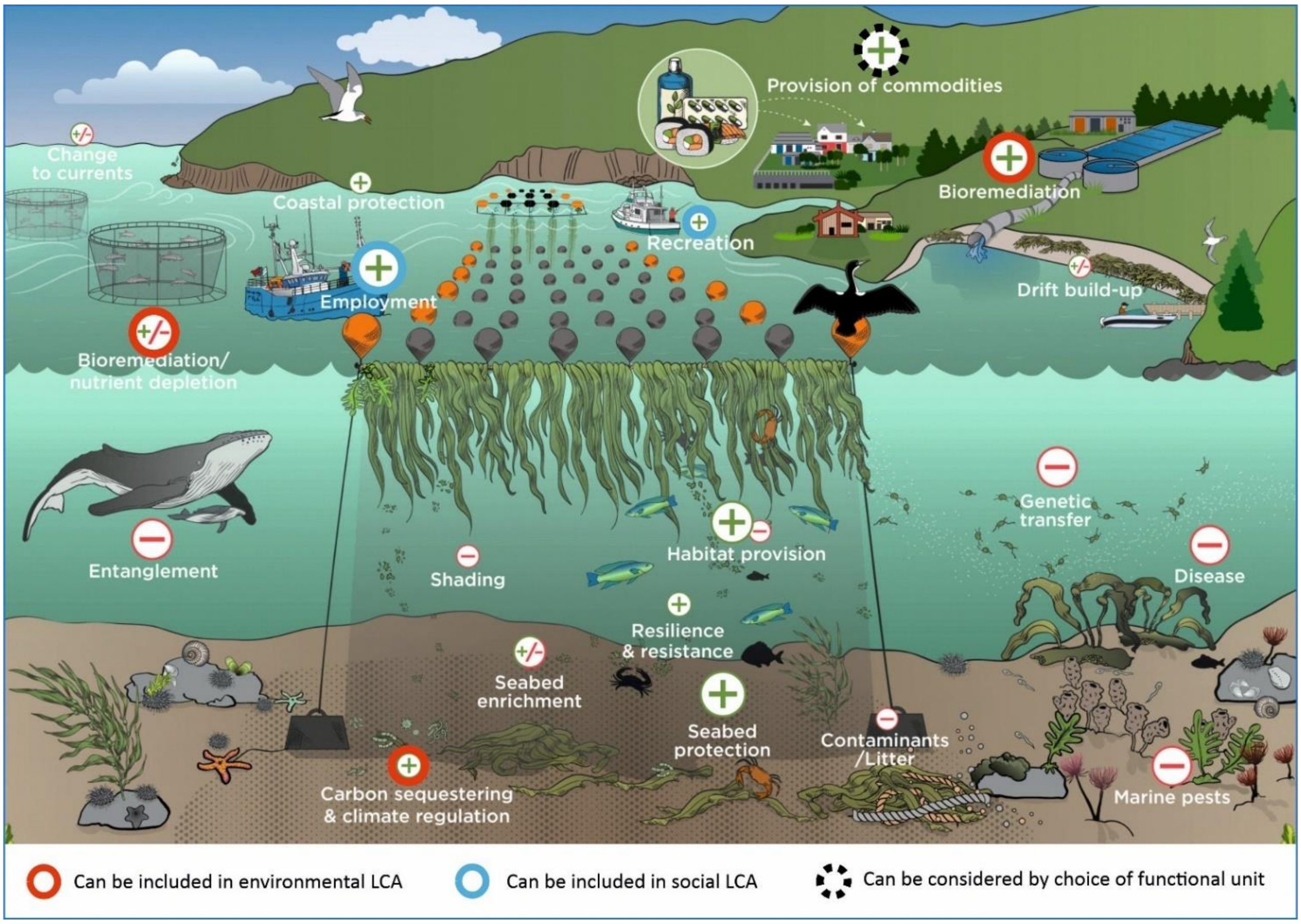

Figure 7. *Overview of environmental processes and human activities included in different LCA methodologies. The likely direction of effect is indicated by large or small '-' or '+' symbols. Adapted from Clark et al. (2021).*

