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Perspectives on aquaculture's contribution to the Sustainable Development Goals for improved human and planetary health

Max Troell[1,2] | Barry Costa-Pierce[3] | Selina Stead[4] | Richard S. Cottrell[5] | Cecile Brugere[6] | Anna K. Farmery[7] | David C. Little[8] | Åsa Strand[9] | Roger Pullin[10] | Doris Soto[11,12] | Malcolm Beveridge[13] | Khalid Salie[14] | Jorge Dresdner[11,12] | Patricia Moraes-Valenti[15] | Julia Blanchard[16,17] | Philip James[18] | Rodrigue Yossa[19] | Edward Allison[19,20] | Christopher Devaney[8] | Uwe Barg[21]

[1]The Beijer Institute, Royal Swedish Academy of Sciences, Stockholm, Sweden

[2]Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden

[3]Graduate Program in Ocean Food Systems, School of Marine Environmental Sciences, University of New England, Biddeford, Maine, USA

[4]Faculty of Environment, University of Leeds, UK

[5]Institute for Marine and Antarctic Studies, College of Sciences and Engineering, University of Tasmania, Hobart, Tasmania, Australia

[6]Soulfish Research and Consultancy, York, UK

[7]Australian National Centre for Ocean Resources and Security, University of Wollongong, Wollongong, New South Wales, Australia

[8]Institute of Aquaculture, University of Stirling, Stirling, Scotland, UK

[9]IVL Swedish Environmental Research Institute, Fiskebäckskil, Sweden

[10]The Irish Sea Centre Ltd, Isle of Man, UK

[11]Interdisciplinary Center for Aquaculture Research, INCAR, Concepción, Chile

[12]Universidad de Concepcion, Puerto Montt, Chile

[13]Faskally, Dollerie, Crieff, Perthshire, Scotland, UK

[14]Department of Animal Sciences, Faculty of AgriSciences, Stellenbosch University, Matieland, South Africa

[15]Aquaculture Center of Sao Paulo State University - CAUNESP/UNESP, Jaboticabal, Sao Paulo, Brazil

[16]Centre for Marine Socioecology, University of Tasmania, Hobart, Tasmania, Australia

[17]Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, Australia

[18]Norwegian Institute of Food (NOFIMA), Fisheries and Aquaculture Research, Tromsø, Norway

[19]WorldFish, Jalan Batu Maung, Penang, Malaysia

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[20]University of Washington, Seattle, Washington, USA

[21]Food and Agriculture Organization of the United Nations (FAO), Rome, Italy

Correspondence
Max Troell, The Beijer Institute, Royal Swedish Academy of Sciences, Stockholm, Sweden.
Email: max@beijer.kva.se

Abstract

The diverse aquaculture sector makes important contributions toward achieving the Sustainable Development Goals (SDGs)/Agenda 2030, and can increasingly do so in the future. Its important role for food security, nutrition, livelihoods, economies, and cultures is not clearly visible in the Agenda 21 declaration. This may partly reflect the state of development of policies for aquaculture compared with its terrestrial counterpart, agriculture, and possibly also because aquaculture production has historically originated from a few key hotspot regions/countries. This review highlights the need for better integration of aquaculture in global food system dialogues. Unpacking aquaculture's diverse functions and generation of values at multiple spatiotemporal scales enables better understanding of aquaculture's present and future potential contribution to the SDGs. Aquaculture is a unique sector that encompasses all aquatic ecosystems (freshwater, brackish/estuarine, and marine) and is also tightly interconnected with terrestrial ecosystems through, for example, feed resources and other dependencies. Understanding environmental, social, and economic characteristics of the multifaceted nature of aquaculture provides for more context-specific solutions for addressing both opportunities and challenges for its future development. This review includes a rapid literature survey based on how aquaculture links to the specific SDG indicators. A conceptual framework is developed for communicating the importance of context specificity related to SDG outcomes from different types of aquaculture. The uniqueness of aquaculture's contributions compared with other food production systems are discussed, including understanding of species/systems diversity, the role of emerging aquaculture, and its interconnectedness with supporting systems. A selection of case studies is presented to illustrate: (1) the diversity of the aquaculture sector and what role this diversity can play for contributions to the SDGs, (2) examples of methodologies for identification of

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aquaculture's contribution to the SDGs, and (3) trade-offs between farming systems' contribution to meeting the SDGs. It becomes clear that decision-making around resource allocation and trade-offs between aquaculture and other aquatic resource users needs review of a wide range of established and emergent systems. The review ends by highlighting knowledge gaps and pathways for transformation that will allow further strengthening of aquaculture's role for contributing to the SDGs. This includes identification and building on already existing monitoring that can enable capturing SDG-relevant aquaculture statistics at a national level and discussion of how a cohesive and comprehensive aquaculture strategy, framed to meet the SDGs, may help countries to prioritize actions for improving well-being.

KEYWORDS
human health, poverty, sustainable development

1 | INTRODUCTION AND RATIONALE

The 2030 Agenda with its 17 Sustainable Development Goals (SDGs) (UN General Assembly, 2015) presents humanity with a pathway to a more prosperous, equitable, and sustainable future. It aims not only to eradicate poverty and hunger and improve health and nutrition, but also to reduce inequalities and build peaceful, just, and inclusive societies while remaining within planetary boundaries. The world's population is projected to reach 9.7 billion by 2050 (United Nations, World Population Prospect 2019) and global demand for animal proteins may rise by as much as 88% (Cottrell et al., 2018; Searchinger et al., 2018), much of which will be consumed at levels exceeding guidelines for healthy eating. How to feed a growing population a healthy (nutritious) and sustainable diet is one of the greatest challenges facing humanity today (Willet et al., 2019) and the food system connects to the SDGs in multiple ways through resources, environments, economics, and people's well-being.

Global expansion of diverse food systems has provided for nutrition, livelihoods, and sources of income but has also come with environmental and social costs, including water scarcity, soil degradation, periodic droughts, biodiversity loss, pollution, overfishing, and greenhouse gas emissions (Gordon et al., 2017; Willet et al., 2019). The global food system is responsible for the yearly release of 25% of all greenhouse gases, occupies 50% of all ice-free land, and is responsible for 75% of global consumptive water use and is an important contributor to eutrophication (FAO, 2011; Poore & Nemecek, 2018). Such impacts not only reduce the potential and capacity of the Earth's life-support systems to provide food and to realize SDGs, but also jeopardizes overall human well-being (Steffen et al., 2015). Increased terrestrial meat consumption accelerates climate change, deforestation, and pollution of both terrestrial and aquatic ecosystems (Machovina et al., 2015; Poore & Nemecek, 2018; Springmann et al., 2018). Agriculture and livestock husbandry dominate decisions about global food system development, but aquatic foods, which are highly nutritious and can have a smaller environmental footprint than other animal source foods, are slowly making their way into high-level food-related decision-making (Bennett et al., 2021; Costello et al., 2020; Gentry et al., 2017).

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The seafood sector's importance for nutrient and food security is increasingly being stressed for many countries with coasts and freshwater systems (Béné et al., 2016; Bennett et al., 2018; Bennett et al., 2021; HLPE, 2014). Recent reviews have drawn attention to the need to derive more proteins from aquatic sources by restoring fish stocks and increasing sustainable aquaculture development (Costello et al., 2019; Hicks et al., 2019; Willett et al., 2019). The summary statement given during the launch of the 2021 UN Nutrition report[1] clearly emphasizes this importance—"There can be no food system transformation without aquatic foods" (G. Johnstone, Worldfish[2]).

Captured or cultured, from freshwater or marine ecosystems, aquatic foods play an important role in food security and nutrition for billions of people and support livelihoods, economies, and cultures all around the world (FAO, 2022). Aquatic foods, and in particular the expansion of aquaculture, may become more important as the world seeks to create just food systems that support the health of people and the planet (Bennett et al., 2018, 2019; FAO, 2022). Global per capita seafood consumption has increased from 9.0 kg (live weight equivalent) in 1961 to 20.2 kg in 2020 (FAO, 2022) and provides about 17% of the world's intake of animal proteins consumed (7% of all proteins) (FAO, 2022). Fish and other seafood provide about 3.3 billion people with almost 20% of their intake of animal protein (FAO, 2022).

Seafood is the most traded food commodity in the world (by value), where a relatively small number of seafood species and countries dominate global trade. Salmon, shrimp, catfish, and tilapia collectively represent approximately one third of internationally traded seafood by value (8% by volume), of which 80%–90% of the fish are farmed (FAO, 2020a, 2020b). However, almost 90% of all aquaculture output enters domestic markets in Asia—where most of global production and consumption takes place (Belton et al., 2018). Production (volumes and types) and values of the aquaculture sector differ significantly between different regions within Asia (Naylor, Hardy, et al., 2021; Naylor, Kishore, et al., 2021). Stagnating and dwindling catches create uncertainties regarding to what extent global capture fisheries can expand, as roughly one third of the world's fisheries are currently fished beyond sustainable limits (FAO, 2020a, 2020b). Recent work suggests that the expansion potential could be substantial if fisheries governance improves (Costello et al. 2020), something that may prove challenging considering the extent of overfishing and enforcement challenges. Regardless of capture fisheries potential, the expectation that aquaculture will be responsible for the bulk of future seafood supply is very high. At the global level, already more than 80 million tonnes (Mt) of fish and shellfish and 30 Mt of seaweeds originate from around 400 farmed species, reared in highly diverse systems under diverse conditions (FAO, 2020a, 2020b; Metian et al., 2019; Naylor, Hardy, et al., 2021; Naylor, Kishore, et al., 2021). Fisheries and aquaculture related activities also support the livelihoods of more than 120 million people worldwide, the majority of whom live in economically developing countries.

Meeting the 2030 global agenda for sustainable development will be challenging and will require partnership, innovation, and holistic and harmonized approaches and strategies at multiple scales. Aquaculture can be well-positioned to be part of the solutions but progress toward its contribution to achieving the SDGs is dependent on good governance at all levels (local, national, regional and international) of decision-making (Farmery, Allison, et al., 2021; Farmery et al., 2020; Farmery, White, et al., 2021; Hambrey, 2017; Stead, 2019). While aquaculture brings opportunities to contribute to most of the SDGs, there are many factors influencing what the outcomes for SDGs will be from different types of aquaculture systems in different situations. Some aquaculture systems (e.g., of naturally low trophic species, including extractive species) have relatively low environmental footprints compared with many terrestrial animal production systems and can even provide environmental restorative functions, but as with all food systems different trade-offs will result, for example, environmental performance versus societal benefits.