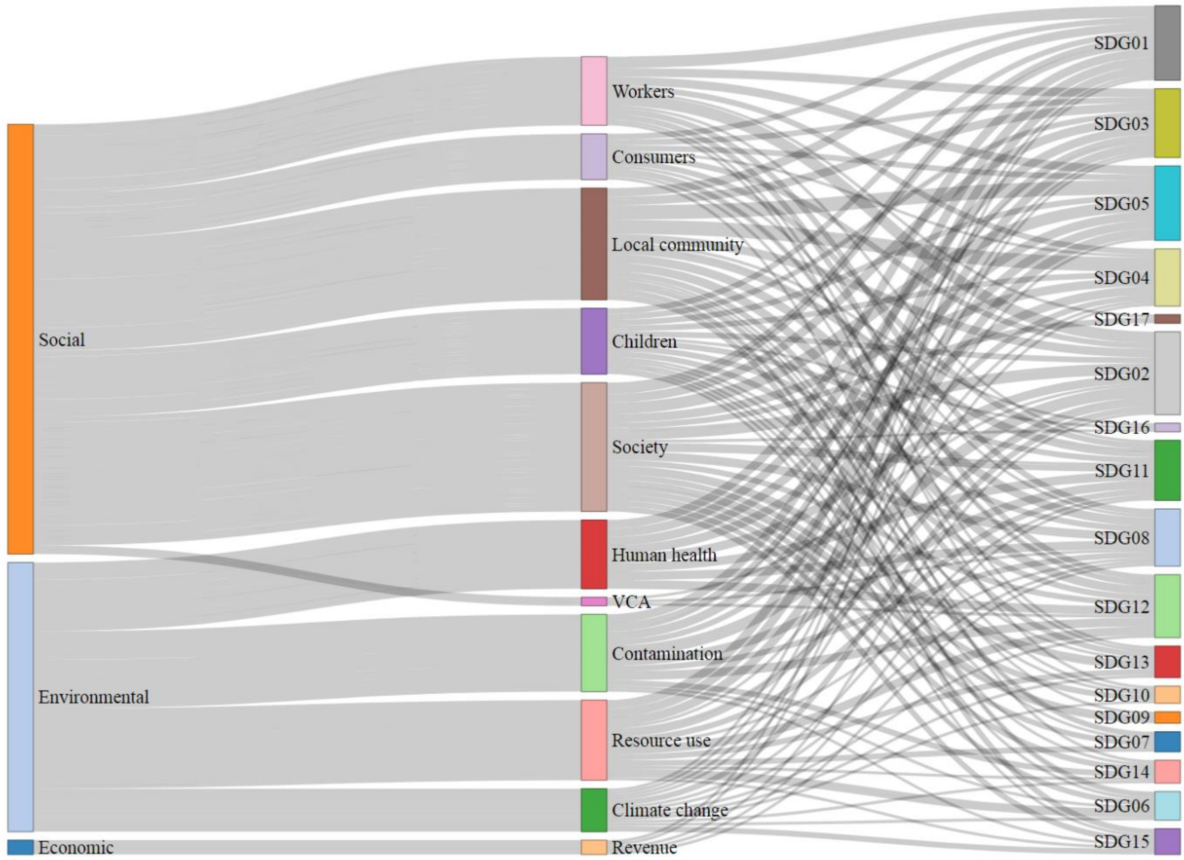

Figure 8. *Mapping the support of LCSA impact categories for achieving the SDGs: an interconnectedness perspective. Adapted from Hannouf et al. (2022).*

Though initially developed as a tool primarily focused on environmental impacts, LCA has since expanded to encompass broader considerations, reflecting a growing recognition of the interconnectedness between environmental, social, and economic dimensions of sustainability. Social LCA (S-LCA) has emerged in view of expanding the scope of LCA to include social aspects such as human health, labour conditions, community well-being, and equity. S-LCA evaluates the social impacts of products or processes on workers, local communities, and society at large, considering factors like occupational health and safety, human rights, and social equity (Figure 7). Similarly, Economic LCA (Eco-LCA) also referred to as Life Cyle Costing (LCC) sheds light on the economic dimensions of sustainability by assessing costs, benefits, and financial implications throughout the life cycle of products or processes. Eco-LCA considers factors such as capital investment, operating expenses, revenue generation, and financial risks to inform decision-making and resource allocation strategies. In addition, Life Cycle Sustainability Assessment (LCSA) is a framework (rather than a method) that integrates environmental, social, and economic dimensions of sustainability. It aims to enable decision-makers to identify trade-offs, synergies, and opportunities for promoting holistic sustainable development. Guinee et al. (2011) specifically differentiate that LCSA should be seen as a framework rather than a specific method, and that it offers the distinct potential to broaden the level of analysis beyond mere products and functions to economy-wide issues, while also deepening the analysis to include spatial, behavioural and economic relations (Guinée, 2016). Ongoing debates and methodological refinements continue to shape LCA practice, ensuring its relevance and effectiveness in addressing contemporary sustainability challenges. The indicator-based assessment approach of LCSA has been compared to the goal-oriented UNSDG framework (Sustainable Development Goals), in which SDG targets were matched up with specific LCA impact category indicators (Wulf et al., 2018). More recently a much more detailed mapping exercise was undertaken by Hannouf et al. (2022) to shed light on the interconnectedness and specific support in progressing towards SDGs that can be offered by LCSA impact categories (Figure 8). In parallel and to support companies to identify SDG hotspots in their organisations, efforts are underway by the UN Environmental Life Cycle Initiative to integrate SDGs into LCA practice using two frameworks: life cycle SDG screening and assessment (Weidema et al., 2020).

In conducting an LCA, various environmental indicators are considered to comprehensively evaluate the environmental impacts associated with a product, process, or service. These indicators encompass a range of environmental aspects such as resource depletion, emissions to air, water, and soil, as well as potential impacts on human health and ecosystems. Core methodologies utilised in LCAs, such as ReCiPe (ReCiPe Midpoint (H) and Endpoint (I) methods), CML (Center for Environmental Studies Method), and others, offer structured frameworks for assessing these environmental impacts. As previously mentioned, these methodologies differentiate between two primary types of indicators: midpoint and endpoint indicators. Midpoint indicators concentrate on direct environmental pressures, such as greenhouse gas emissions and their associated global warming potential. Endpoint indicators, on the other hand, capture broader environmental effects by aggregating data from several indicators.

2.4.3. Setting sustainability targets

The central approach of our study is to establish a unified methodology that simplifies the quantification of sustainability indicators. We will achieve this by setting targets, comparing systems, or assessing progress against a baseline. This will enable a comprehensive evaluation of sustainability across multiple dimensions. Once the targets and baselines have been aligned with the sustainability objectives, this alignment enables us to calculate the percentage of achievement across different sustainability topics and, when these topics are combined, to provide an overarching sustainability assessment. This approach facilitates comparisons across indicators and themes, as all indicators are expressed in the same unit. The first set of indicators and methodologies developed serve to bridge the gap between theory and practice, facilitating informed, evidence-based decision-making to achieve sustainable development goals. By delving deeply into a limited set of carefully selected indicators, the framework aims to provide a robust, scientifically sound basis for assessing the sustainability of micro- and macroalgal value chains.

To accurately assess our progress on the sustainability journey, it is essential to set clear targets and baselines. Setting targets for some indicators is relatively straightforward, while for others it is more challenging. In this context, the APB framework suggests several methods for setting these targets, as described below. Environmental indicators often have well-established regional values that can be smoothly integrated into the framework, such as the WFD thresholds for achieving good environmental status. If our indicators fall within acceptable thresholds, this means that our development is sustainable. However, when assessing the environmental impact of algae-based activities, it is important to consider only those environmental impacts that are directly related to these activities. It is inappropriate to attribute poor environmental quality to macroalgal farming when environmental degradation is primarily caused by other human pressures. It is therefore crucial to choose appropriate indicators when assessing these impacts. For example, in the context of macroalgal farming, an indicator related to nutrient sequestration may be more relevant than measuring environmental nutrient concentrations in water or sediment. The latter often reflects the influence of other human pressures in the area.

For some indicators, targets may not be set or may not be known. In such cases, it is useful to look at the latest policy and environmental management documents for guidance or to develop targets collaboratively. An effective approach is the community of practice approach, where all relevant stakeholders come together to define a common vision. This can be achieved through structured questionnaires, workshops or similar methods to ensure that objectives are set in a collaborative and informed way.