Countries may be uncertain about where to focus efforts and resources when deciding on what type of aquaculture to invest in, whether new or an expansion of existing industries, large or small scale, and where it can make the greatest contribution. However, the importance of underlining financial viability should be considered as a point of departure. Similarly, policies that integrate social perceptions that influence peoples' attitudes toward aquaculture thus eliciting positive behaviors determine acceptability and success of the sector in an area. Understanding the

[1]FAO, IFAD, UNICEF, WFP and WHO. 2020. The State of Food Security and Nutrition in the World 2020. Transforming food systems for affordable healthy diets. Rome, FAO. https://doi.org/10.4060/ca9692en.

[2]Plenary speech at the launch of the UN Nutrition paper on "The role of aquatic foods in sustainable diets." Webinar, May 7, 2021.

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extraordinary diversity of aquaculture, both species and systems, becomes crucial for development of the sector's present and future contributions to the different SDGs.

Having a broader value-chain perspective will be imperative for gaining deeper insights about its overall contribution and for outcomes from investments and transformation efforts (Phillips et al., 2016). In addition, an understanding of "framing conditions" (Krause et al., 2015) and the role of "contexts" in which aquaculture development will be embedded are needed in order to realize how aquaculture can deliver on the SDGs, that is, "the rules of the game" (Figure 1). Framing conditions encompass political (including governance), economic, and environmental factors acting on decisions (governments, companies, NGOs, donors, and individuals) about aquaculture's possibility and suitability versus other viable options (i.e., for terrestrial food production or other desired outcomes) as well as selection of specific types (species/systems) of aquaculture, resulting in different potential outcomes. Contexts involve how the production and aquaculture value chains will generate benefits (and impacts), framed by both local characteristics and global connections of a society and the environment, that is, its relationship to distant resource systems (e.g., feed ingredients) and markets (export benefiting consumers elsewhere, etc.). Figure 1 is a conceptual representation of an "iterative process" where the outcomes from aquaculture development are benchmarked against some targets—like the SDGs and their indicators—and are then circulated back and influence decisions and potentially also the framing conditions enabling certain aspirational developments.

While developing aquaculture production is gaining increased interest, less attention has been paid to understanding how the sector can be better coordinated and governed, especially in a cohesive strategy to fully harness its potential to help meet many of the SDG targets (Stead, 2019). The formulation and content of the SDGs have also not captured the potential contributions that the diverse and complex aquaculture sector can offer. This gap partly reflects the infancy around the development of policies for aquaculture compared with its terrestrial counterpart, agriculture. Important for policy development and implementation is that an overemphasis on aquaculture production growth, rather than equitable distribution of benefits (Brugere et al., 2021), may reduce its positive contribution to the SDGs, especially to food security, nutrition, sustainable production and consumption, and human well-being.

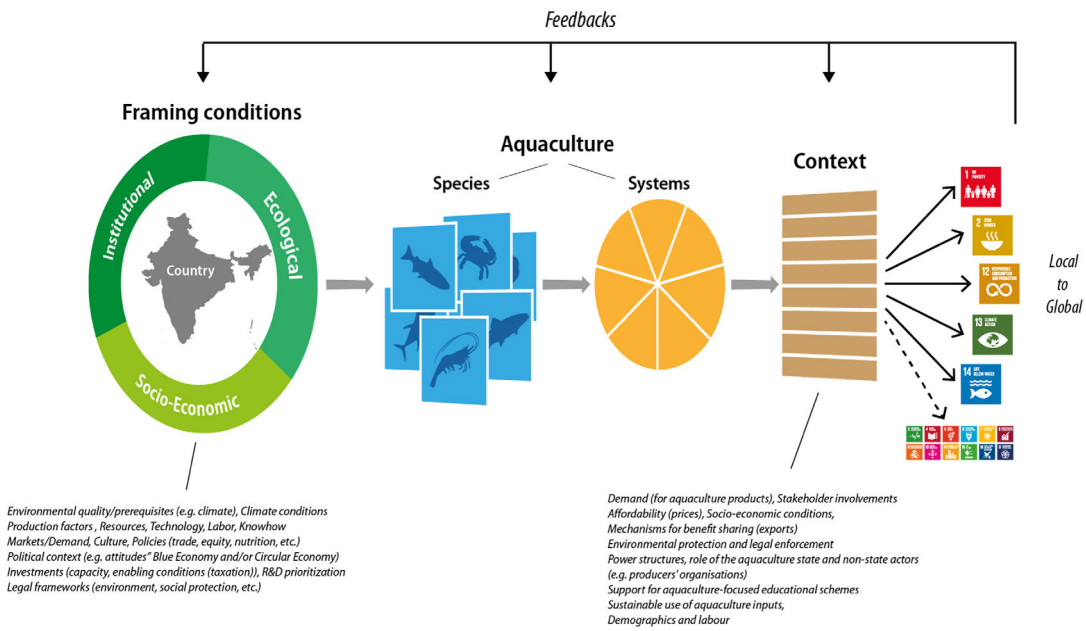

FIGURE 1 Conceptual figure illustrating what is "shaping" aquaculture's contribution to the Sustainable Development Goals ("rule of the game") and also the feedback enabling adjustments for reaching desired targets/outcomes.

Thus, production/export orientation of some forms of aquaculture may risk limiting overall potential positive contributions to the SDGs, for example, if competing with food resources and benefits from production are not being shared (Belton et al., 2020; Farmery, Allison, et al., 2021; Farmery, White, et al., 2021).

Greater SDG contributions are usually achieved when aquaculture production is linked with distribution and contribution to food and nutrition, either from consumption, or increased income that is spent on healthy food. This outcome, however, may not happen "naturally": considerations of equity and benefit sharing need to be built into the governance of the aquaculture sector if the benefits of aquaculture production are to result in more than tons and dollar values—that is, contributing more broadly to the SDGs (Brugere et al., 2021; Eriksson et al., 2018). As illustrated in Figure 1, aquaculture's contribution to improved nutrition and health outcomes is conditioned by the social, economic, and institutional context within which it occurs: forms of aquaculture taking place in a context of harmonized international trade and economic policies, with equity concerns at the heart, are more likely to achieve improved health outcomes (Gephart et al., 2020). Aquaculture represents an ideal candidate—as a diverse and young sector—to demonstrate the positive outcomes that can be generated by integrating common benefits of a farming system to contribute to multiple policies relevant to achieving the SDGs.

This review attempts to unpack and increase the understanding about aquaculture's present and future potential contribution to the SDGs. Aquaculture is presented as a unique sector that transcends all aquatic ecosystems (freshwater, brackish/estuarine, and marine) and is also tightly interconnected with terrestrial systems. This is not a comprehensive review but aims at identifying key questions and knowledge gaps related to understanding the sector's contribution to the SDGs to inform science policy priorities. The review consists of a literature survey based on the SDGs indicators and how they link to aquaculture. A selection of case studies is presented to illustrate: (1) the diversity of the aquaculture sector and what role this diversity can play for contributions to the SDGs, (2) mapping of methodologies and identification of delivery of the SDGs to aid decisions about trade-offs between farming systems' contribution to the SDGs. The uniqueness of aquaculture's contributions to the SDGs is discussed to capture a richer context for debates on the future direction of relevant policies. The discussion includes species/systems diversity, the role of emerging aquaculture species/systems, interconnectedness between supporting systems, and resilience properties. This review explains how some of the lesser known types of sustainable aquaculture and their wider benefits can assist countries when making trade-offs between aquaculture and other aquatic resource users competing for access to the same aquatic environment or resources. The review ends by identifying pathways for transformation that will allow further strengthening of aquaculture's role for contributing to the SDGs, including how a cohesive and comprehensive aquaculture strategy framed to meet the SDGs may help countries to prioritize for improving health and well-being.

2 | UNDERSTANDING THE SDGs, THEIR USE, AND ROLE FOR HUMAN AND PLANETARY HEALTH

The 2030 Agenda for Sustainable Development provides a high-level policy and monitoring framework, designed to stimulate and coordinate the activities of national governments, the UN, and other intergovernmental organizations, civil society organizations, and other institutions. The 2030 Agenda comprises 17 goals and 169 targets (UN General Assembly, 2015). It advocates sustainable development in all of its three dimensions (economic, social, and environmental), for all countries (developing and developed), based on the fundamental recognition and protection of human rights, dignity, and equity, today and into the future (UN General Assembly, 2015). Its focus is on the elimination of hunger and reduction of poverty and inequality (opportunity, resource access, by gender, age, and ethnic diversity), innovation and business development, and also social protection. It promotes energy efficiency and clean energy and seeks to increase resilience to climate change, market volatility, and political instability. Reduction of the pressure of human economic activities on the natural environment emphasizes sustainable production and consumption, improved resource use efficiency, and circular economy practices. Overall aspirations, that indeed are ambitious, can be summarized under five "Ps": people, planet, prosperity, peace, and partnership (Box 1). The 2030 Agenda also

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BOX 1 The five "Ps" representing the aspirations of the 2030 Agenda.

People: We are determined to end poverty and hunger, in all their forms and dimensions, and to ensure that all human beings can fulfill their potential in dignity and equality and in a healthy environment.

Planet: We are determined to protect the planet from degradation, including through sustainable consumption and production, sustainably managing its natural resources, and taking urgent action on climate change, so that it can support the needs of the present and future generations.

Prosperity: We are determined to ensure that all human beings can enjoy prosperous and fulfilling lives and that economic, social and technological progress occurs in harmony with nature.

Peace: We are determined to foster peaceful, just and inclusive societies which are free from fear and violence. There can be no sustainable development without peace and no peace without sustainable development.

Partnership: We are determined to mobilize the means required to implement this Agenda through a revitalized Global Partnership for Sustainable Development, based on a spirit of strengthened global solidarity, focused in particular on the needs of the poorest and most vulnerable and with the participation of all countries, all stakeholders, and all people.