Alternatively, in the absence of indicator targets, several other methods and approaches can be used to set them effectively. It is possible to compare the case's performance with similar initiatives or industry standards, using successful entities as benchmarks. Seeking advice from subject matter experts, scientists or professionals with expertise in the relevant field can provide valuable insights into setting realistic and scientifically sound targets. Including community participation in the assessment, particularly for social tolerance indicators, ensures alignment with community expectations and experiences and promotes a more inclusive and comprehensive sustainability assessment. Analysing historical data and trends, consulting international standards, conducting research and data analysis, and applying sustainability science methodologies are all useful approaches. It is also possible to implement adaptive management, where targets are initially set and later adjusted based on ongoing monitoring and evaluation. Adopting a philosophy of continuous improvement involves regularly reviewing and revising targets in response to evolving knowledge and circumstances. The choice of method or combination of methods should be based on the specific context, data availability and indicator characteristics to ensure well-founded, achievable targets that are consistent with sustainability objectives.

2.5. Aligning Life Cycle Assessments within micro and macroalgal value chains

LCAs of micro- and macroalgae value chains have been conducted for over a decade, with the majority having been produced with a focus on cultivation and bioenergy, though more recently diversifying toward food, feed, materials, biostimulants and fertiliser. Methodological variations arise due to diverse objectives and contexts in LCAs, including functional units, system boundaries, environmental impact categories, and characterisation methods. For example, Langlois et al. (2012) used a functional unit of "a 1km trip with a gas-powered car" and the ReCiPe method, while Alvarado-Morales et al. (2013) focused on *Laminaria digitata* biogas production, using "one tonne dry seaweed biomass" and the EDIP 2003 method. Despite disparities, common themes emerge for both macro- and microalgae LCAs: yield's pivotal role in mitigating impacts, and the impact hotspots resulting from energy intensive land-based cultivation systems and post-harvest processing such as drying (Braud et al., 2023). For macroalgae, additional hotspots in the literature include material infrastructure at sea, and depending on how sea transport is modelled, transport at sea also can be a key hotspot.

In reviewing LCAs of salmonid production, Philis et al. (2019) noted methodological variance and low transparency hindering statistical comparisons. Henriksson et al. (2021) highlighted inconsistencies in review protocols for dietary LCAs, suggesting the need for harmonisation. Ziegler et al. (2022) emphasised the importance of harmonising LCA methods and data for comparability. The Product Environmental Footprint (PEF) represents progress but lacks Product Category Rules (PCRs) for low trophic aquaculture (e.g., seaweed), for land-based algae production, and for associated product systems.

In order to ensure comparability of the LCA work conducted in AlgaeProBANOS, an LCA methodology discussion group is being developed to coordinate algae LCA practices across a number of ongoing algae projects funded by the EU, notably CIRCALGAE, TETRAS, LOCALITY and SeaMark. Key methodological aspects will be discussed, and suitable practices will be recommended to ensure robust and lasting results can be produced from these projects, including for:

- Defining goals and scopes, notably the use of multiple functional units including mid-point functional units (e.g. per unit fresh biomass at harvest gate) for comparability;
- Strategies to quanitfy and assess environmental benefits, e.g. how to account for biogenic carbon, nutrient uptake and other bioremediation;
- Life Cycle Inventory data collection and sharing;
- Recommendations for impact category selection;
- Recommendations for managing system boundaries and burden allocations;
- Recommendations for how to report and make LCA data available and useful for subsequent use.

This process will include an evaluation of the latest PEFCRs (Product Environmental Footprint Category Rules) for similar sectors/products and aim to adapt the proposed approaches to be in line with other standards that are being developed.

2.6. Quantifying sustainability: a multi-dimensional approach across environmental, economic, social, and governance dimensions

This section describes the methodology for assessing sustainability across the four dimensions and explains how the framework derives the overall sustainability score for the value chain or product under consideration (Figure 9). The primary objective of the framework is to establish a straightforward link between different dimensions (environmental, economic, social and governance) by incorporating indicator targets or baselines and calculating the percentage of target achievement in order to standardise different indicators into a single unit. Within each dimension, a more sophisticated methodology can be applied where appropriate. In addition, some tools such as LCA span multiple dimensions, allowing simultaneous and integrated assessments of different aspects of sustainability.