Source: Hambrey (2017); Preamble to The 2030 Agenda: UN General Assembly (2015).

emphasizes that goals and targets must be implemented together, thus accounting for potential interlinkages, trade-offs, and synergies. The SDGs are referred to as indivisible, which emphasizes the interdependence of social (incl. economic) and ecological concerns, something that poses great challenges for research implementation and monitoring of the SDGs (Biermann et al., 2017).

The global development planning for sustainable development, that is, shifting the world onto a sustainable path, advanced from a fragmented approach to a more integrated and aligned strategy initiated through the Millennium Development Goals (MDGs) (2000–2015) and further advanced by the SDGs (2015–2030) (UN General Assembly, 2016). The MDGs were seen as "halfway" goals, whereas the SDGs are considered more ambitious but with realistic targets set against "zero" goals. The MDGs were criticized for being expert-led and hindered by a top-down approach. SDGs were instead designed to empower collaborative working between nations to assist working together for the greater good—that is, originating from a co-creative process that embraced a more participatory governance approach, enabling a widespread feeling of ownership. The SDGs are also considered more universal than the MDGs, that is, applicable to both economically developed and developing countries. SDGs have engendered a wider commitment to certain global challenges (e.g., climate change, poverty, water, and peace), and the overarching nature of the SDGs enables addressing wider values of multiple groups and actors. They are therefore considered to have gained more traction in governments around the world than the MDGs, and in consequence, gather greater support for the 2030 Agenda. However, the impacts of the COVID-19 pandemic have further driven inequality among and within wealthier and developing countries, with sustainability goals considered by some nations more a luxury in the short-term recovery process. One might question whether the SDGs are appropriate to achieve the rate of progress required in a post-pandemic world. Even if countries do not fully reach the expected rate of progress, it is important that they try and that they have a structure in place for monitoring progress.

Year 2020 marked the start of the "Decade of Action" to deliver on the Sustainable Development Goals by 2030. To monitor progress toward achieving the 2030 Agenda for Sustainable Development, a global indicator framework for the SDGs was adopted by the UN General Assembly in 2017 (Resolution A/RES/71/313, UN, 2021). Under each goal there are a number of targets, and for each target, one or more indicators. The global indicator framework includes 231 unique indicators. Country level is the starting point for reporting on progress toward the

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SDGs. Forty-nine custodian agencies, which are mainly UN bodies but also include international organizations, conventions, and a small number of member countries, request data from countries or retrieve data from national statistics and publicly available data sources (UNECE, 2018). Once national data are obtained, custodian agencies validate the data in consultation with the countries, compile it in regional and global aggregates, and send it to the UN Statistics Division. There, it is aggregated for all indicators and disseminated in an annual SDG progress report. Some of the data used by custodian agencies to report on the SDGs may come from their own thematic reporting. An additional responsibility of custodian agencies is to strengthen national reporting capacity, harmonize data collection methods, and identify data gaps that need to be filled. FAO is one of the custodian UN agencies for 21 indicators, for SDGs 2, 5, 6, 12, 14, and 15, and a contributing agency for a further five.

3 | AQUACULTURE'S PRESENT AND FUTURE ROLE IN MEETING THE SDGs

Aquaculture is an important sector contributing to human well-being and plays an increasingly important role in efforts to meet the SDGs (Hambrey, 2017). Aquaculture may contribute to all 17 SDGs but the most obvious are those related to (A) eliminating hunger and improving health (SDGs 2, 3); (B) increasing environmental sustainability of oceans, water, climate, and land through responsible production/consumption (SDGs 6, 12, 13, 14, and 15), and (C) reducing poverty, achieving gender equality, improving livelihoods, and reducing inequalities (SDGs 1, 5, 8, and 10) (Figure 2). Not so obvious but also relevant relates to aquaculture's potential for energy production (e.g., algal biomass), adding food production in cities (e.g., vertical farming, aquaponics, community farming), contribution to technology development and development of various partnership (local to global) (SDGs 7, 9, 11, and 17).

Considering the present importance of aquaculture, it is surprising to find that aquaculture is almost invisible in the declaration. Only in SDG Goal 14—"Conserve and Sustainably use the oceans, seas and marine resources for sustainable development" under indicator 14.7 is aquaculture specifically mentioned. Agriculture constitutes the core of Goal 2—"End hunger, achieve food security and improved nutrition and promote sustainable agriculture." Agriculture (and fisheries) is explicitly mentioned in the declaration related to poverty, food security, production, employment, and economic growth, but aquaculture is not mentioned despite world aquaculture production overtaking fisheries production in 2012 and being the fastest growing food sector globally. The nutritional importance of aquatic foods in general is also absent from SDG 14 that is dominated by Ocean Health indicators rather than acknowledgment of its strong link with human nutritional security (Little et al., 2018; Tlusty et al., 2019). The association of aquaculture only with aquatic environments (in particular marine), despite clear evidence that it is fundamentally interlinked to land ecosystems and people embedded within these (Cottrell et al., 2018; Johnson et al., 2019; Naylor, Hardy, et al., 2021; Naylor, Kishore, et al., 2021; Troell et al., 2014), tends to perpetuate the erroneous perception that aquaculture falls solely under SDG 14. Most aquaculture, however, takes place in inland freshwater systems (FAO, 2020a, 2020b) and therefore the key factors that affect its development and impacts, both socioeconomic and geographical, on development are different from those affecting marine systems (Naylor, Hardy, et al., 2021, Naylor, Kishore, et al., 2021). Moreover, its absence from SDG 6, Clean water and sanitation, also suggest that the roles of aquaculture in water use and consumption remain "off the radar" for policymakers and practitioners with regard to water supply and health.

3.1 | Mapping aquaculture's linkages to the SDG indicators—Rapid survey of the scientific literature

A literature review was conducted on Web of Science to get a first indication that aquaculture does connect to the different SDGs. This resulted in 178,549 hits that were analyzed using each of the SDG indicators as keywords. The number of hits for each of 244 indicators was recorded, which were then transformed to the 169 targets of the SDGs by calculating

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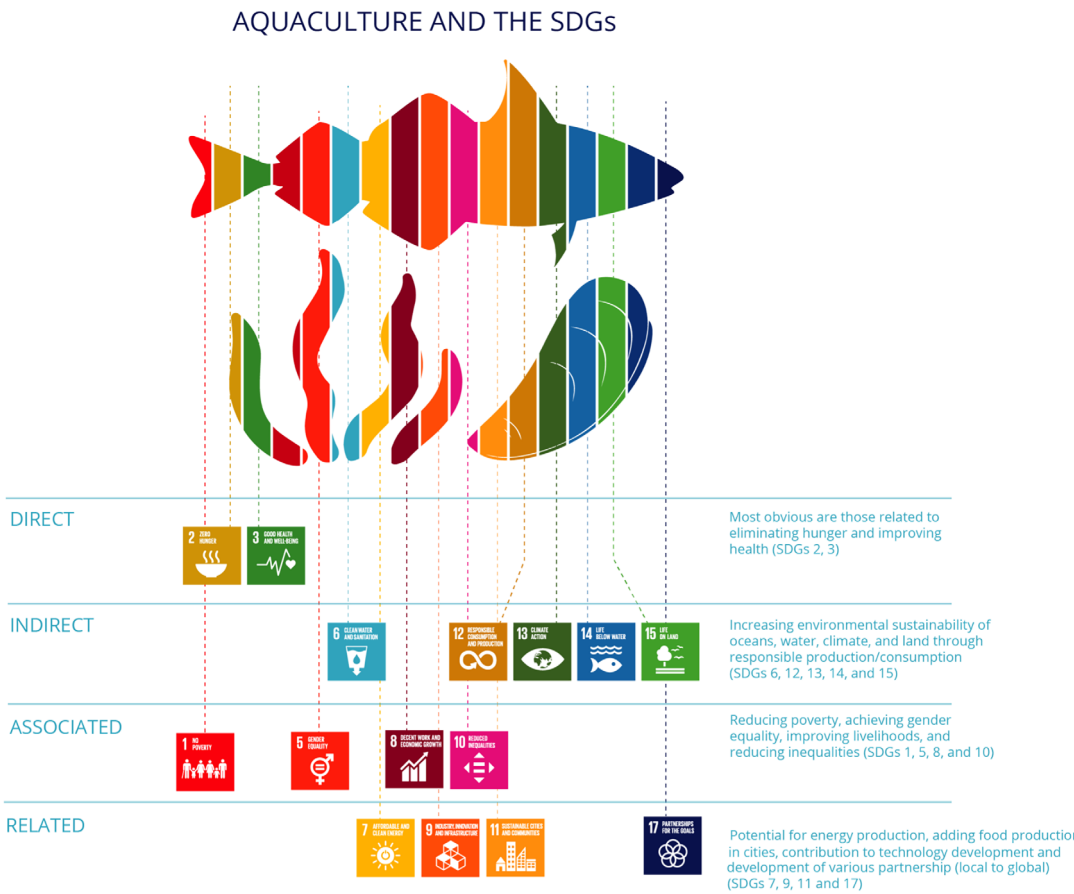

FIGURE 2 Simplified overview of aquaculture's main contributions to the Sustainable Development Goals.

mean results for each target (total no. of indicator hits/[divided by] no. of indicators). Mean "hits" for each SDG were calculated by dividing the total of indicator hits by number of indicators enabling ranking of the data. The results are presented in Figure 3 and in Figure A1 (Appendix A). The analysis did not reveal directional contributions to the SDG targets (i.e., ± or "what kind") which reduces the understanding about the specific contribution from aquaculture. These aspects are however further investigated by a selection of case studies later in the text. A key finding from the survey is that it shows that aquaculture is connected to and has a potential or realized role, for all SDGs. SDG 6 "Clean water and Sanitation" was ranked the highest—something that probably arising from the dominance of freshwater aquaculture, as well as its connection to agriculture through feed. While acknowledging that the analysis is somewhat superficial and would need further in-depth analysis, as well as considering a possible bias towards developed countries, it fulfills its purpose here to illustrate the numerous links between aquaculture and the SDG indicators.

3.2 | Aquaculture's centrality in the global food system—Food security and nutritional health (SDGs 2, 3)

Aquaculture plays a central role in food security and nutrition for billions of people and constitutes a cornerstone of many people's livelihoods, economies, and cultural practices. The rising per capita consumption of farmed seafood has been fuelled by the expansion in global trade, declines in the availability of wild fish, competitive product pricing, rising incomes,

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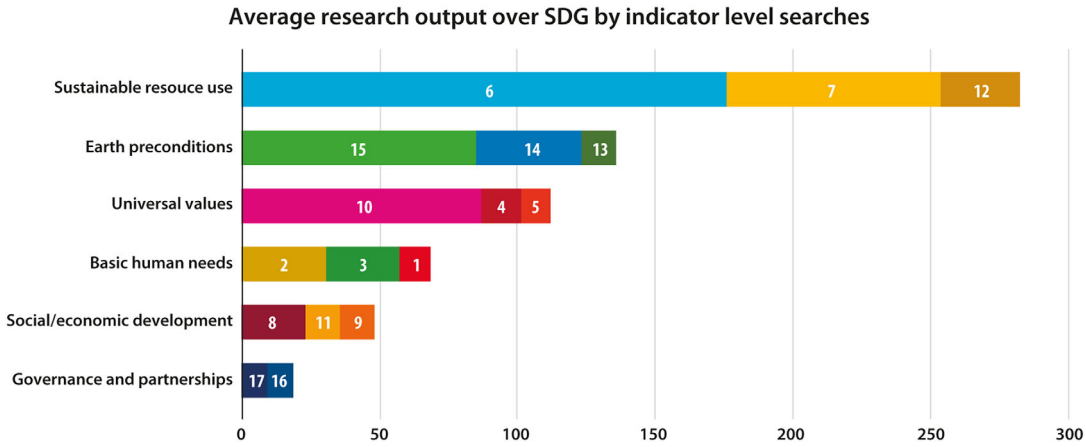

FIGURE 3 Aquaculture's multiple connections to the Sustainable Development Goals (SDGs) based on an extensive search of the SDG indicators through Web of Science.

and urbanization, with incomes and markets in the global South expanding more rapidly than the global north in recent decades (Bush et al., 2019; Pieterse, 2017). Global aquaculture production more than tripled in live-weight volume from 34 M in 1997 to 112 Mt in 2017 (Naylor, Hardy, et al., 2021; Naylor, Kishore, et al., 2021). The increase has mainly taken place in Asia, and with the exception of Asia and countries such as Norway, Egypt, Chile, and a few others, aquaculture must be considered underdeveloped in many parts of the world. Thus, Asia, and especially China, account for more than 90% of the live-weight volume of both aquatic animals and aquatic plants. China's aquaculture is very dynamic, having evolved over more than a thousand years, and is entering its next phase with the nation's rapid economic rise and massive urbanization of its coastal zone (Crona et al., 2020; Newton et al., 2021). There are two distinct aquaculture production worlds: the "aquaculture-developed countries" (most of Asia), and "aquaculture-under-developed countries" (most of Africa, Europe, the Americas, and Oceania—the rest of the World). The latter comprises most of Earth and Oceans, where there is only a proportionally tiny contribution to global aquaculture production (Figure 4).

Seaweeds, carps, bivalves, tilapia, shrimp, and catfish contribute most to overall global aquaculture volumes (FAO, 2020a, 2020b). Farming of marine and diadromous fish and crustacean species has increased significantly but volumes are small compared with farmed freshwater fish that accounts for 75% of global edible aquaculture volumes (Naylor, Hardy, et al., 2021, Naylor, Kishore, et al., 2021). The aquaculture sector is highly diverse with over 500 farmed species across finfish, invertebrate, macro and microalgae, and aquatic plant taxa that are cultivated using highly diverse methods, technologies, and inputs, in freshwater, brackish water, marine waters, or in artificial environments to produce a range of products with diverse end uses (depending on e.g., cultures and diets) and consequences for people and the environment (FAO, 2019; FAO, 2020a, 2020b; Metian et al., 2019; Naylor, Hardy, et al., 2021; Naylor, Kishore, et al., 2021). Despite this diversity, production remains concentrated with just 22 species accounting for 75% of global live-weight production in 2017 (Naylor, Hardy, et al., 2021, Naylor, Kishore, et al., 2021). However, within these species groups there is considerable diversity, for example, for a given species, a number of strains, varieties, and hybrids (farmed types) may be bred and produced (FAO, 2019; Troell et al., 2014), and farmed seafood are compared with terrestrial crop and animal farming more close to their wild counterparts. That same species may also be produced in different systems—freshwater ponds or lakes in one place but using recirculation tank technologies in others—as part of small-scale/family "backyard farming," or through large enterprises mainly serving globalized markets, etc. Likewise, in similar production units (e.g., freshwater ponds), one or many species may be cultivated with differing intensification levels including stocking densities, or dependence on fertilizers, external feeds, and wild seed. Such diversity again illustrates how the affective mechanisms with which aquaculture may influence the SDGs will be highly system and context dependent.

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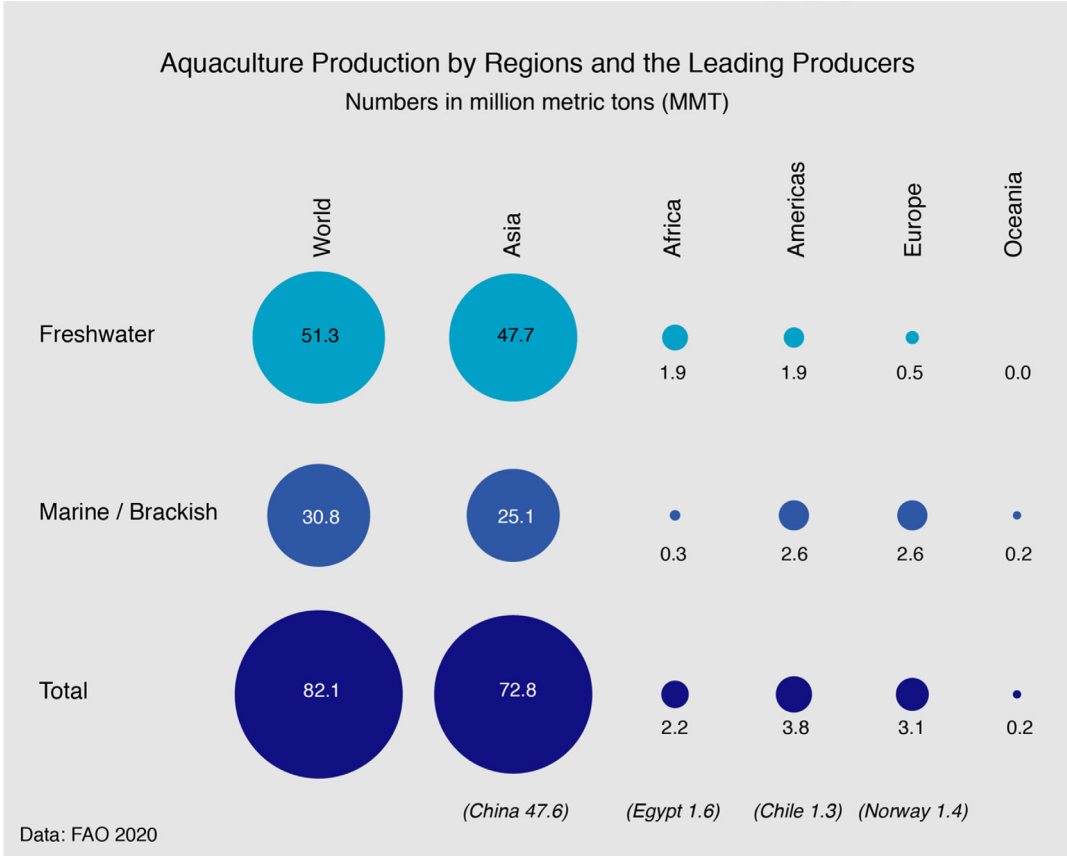

FIGURE 4 Global animal aquaculture production by regions and the leading producers (numbers in million metric tons [MMT]) (FAO, 2020a, 2020b).

Aquatic foods including farmed animals and plants provide unique sources of essential fatty acids (in particular omega 3 fatty acids [EPA + DHA]), protein that easily can be digested and taken up by humans, and essential micronutrients (including vitamins A, B [B12], and D and minerals such as calcium, phosphorus, iodine, zinc, iron, and selenium) (Bennett et al., 2021; Beveridge et al., 2013; Golden et al., 2021; Hicks et al., 2019). Deficiencies of these vital nutrients affect the growth, development, and well-being of hundreds of millions of people (Golden et al., 2021). Aquatic foods are particularly important in many developing countries for providing nutrient densities important for critical life stages, especially the first 1000 days of child development. Small fish are of specific importance but these species are not targeted in farming, although there have been earlier attempts to introduce small-scale farming of species that can be consumed whole (Byrd et al., 2021; FAO/NACA, 2012; Thilsted et al., 2016). Nutritional qualities in feed-farmed organisms reflect in large part the feed composition, something that can result in the same farmed species having different nutritional qualities because of different feed qualities (Kwasek et al., 2020).

3.3 | Environmental sustainability and resilience (SDGs 6, 12, 13, 14, and 15)

Aquaculture provides options for improving environmental performance of food production systems, including reducing nutrient and carbon emissions, compared with many terrestrial animal-sourced foods (Gephart et al., 2021; Hallström et al., 2019; Hilborn et al., 2018; Poore & Nemecek, 2018). Much of aquaculture production is a key part

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of freshwater use, reuse, and recycling, with the strongest link to freshwater use through crop-based feeds (Gephart et al., 2017). Freshwater aquaculture ponds can be a key strategy in ensuring water use efficiency and avoiding scarcity on farms and there are historical and contemporary models for aquaculture being a cost-effective part of wastewater treatment that appears to be totally ignored (Edwards, 2015). Fulfilling aquaculture's future potential and its positive contribution to Agenda 2030 will require accounting for the environmental performance of different types of aquatic foods, and foods in general, and their different nutritional qualities (Béné et al., 2019; Golden et al., 2021; Poore & Nemecek, 2018). This includes considering potential negative impacts from wastes, dependencies of land and aquatic sourced feed ingredients, implication for biodiversity from appropriation of land and sea areas, and potential for being regenerative or contributing to environmental restoration (Gephart et al., 2021; Troell et al., 2014). Thus, depending on the farming system and management/planning, aquaculture also risks resulting in different negative environmental impacts (Gephart et al., 2021; Troell et al., 2014) that need to be considered from a broader social–ecological systems perspective to allow for understanding about SDG outcomes.