The framework recognises the paramount importance of **environmental constraints and limits** imposed by the natural environment. To address these constraints, the framework includes tolerance indicators that cover all sub-themes within the environmental dimension. These tolerance indicators assess whether any of the environmental sub-themes exceed the sustainability limits attributable to the specific value chain or product under consideration. If a sub-theme exceeds these sustainability limits, it is assigned a value of 0. Conversely, if sustainability levels remain within acceptable limits, it is assigned a value of 1. Environmental indicators classified under tolerance indicators often have clearly defined thresholds for acceptable and unacceptable levels, as seen with the WFD and MSFD indicators. When threshold values are not yet established (e.g. in the case of microplastic pollution) these can be determined using the most recent scientific research, policy documents, and environmental management guidelines for direction, or through collaborative target setting (for more details, refer to the subsection above).

The average of key environmental constraints across the sub-themes is then calculated to give the overall score for the tolerance indicators, ranging from 0 to 1. To address these environmental challenges, it may be necessary to implement process improvements or mitigation measures in the natural environment. It is important to note that these challenges cannot be offset by improving sustainability in other dimensions, such as social, economic and governance. Importantly, when assessing tolerance indicators, it is essential to consider only those pressures that are directly attributable to the activity under consideration, and to avoid penalising e.g. macroalgal farming for impacts caused by unrelated human activities in the same region.

When assessing value chains in the context of AlgaeProBANOS Task 1.2, it is crucial to assess whether the framework requires the introduction of **tolerance indicators for other dimensions** (social, governance and economic). Although certain issues may not be directly relevant to the territory of the EU, the reality of globalisation demands that these aspects be taken into account. For example, child labour is clearly intolerable and should not be assessed in the same way as performance indicators. Similar concerns may arise in other dimensions, underlining the need for an adapted approach to sustainability assessment.

In addition, the framework includes **performance indicators** across all dimensions - environmental, social, economic and governance. The assessment is carried out using a core set of essential indicators for algal value chains. Optionally, for those able to undertake a more detailed analysis, an extended assessment can be carried out using our comprehensive list of recommended indicators. However, in both cases, as the framework maintains a fixed number of sub-themes, the results are easily comparable across studies and cases.

The value of these performance indicators is compared to targets and baselines derived from different policy documents or gathered through participatory stakeholder interactions, standardising performance indicators on a common scale. If the indicator is equal to the baseline, it receives a score of 0. If the indicator meets the target, it receives a score of 100, and if the target is exceeded, the score may actually exceed 100, reflecting the degree of overachievement (e.g. a score of 200 if the target is exceeded twice). Importantly, the framework preserves the original units of the indicators, facilitating various transformations of scale and/or further refinement of the analyses. Once all the performance indicators have been assessed, the overall performance within each dimension is calculated as the average performance across these indicators. This process must be carried out separately for each dimension, as different dimensions are likely to have different numbers of sub-themes. This hierarchical averaging ensures a balanced calculation design, taking into account that some sub-themes may include several indicators. When tools that span multiple dimensions, such as LCA analysis, are employed, the LCA is complemented by a core set of socio-economic and governance indicators and hierarchical averaging is performed at the appropriate levels (tool and dimension). Finally, the overall performance for each of the four dimensions is the average of the performance indicators within each dimension.

The framework refrains from assessing overall sustainability performance across all four dimensions to produce a single score for the value chain or product in question. Such an approach would oversimplify sustainability assessments and potentially mislead readers. Even assigning a single score to each dimension is an oversimplification. It is essential that users of the assessment have easy access to the results at the more detailed levels of the framework hierarchy. To achieve this, the AlgaeProBANOS sustainability assessment framework will be integrated with the ODSS tool (https://gis.sea.ee/odss). This integration allows for dynamic graphical representations of sustainability aspects at all hierarchical levels, providing a more holistic understanding of the value chain under consideration (Figure 10).