If not explicitly mentioned aquaculture may not be prioritized in relation to other food systems/activities, and consequently the full potential of aquaculture to support sustainable development by replacing less sustainable food production systems may not be realized. Its omission may also reflect a lack of understanding about the potential contribution that aquaculture can make to many of the SDGs and partly explain the general lack of inclusion of seafood in global dialogues on food systems (Stetkiewicz et al., 2022). The diversity of species and habitats for farming makes aquaculture an ideal candidate for better integration of policies to meet all the SDGs, that is, where water is fundamental to life more broadly—indicating the need for comprehensive and cohesive strategies built on planning systems that transcend land and aquatic ecosystems while integrating natural resource use.

The great richness of species and systems obscures the fact that few of them are close to optimization (Henriksson et al., 2021) or that the development of farming of extractive species for food remains under-resourced. Development of novel feeds, partly driven by growth in demand and economic incentives to reduce dependency on marine ingredients, has gained pace in the last decade but the potential for expansion both in oceans and on land remains unfulfilled (Cottrell et al., 2020). Published research has drawn attention to the specific role of how aquaculture may add resilience to the global food portfolios (Troell et al., 2014). However, as a result of the huge diversity of species and farming methods employed, and the aquaculture sector's interlinkages and reliance on a wide range of ecosystem services and resource systems (land/space, water, seed, feed), it is widely directly and indirectly affected by climate change (Barange et al., 2018; Tigchelaar et al., 2021) and other environmental stressors and challenges (e.g., pollution, diseases) (Cao et al., in review), as well as stressors related to globalization (i.e., market dynamics, pandemics, etc.). Stressors operate both cumulatively and synergistically at varying spatial (species and farm level to land- and seascape, country and global), and temporal scales, impacts being inequitably experienced throughout the value chain by different value chain actors (Dabbadie et al., 2018). Climate change is already affecting aquaculture, with effects unevenly distributed across the world (Barange et al., 2018; De Silva & Soto, 2009). Future climate changes are most likely to negatively affect or challenge aquaculture production in low latitude countries, through a combination of impacts and limited adaptive capacity (Dabbadie et al., 2018, Soto et al., 2018; Tigchelaar et al., 2021). If unaddressed (e.g., no proactive planning for climate smart aquaculture) climate change and other environmental stressors are likely to undermine the ability of the sector to maximize its potential contribution towards meeting SDGs targets.

Aquaculture technology development, where a broader resource efficiency perspective is prioritized, includes farming of extractive species and integrated farming systems (Chopin & Tacon, 2021). These systems have the potential for strengthening the circular economy and can be essential for the recapture of finite nutrients (i.e., nitrogen and phosphorus) from sea-based systems or land (i.e., agriculture) and used for restorative purposes. However significant changes are needed to impact market and consumer demand and preferences to facilitate increased production of this type of aquaculture, especially outside Asia. Aquaculture depends on ecosystem services to support production in a variety of ways. Although aquaculture can result in negative ecosystem impacts, it can also provide various ecosystem services and also contribute to restoration of aquatic ecosystems (Costa-

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Pierce, 2002; Hoegh-Guldberg et al., 2019). Based on modern hatchery and nursery technologies, aquaculture can support endangered species (e.g., Canadian Atlantic salmon) and ecosystem rehabilitation, for example, kelp forests, seagrass, and coral reefs. Marine aquaculture of lower trophic level aquatic species (mostly aquatic invertebrates), such as bivalves, urchins, sea cucumbers, and seaweed aquaculture have the ability to improve water quality, serve as buffers to coastal erosion, ameliorate nutrient pollution, provide essential habitats for other species, and transform carbon, nitrogen, and phosphorus cycles (Alleway et al., 2019; Gentry et al., 2020; Theuerkauf et al., 2021; zu Ermgassen et al., 2020) (see later in the text examples of oyster cultures links to SDGs). Such production systems mirror agroecosystems, aiming at broad preservation of ecosystem functionality, and have been termed "restoration aquaculture." There exist clear definition, principles, and practices of restoration aquaculture and a working definition proposes "…commercial or subsistence aquaculture provides direct ecological benefits to the environment, leading to improved sustainability and the potential to generate an overall or net environmental outcome, in addition to the supply of seafood or other commercial products and opportunities for livelihoods" (Jones, 2017).

3.4 | Poverty, livelihoods, and reducing inequalities (SDGs 1, 5, 8, and 10)

Aquaculture provides opportunities to improve food security and livelihoods through strengthening local production and trade to supply fresh products to communities where supply chains/trade is limited. Aquaculture's specific contribution to employment remains unknown but was estimated in 2016 to be somewhere between 27.7 and 56.7 million full- and part-time jobs (Phillips et al., 2016). Aquaculture's contribution to economic, social (e.g., food security), and environmental issues varies across countries/regions, diversity of species, production systems, and contexts (Hambrey, 2017; Harvey et al., 2017; Troell et al., 2014). Support for local and regional value-chain development and an emphasis on nutritional value (i.e., nutrient-sensitive production, Gephart et al., 2020) will be key to aquaculture's positive contribution to the SDGs. The large increase in world aquaculture production since 1990 and the expansion of trade in these products have allowed seafood prices to remain stable globally, regardless of where the production originates, and despite the enormous growth in demand that has occurred as a result of population and income growth (Asche et al., 2022; Troell et al., 2014). This has made it possible to maintain a supply of nutritious and healthy seafood products at an affordable cost for a growing world population. This impact has been especially important in many lower income countries (Belton et al., 2014). Aquaculture offers livelihood opportunities for women, youth, and indigenous communities in seafood processing and trade, although it may not be the first choice for young women and men (Arulingam et al., 2019). In the supply of inputs such as locally produced feed and seed for aquaculture, the aquaculture sector creates many jobs and has positive multiplier effects on local, regional, and national economies (Filipski & Belton, 2018; Hernandez et al., 2017). It supports the marketing and distribution of nutritious seafood (mainly fish-based products) for maternal and child health (Bennett et al., 2018; Golden et al., 2021).

There are many opportunities for aquaculture to continue to expand and contribute to the SDGs. Foremost among these are demand-side opportunities where recent models predict rapid growth in demand in areas where aquaculture is well-established and in areas where it has begun to develop (Naylor, Hardy, et al., 2021, Naylor, Kishore, et al., 2021) and based on the current status that globally aquaculture products still remain absent from most peoples' diets. Aquaculture's "new geographies," for example, almost everywhere outside of Asia where aquaculture is new or not traditional, needs greater attention by food systems policy makers and planners at all levels of GOs and NGOs. In contrast to Asia, where current dominant forms of aquaculture can be viewed in a historical perspective and are highly integrated into socio-ecological and political/governance contexts, this new aquaculture milieu is characterized by limited experiences of aquaculture in public, social, and political spaces in society, or by the decimation of traditional systems following colonization and removal of access to land and water by indigenous peoples. For all the benefits we see aquaculture generate, aquaculture in its new geographies outside of Asia in general still constitutes only a minor part of agriculture and natural resource economies, even within the ocean/aquatic

economy. This can perhaps to some extent explain its status in the SDG declaration and indicates the opportunities that can be realized as more experience is gained in new geographies, including through engagement with traditional custodians and systems.

4 | AQUACULTURE DIVERSITY AND ITS IMPLICATION FOR SDGS

Aquaculture is highly diverse in terms of intensities, farmed types (species, strains, and hybrids), seed supply (hatcheries, nurseries, or wild supply) and grow-out systems (cages, pens, ponds, rafts, recirculating aquaculture systems, ropes, intertidal on-bottom, silos, stakes and tanks, and multicomponent systems), integration with agriculture and monoculture or integrated/ multi-trophic aquaculture (FAO, 2020a, 2020b; Troell et al., 2014). While global production is dominated by a few major species (e.g., common carp, Nile tilapia, Atlantic salmon, Japanese carpet shell, cupped oysters, Japanese kelp, and a few key galactan seaweeds), the range of cultivation contexts, value-chain complexities, and end uses drive large differences in the social–ecological outcomes among, and crucially within, aquaculture forms. Harvey et al. (2017) recognized that aquaculture can and may diversify further in terms of species, technologies, geography and the environment, markets, and governance, and identified the main drivers and mechanisms of such diversification (Table 1). Emphasis in that review was on development of a profitable aquaculture sector at multiple scales able to meet future seafood demands in environmentally sustainable ways. Some of the identified drivers can, however, have the opposite effect and drive development of monocultures. This is at least the case in countries where aquaculture is new (e.g., Chile, Ecuador, Brazil, Norway, Egypt). This kind of development risks resulting in "blind spots" with respect to equity (Farmery, Allison, et al., 2021; Farmery, White, et al., 2021). This is not to say that monocultures do not fit within a sustainable diversified aquaculture portfolio, but that a broad system perspective is needed for a fuller understanding of the sustainability challenges. Diversification is ongoing and examples include sustainable intensification of existing systems, integrated systems both on land and in seas, and different offshore solutions for both fish and shellfish (Naylor, Hardy, et al., 2021; Naylor, Kishore, et al., 2021). Large-scale aquaculture has also evolved substantially in the past 20 years (Naylor, Hardy, et al., 2021, Naylor, Kishore, et al., 2021) and production innovations are reported globally almost every week. In addition, new ecological aquaculture production systems have arisen with new monikers that have attracted new communities of practice that identify themselves with these innovations, not necessarily with "aquaculture" (see Beveridge & Dabbadie, 2019).

TABLE 1 Main drivers for aquaculture diversification (from Costa-Pierce, 2002).

Driver	Mechanism
Market demand	As the world becomes more populated, urbanized, and rich, more people will want, and be able to afford more fish and fish products
Climate change	Changing environments will necessitate new species/strains, or the movement of established species into new areas
Desire for increased resilience	Aquaculture will need to supply consistent products in spite of external impacts
Consumer demand	Consumers want to continue to eat fish that they are accustomed to eating and at affordable prices; tastes may change in response to new trends or the introduction of new species
Environmental concerns	Governments and consumers will want to promote and eat fish that are efficiently grown in an environmentally friendly manner
Profit	Aquaculturists will strive for species, breeds, and systems that are efficient and meet market/ consumer demands
Competitive advantage	Developing new species, breeds or farming systems often gives the innovator an initial competitive advantage

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The diversity of species (including strains, breed, and varieties) and systems will have implications for how aquaculture may deliver on the—especially so in the long term. Promoting further diversification of species and production systems will be important for long-term performance in a changing world but selection and focus on improving only a limited number of species (e.g., genetics, feed efficiency, etc.) may lead to more rapid improvements in terms of producing the most environmentally performing species from the most sustainable systems (Henriksson et al., 2021); a pattern commonly seen in sociotechnical transition pathways (Elzen et al., 2004; Geels & Schot, 2007). Interventions that allow for rapid upscaling of such farming to support sustainable diets, that is, in responsible ways, will be key.

4.1 | Aquaculture archetypes and the SDGs

Categorization of aquaculture into "archetypes" is a useful step towards enabling a simplified representation of how species and systems are connected to, and to some extent may deliver on, the SDGs. The archetypes would preferably capture aspects related to; degree of technology/technology reliance, labor inputs/dependency, ownership structures, reliance on input resources, linkages to specific access rights (land for ponds, marine concessions for cages, open access lagoons for seaweed plots), extent of investments needed and capital costs, profitability, target markets (international/ national), dependency on R&D, nutritional values of products, need for and existence of knowledge, required training, etc. Degree of intensification is a valuable indicator as it brings in biology and husbandry of the cultured organism, physical characteristics of the systems, and key social and economic contexts. Costa-Pierce (2003) suggested a simplified classification that allows capturing characteristics of farm systems (Table 2), allowing for deeper understanding about the diversity and how this will influence various inputs and outputs.

Integrated aquaculture or aquaculture based on the principles of ecology and circular economy may contribute to better attain the environmental dimension targets by improving the efficiency in using natural resources, and possibly reducing the extraction of natural resources and liberations of pollution and wastes (Boyd et al., 2020; Soto

TABLE 2 Archetypes/classifications of aquaculture systems.

Variables	Kinds and levels
Stocking, management, and economic intensity levels	Intensive; semi-intensive, extensive
Water salinities	Freshwater; brackish water; seawater
Water flow characteristics	Running water; standing water with flushing; standing water
Amount of on-site water treatment and recirculation	Open, no recirculation; semi-closed, partial recirculation; closed, full recirculation
Environmental location	Indoor; outdoor—natural; outdoor—artificial
Feed qualities	Complete; supplemental; natural
Feeding strategies	Continuous; scheduled; natural
Species stocking strategies	Monoculture; janitorial polyculture; polyculture
Species temperature tolerance	Eurythermal; stenothermal, coldwater; warmwater
Species natural food habits	Carnivorous; omnivorous; herbivorous; opportunistic
Fry/larvae sources	Hatcheries; wild capture of broodstock; natural
Level of system integration	Stand-alone; integrated
Unit types	Raceways; tanks and cages (floating, fixed; net pens (fixed); rafts (roles, nets); ponds
Marketing channels	Human food (local, export); sport, recreation, tourism

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et al., 2008). However, its performance still needs to be supported by evidence reflecting commercial situations. Intensification means different things for fed species and extractive species (e.g., mussels and seaweeds) where the main focus within fed aquaculture has been on increasing densities and at the same time reducing resource use per production inputs. The ways by which aquaculture contributes to efficient use of financial resources, generating and distributing wealth to local people, creating jobs positions and self-employment can contribute to the economic and social targets of the SDGs, but how this plays out for different systems and conditions is very much dependent on the contexts (see Sections 1 and 2). Development of participatory governance for aquaculture can contribute to aligning effort and matching resource needs to specific aquaculture contexts thus helping to realize institutional targets of the SDGs efficiently.

5 | FRAMEWORKS AND INDICATORS FOR CAPTURING BROADER SUSTAINABILITY PERFORMANCE OF AQUACULTURE

No single framework that could be applied to assess or guide the contribution of aquaculture to "sustainability" currently captures all its dimensions and at multiple spatiotemporal scales. A number of frameworks, however, enable assessing the contribution of aquaculture to some of the dimensions of sustainability, or of all its dimensions at some specific scale. For example, the sustainable livelihoods framework (Scoones, 1998) can be applied to understand the contribution of aquaculture activities at household/farming system or local scale, and especially so because it considers influences outside aquaculture (e.g., governance/institutions, access, assets, capabilities, etc.) that makes it contribute (or not) to livelihoods and household well-being. The diagnostic framework for equitable mariculture, with application to all aquaculture systems more generally (Eriksson et al., 2018), focuses on assessing ex-ante whether aquaculture development initiatives (private or public) contribute to the fair appropriation and maintenance of space, habitats, and ecosystem integrity, and provide fair access to opportunities, benefits and shared growth. Zooming out from the farm level, Krause et al. (2015)'s framework to account for social, economic and ecological issues in aquaculture management and governance—or framework to fill the "people-policy gap"—considers equity dimensions at a larger scale (sectoral, national, and global), focusing on how aquaculture should be governed to be more inclusive. The ecosystem approach to aquaculture (EAA) (FAO, 2010) enables effective capture of the environmental and productive aspects of aquaculture at a sectoral level, but its social and economic dimensions less so, despite its ambition to guide the development of the sector in a holistic manner and also enable building resilience (Brugere et al., 2019).

The insights gained from the applications of these frameworks to the SDGs are only partial, and there is still a step to cross to relate these to the five "essences" of the SDGs 5 P's (Hambrey, 2017; Box 1) to enable co-development of cohesive aquaculture strategies. Nevertheless, applying a framework, chosen on the basis of circumstances and pragmatism, or extended with complementary concepts (Stephenson et al., 2021), in order to initiate proper stakeholder dialogue and help mitigate against unwanted negative externalities of aquaculture development, is recommended, with the caveat that the framework alone cannot ensure all "essences" of the SDGs will be comprehensively addressed.

5.1 | Impact pathways—A framework for mapping and understanding the consequences of oyster farming for the SDGs

Herrero et al. (2020) investigated impact profiles of a few emerging new food technologies and social solutions and could through mapping of "impact pathways" identify consequences for SDGs. The analysis allowed for identifying positive contributions to specific SDGs but also unintended adverse side-effects for other SDGs. Thus, their methodology enabled capturing effects on multiple sustainability dimensions and gaining understanding about systemic changes through emergence of SDG trade-offs. Identification of desired and undesirable spatiotemporal

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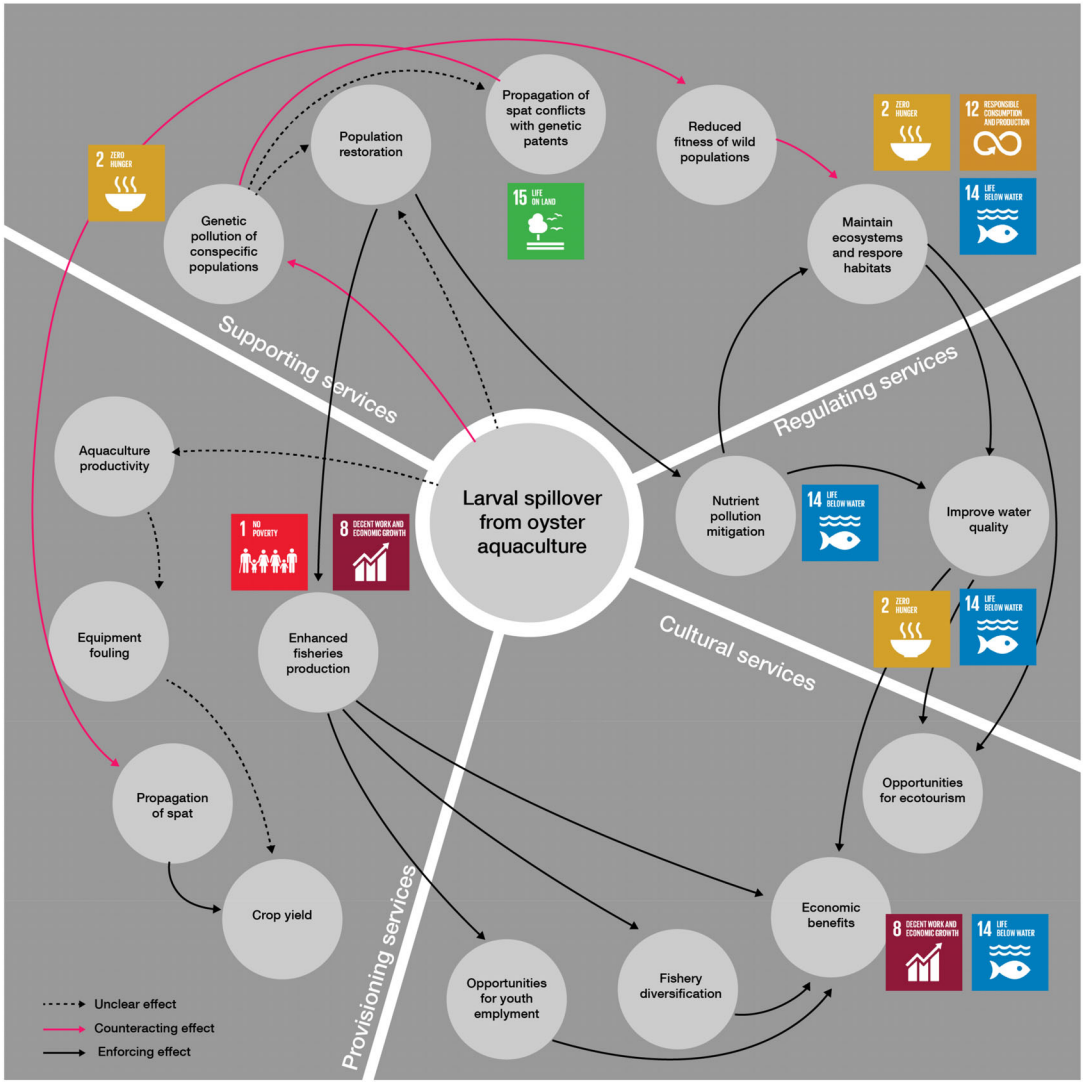

FIGURE 5 Case study of larval spillover from oyster aquaculture and linkages to Sustainable Development Goals (based on Delago, 2021).

consequences provided the basis for development of planned transition pathways and careful monitoring of key indicators. The authors concluded that developing the suggested framework would call for the integration of economics and natural sciences—with a rich array of social sciences that study different facets of transformation in multiple sectors.