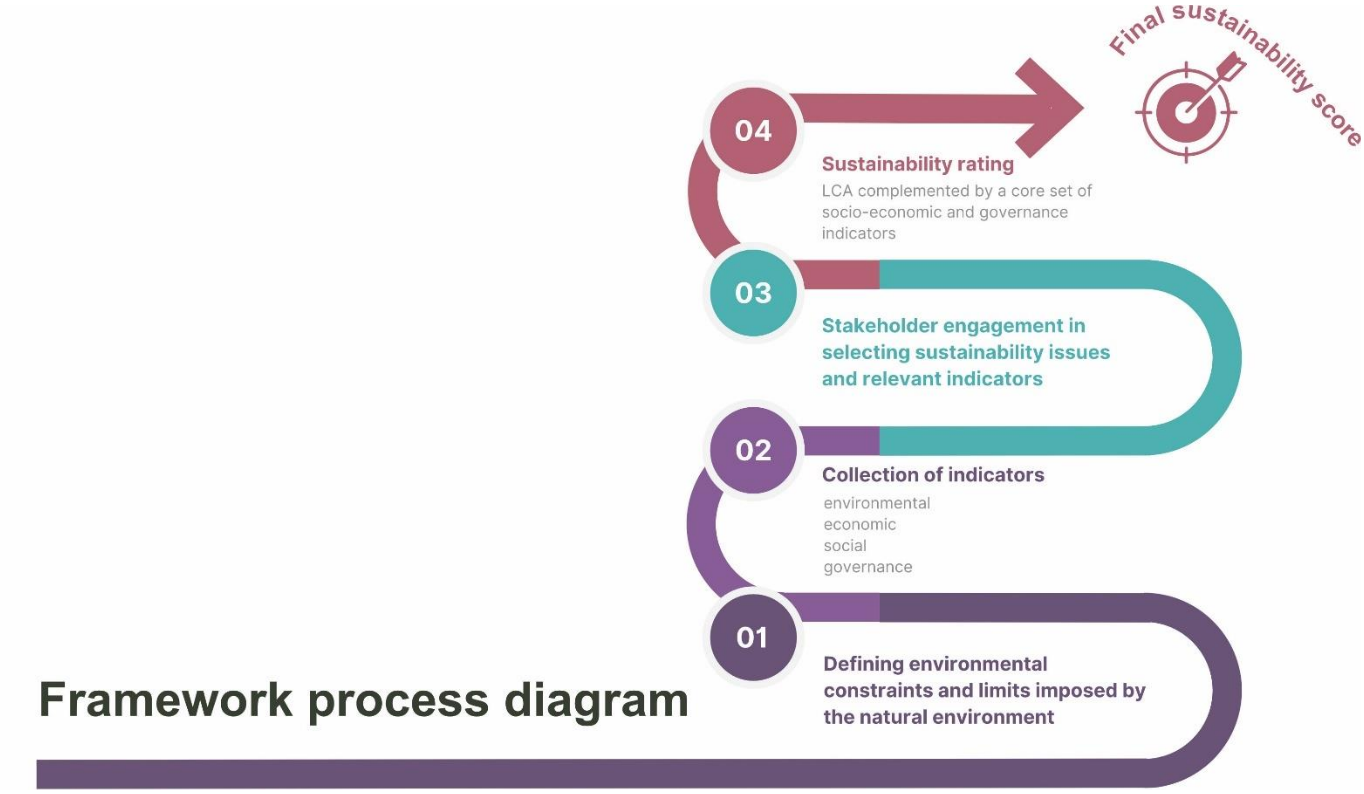

Figure 9. *AlgaeProBANOS Sustainability Assessment Process: (1) The assessment framework starts with the identification of environmental constraints and natural limits that guide the sustainable development of algae value chains. (2) This is followed by a collaborative effort to collect comprehensive indicators across environmental, economic, social and governance dimensions, ensuring a full spectrum analysis of sustainability. (3) Stakeholder engagement is crucial at this stage, enabling the definition of key sustainability issues and the selection of relevant indicators, as well as ensuring that the assessment meets both scientific and societal expectations. (4) The process*

progresses through a careful comparison of the performance of the algae value chain against established baselines and targets, using tolerance indicators to ensure that environmental thresholds are not exceeded, thereby safeguarding the integrity of the ecosystem. At the heart of the assessment is the application of Life Cycle Assessment (LCA) tools that integrate and assess impacts across different sustainability dimensions, enriched with socio-economic and governance insights. This multi-dimensional analysis culminates in a sustainability score that reflects the environmental, socio-economic and governance performance of the algae value chain. Uncertainty analysis within the LCA framework further strengthens the assessment by addressing variable factors and identifying opportunities for optimisation. This condensed yet thorough assessment process, underpinned by stakeholder collaboration and advanced LCA analyses, underlines the commitment to a sustainable future for algae cultivation and processing, ensuring a balanced approach to environmental stewardship and socio-economic development.