Delago (2021) applied Herrero and colleagues' framework for a case study of larval spillover from oyster aquaculture establishing a new oyster fishery (Figure 5). Oyster farming is a highly relevant cultivation system as shellfish aquaculture (including mussels and clams) has gained increased attention worldwide, contributing 7% of all aquaculture production globally (live weight, FAO, 2020a, 2020b). Even though growth of the sector has slowed over the last few years, shellfish farming may become increasingly important for our future food portfolio (Costello et al., 2020; Troell et al., 2017) and provide a suite of social–ecological benefits linked to many of the SDGs, including food/nutrition, income generation in remote/rural communities, provisioning and supporting ecosystem services

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that include nutrient removal, water clarification, coastal protection, and habitat creation (Dame, 2011; Gentry et al., 2020; Grizzle et al., 2008; Kellogg et al., 2014; van der Schatte Olivier et al., 2020). However, uncertainties with respect to climate change driven acidification of coastal waters and also increased occurrence of HABs exist (Barange et al., 2019).

As marine resource managers strive to find innovative solutions to halt fisheries decline, shellfish aquaculture has also gained increasing social acceptance in some regions as a sustainable solution for ecosystem restoration and enhancement (Beck et al., 2011; Jones, 2017; Theuerkauf et al., 2021). Delgado and colleagues' case study was in the Damariscotta River estuary in Maine, USA, and while the social acceptance of bivalve aquaculture has increased in this area, the high market value of oysters in Maine make oysters a luxury protein and has marginalized parts of the rural fishing communities and consumers. The study demonstrates not only the positive interactions of multiple SDGs with oyster aquaculture but also the trade-offs resulting from an expanding aquaculture industry—including the creation of a new wild oyster fishery and interactions with marine conservation initiatives (Figure 5). There are also trade-offs with low and higher cost strategies with fisheries and restoration interests within a reciprocal conservation paradigm. Despite the far-reaching value of shellfish aquaculture from ecosystem and fisheries enhancement perspectives, contributions of larvae from aquaculture sites have not been identified previously as an ecosystem service (van der Schatte Olivier et al., 2020). Larval spillover from expanding mussel aquaculture has assisted restoration of the native green lipped mussel, *Perna canaliculus*, in New Zealand (Norrie et al., 2020).

5.2 | Wheel of sustainability framework—Aquaculture case studies

In an attempt to map how different aquaculture certification schemes address and relate to sustainability, Osmundsen et al. (2020) investigated the most widely used aquaculture certification schemes (including ASC [Aquaculture Stewardship Council], Global G.A.P [Global Good Agriculture Practices], GAA [Global Aquaculture Alliance], FOS [Friend of the seas], etc.). They developed a "Wheel of Sustainability" that effectively communicated the difference in how sustainability is addressed by certification schemes. For this study, this approach provides a comprehensive overview of the main sustainability issues within aquaculture and presents key indicators within four key sustainability subdomains. The subdomains have been modified slightly and instead of governance, economic, environment, and culture, governance was replaced with institutional and culture with social (Table A1 in Appendix A). Then this framework was applied for linking key SDG targets to the sustainability indices that the model provided. The indicators used by Osmundsen et al. (2020) were complemented by addition of a selection of recent indicators developed by FAO for mapping agriculture's contribution to the SDGs (FAO FSN, 2021). The indicators were then also mapped to relevant SDG targets that were relevant for aquaculture, even if some targets had been defined more narrowly, for example, towards only agriculture.

Using this modified framework, a few key aquaculture archetypes were identified and explored from how they might influence the SDGs—viewed from the perspective of, for example, their resource demands (fed/filter/extractive), the markets they predominantly serve (local/global), the various requirements for mechanization versus labor (high-tech/labor-intensive), and the accessibility of the final product (high value/low value/non-food uses), etc. Each of these variables influences various aspects of sustainability across its multiple domains, including food security and nutrition, livelihood opportunities and employment, equity and gender equality, and environmental impacts. Looking across various permutations of these factors, case studies of different aquaculture archetypes were explored to illustrate the diversity of aquaculture's contribution to the SDGs (Figure 6). The case studies were selected to represent systems of significance for global aquaculture as well as to some extent representing the differences outlined above. They include two seemingly similar seaweed cases selected to highlight how different contexts may play a role in sustainability outcomes and the SDGs. The five case studies included are listed below and extended information of each case is found in Box 2:

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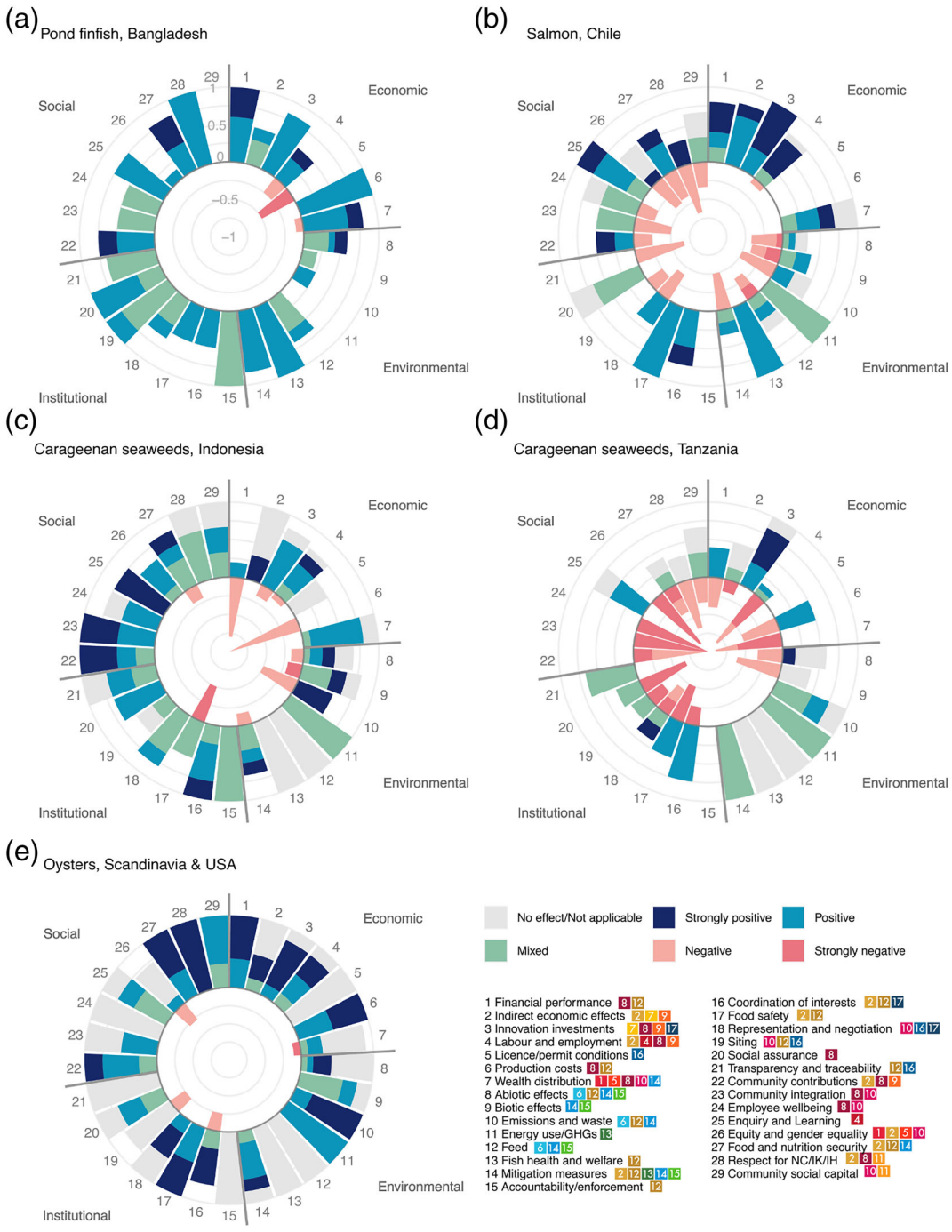

FIGURE 6 Results from case studies where Sustainable Development Goal (SDG) targets mapped onto sustainability indices adapted from Osmundsen et al. (2020) and FAO core agricultural indicators of SDG contribution. Bars represent the proportion of relevant SDG targets within each sustainability indicator of a given polarity where each concentric ring represents a proportion of 0.25. All negative contributions within each sustainability indicator are plotted inward, all mixed and positive contributions are plotted outward. The overarching SDGs relevant to each indicator are displayed in the legend. See Table A1 in Appendix A for comprehensive detail of contributions towards each SDG target.

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BOX 2 Description of case studies.

Seaweed farming—shallow bottom rope culture

A. In Indonesia, carrageenan seaweed farming has been a major driver of rural development and increased living standards for coastal communities. As a labor-intensive industry, farming of seaweeds supports a wide network of small-scale farming cooperatives, collectors, and agents throughout the domestic value chain (SDG 2.3, Valderrama et al., 2013). Carrageenan seaweed farming is also lucrative in Indonesia, raising many well above the poverty line (SDG 1.2), creating more equitable access to natural and financial resources for women (SDG 1.4, 2.3, 4.3, 5.a, 10.2), and leading to indirect benefits such as increased education opportunities (SDG 4.3–4.5, 8.6, 10.3) and communication infrastructure (SDG 2.a, 9.1) (Larson et al., 2021; Valderrama et al., 2013). In some regions, for example, Sulawesi, increasing dependence on seaweed farming as a sole source of livelihood has left some communities more vulnerable to shocks (SDG 1.5) as other less lucrative security activities such as copra production are abandoned (Steenbergen et al., 2017). Nonetheless, for many, seaweed farming has improved household productivity and production efficiency (SDG 8.4) as the major income stream that occupies half or less of a farmers' time (Larson et al., 2021, Valderrama et al., 2013).