Uncertainty analysis will be built into the LCAs. Key parameters that vary in practice (e.g. temperature control fluctuates throughout the year) will be subject to ranges/means, and impact hotspots will be re-examined in LCA model iterations to double-check results and explore optimisation strategies/alternatives. For indicators covering other dimensions, uncertainty can be explored and quantified either through direct assessment of the assessment errors of the indicator, or through qualitative assessment using a participatory approach. The latter involves stakeholders in discussions to assess the reliability of data and underlying assumptions, providing a comprehensive view of the potential variability of sustainability indicators across socio-economic and governance dimensions.

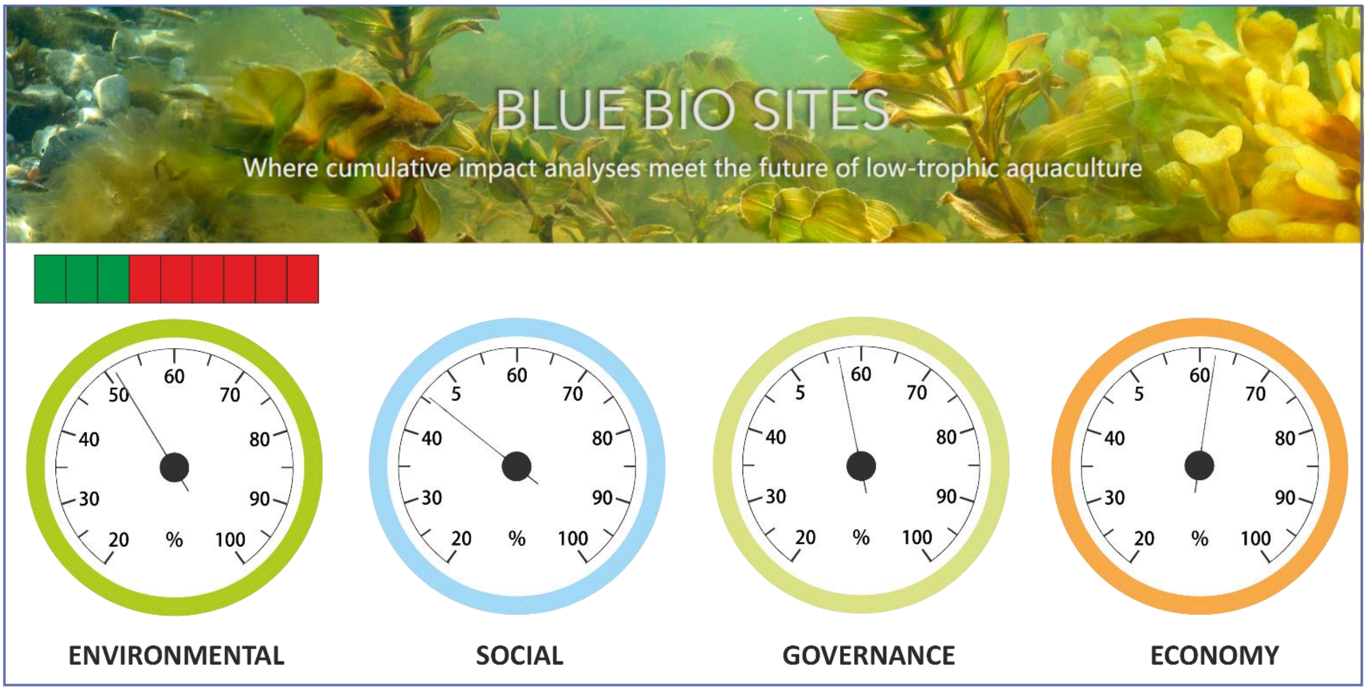

Figure 10. *When implemented in the BlueBioSites portal (ODSS tool), the AlgaeProBANOS sustainability assessment framework graphically displays aggregated scores across different dimensions, as well as consolidated scores for themes, sub-themes and various indicators. This provides a detailed sustainability assessment of the analysed value chain. The graph shows that only three out of nine tolerance indicators meet the criteria, while the rest exceed the environmental carrying capacity. The dashboard includes gauges that reflect the overall sustainability score for each dimension. By selecting one of these dimensions, users can zoom in to see the assessment results at finer hierarchical levels, down to individual indicators.*

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