   Seaweeds do not depend on feed, can improve local water quality (SDG 6.3), and do not contribute substantially to marine pollution (SDG 14.1), yet there remain considerable uncertainties and trade-offs for localized environmental impacts. Off-bottom lines may denude coral or seagrass habitat, poles to support suspended lines are often harvested from mangrove forests (SDG 2.4, 15.2, 15.5, Malik et al., 2017), and while they may provide habitat/refuge for marine species (Thauerkauff et al., 2021) it is uncertain whether this comes as displacement costs for surrounding habitats or whether species are being lured into "ecological traps" (Hale & Swearer, 2016). Decentralized governance of seaweed aquaculture systems means that decisions about siting and management are made at more local levels where impacts are felt (Valderrama et al., 2013). But to what extent decision-making promotes inclusivity and empowerment of all involved (SDG 2.3, 10.2, 16.5–16.6), is unclear; it is hard discerning the role of forced labor in family oriented business models but public pressure for greater transparency in fair trade and product standards is growing (Valderrama et al., 2013). At an industry level, improved resource efficiency (SDG 8.4) and development opportunities could emerge if the value chain can evolve toward exporting more value-added products (e.g., refined carrageenan) rather than the raw seaweed biomass, which currently leads to added costs and losses (SDG 12.2–12.5) through transport to major domestic hubs and offshore processing in China (Valderrama et al., 2013). Thus, despite the many social benefits of the sector's growth, there remain considerable uncertainties among the environmental and institutional sustainability domains.

B. The two types of seaweed species grown in Zanzibar are *Eucheuma* and *Kappaphycus*, commercially known as Spinosum and Cottonii respectively. The dominant technology to grow them is the traditional off-bottom method, using wooden stakes (pegs) planted in the sand and ropes to which seaweed bunches are attached. This method is, however, suboptimal because it is used in shallow waters where, with the onset of climate change, environmental conditions change rapidly and affect productivity (SDG 13), and it is very labor-intensive. The lack of depth increases seaweed exposure to variations in sea surface temperature and salinity, especially during the rainy season, resulting in disease outbreaks such as "ice–ice," a discoloration of the seaweed thali which affects the quality of seaweed, and epiphyte infestation which suppresses growth (SDGs 14, 15) (Largo et al., 2020). The nature of the technology makes it particularly vulnerable to currents and storms, often resulting in tangled ropes, broken, and lost seaweed. As a consequence, maintenance of the seaweed plots is physically demanding and

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hazardous work (SDG 8), requiring daily attention and placing a heavy burden on women's lives (SDG 5), far from commensurate with the economic returns the activity generates (SDGs 1, 8).

Although Cottonii fetches a slightly higher market price because of its higher carrageenan content (US$ 0.4/kg of dried Cottonii compared with US$ 0.2/kg of dried Spinosum), it does not grow well in shallow waters because it requires optimal environmental conditions, such as cooler water and constant salinity in order to overcome die-offs. As a consequence, women producers have reverted to the culture of Spinosum despite the very low income they make. Furthermore, the marketing potential and consumption benefits of seaweed products are under-exploited in Zanzibar and in the WIO region. Seaweed can be transformed into many products with health and nutrition benefits such as cosmetics (soap, shampoo, and lotions) and food (juice, jam, seaweed sticks, salads, cakes, and noodles) (SDGs 2, 3), but over 90% of Zanzibar seaweed production is exported untransformed, missing out on opportunities for local value addition and benefits (SDG 8), including income generation for the women involved in the industry (SDGs 1, 5).

Carp farming—earthen pond farming, Bangladesh

C. Inland pond culture in Bangladesh remains dominated by polyculture of low trophic species based on a range of indigenous and exotics carps, together with tilapia and pangasius, which ensures efficient use of natural resources (SDG 12.2). Widespread adoption of commercially oriented production has increased the comparative affordability of freshwater fish, improving nutritional security (SDG 2), and, because of its labor intensity, increased employment throughout the value chain (SDG 4.4). This in turn has contributed to reduced poverty (SDG 1.2) in areas where aquaculture production has become geographically concentrated but also generated spillover economic and social impacts further afield (SDG 1.2, Filipski & Belton, 2018). Apart from the culture of giant freshwater prawn that are generally exported after processing, most inland cultured fish is sold to local markets. Coined the "silent revolution" (Hernandez et al., 2017), commercialization of pond-based aquaculture has driven employment and growth of micro, small and medium enterprises in value chains (SDG 8.3). Although production in general remains dominated by the better off, increasingly flexible norms around leasing ponds have enabled poorer actors to become producers in some contexts, especially around juvenile production, improving inclusion (SDG 10.2). Strong demand for farmed fish is linked to urbanization and has incentivized intensification and higher productivity (SDG 2.3), particularly in the face of a steady decline in wild supply. Pond aquaculture has led to loss of wetlands (SDG 6.6, SDG 14 and 15) and elite capture of resources (e.g., Toufique & Gregory, 2008; SDG 10.2) in some contexts but also acted as foci for building resilience in the food supply of poorer groups (SDG 1.5) and improving water use efficiency through integrated water use in associated horticulture (SDG 6.4; e.g., Karim & Little, 2018). The development and dissemination of improved strains of farmed fish, notably tilapias, an outcome of international cooperation (SDG 17.16) that is evident throughout the sector, have been a component in their relative rise to importance. Such investments in genetic improvements have yet to significantly impact on other commonly farmed species suggesting significant potential productivity gains are possible given future investments in research and innovation (SDG 9.5). Increased use of feeds and improved feed technology, both highly dependent on imports, have been the major driver of intensification but without complementary improvements to system development, such trends cannot be sustained without exceeding environmental limits within the pond and off farm (SDG 2.4, SDG 6.3). Enhanced access to green energy at the pond side through investments in appropriate technology will be essential for sustainable intensification (Little et al., 2018; SDG 7a). There is also interest and enthusiasm for reducing degradation of threatened species (SDG 15.5), particularly small indigenous species known to be particularly rich in micronutrients and critical to nutritional security (SDG 2.1). The widespread adoption of

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simple technologies around freshwater pond aquaculture while stimulated by short-term development projects often supported through international partnerships (SDG 17.16), has largely been a consequence of market response to growing demand rather than an outcome of effective, centrally driven governance (SDG 16.6; Belton & Little, 2011).

Salmon farming—coastal cages, Chile

D. Chile is the second largest producer and exporter of farmed salmon, after Norway. Production of salmon reached 1 Mt with a value of US$ 4.6 billion in 2020 (SERNAPESCA, 2020). The sector provides about 7% of the country's total exports, contributing more than 14% to the "non-mineral" exports; thus, the activity is a relevant economic sector contributing significantly to reduce poverty in some remote areas (SDGs 1), especially in remote places and fishery-dependent coastal communities where there are often no other permanent sources of income (Ceballos et al., 2018; Cardenas-Retamal et al., 2021; Soto et al., 2019; Soto et al., 2021). The sector also contributes to improved technical skills (SDG 4) and increased economic productivity at local level (SDG 8) as well as fostering local innovation and services (SDG 8). Yet this industry has relevant environmental impacts to marine ecosystems (SDG 14) (Quiñones et al., 2019), generates conflicts about the use of common spaces (SDG 11), is vulnerable to shocks (SDG 13), among other governance and social issues (Chavez et al., 2019). Despite the high levels of production, national seafood consumption is below the global average, at 13.3 kg per capita in 2013, which was down by 1.3% from 1993 (Mancini, 2020). The government has listed a target to increase the consumption of seafood by 1 kg per capita by 2022 within the Chilean Action Plan for Sustainable Production and Consumption 2017–2022 (Farmery, Allison, et al., 2021; Farmery, White, et al., 2021). The above sector description is well reflected in the Figure showing important advances in economic indicators, while institutional, social, and environmental indicators show advances but also relevant drawbacks. Special attention is needed to address biotic and abiotic impacts on ecosystems, better social integration, and more equitable income distribution.

Oyster farming—temperate coasts, Scandinavia/USA

E. Oyster farming in Scandinavia and in the Northeast USA is based mainly on native species and is often operated as small-scale family and part-time farms integrating different age groups and educational levels and is combined with other activities such as oyster fisheries, tourism, or other part-time employment (SDGs 8 and 9). The practices are characterized by strong legal institutions and governance hence several of the institutional and social associations to the SDG targets are not applicable; however, overregulation of the sector reduces overall institutional sustainability. Despite the small scale of activities and heavy regulatory burden connected to licensing and strict food safety standards, oyster farming is profitable as the product is aimed for the luxury, high-end, high-value market (SDG 8). The products are mainly aimed at local markets, hence increasing access to healthy, low-carbon foods (SDGs 2 and 13). The small-scale activities are very beneficial from a socioeconomic perspective and promote numerous, positive social feedback loops and activities maintaining cultural identities along with preserving and advancing the added values of working waterfronts in terms of spin-off values achieved (SDGs 8 and 9). Similarly, because of the scale of operations, negative environmental impacts such as bottom effects and interactions with wildlife are limited while positive effects are high on ecosystems goods and services at a local scale, such as biodiversity enhancement, enhancement of wild populations through larval spillover and nutrient recapture potentials (SDG 14). The sector is also characterized by significant innovations and collaborations between industry and academic institutions, as well as international collaboration (SDGs 9 and 17).

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A. Carrageenan seaweed production (*Eucheuma* spp., *Kappaphycus* spp., and *Graciliaria* spp.), Indonesia (Selection criteria: extractive, global markets, labor-intensive, and non-food industries)
B. Carrageenan seaweed production in East Africa, that is, Tanzania (selection criteria: extractive, global markets, labor-intensive, and non-food industries)
C. Carp pond production, freshwater (inc. polyculture), Bangladesh (selection criteria: filter, local markets, labor-intensive, and low-valued)
D. Salmon production (Atlantic, Coho, Rainbow trout), marine cages, Chile (selection criteria: fed, global markets, high-tech, and high-valued)
E. Oyster, rope/basket culture, Nordic Countries and United States (selection criteria: extractive and global markets)

These case studies highlight the complexity of sustainability (SDG) outcomes from aquaculture development. For any given archetype there are clear trade-offs across and within environmental, social, institutional, and economic domains. For instance, salmon farming in Chile has resulted in widespread economic benefits, increasing coastal livelihood opportunities and reducing poverty in many remote regions. Yet concerns remain over the quality of work, environmental impacts, and equitable distribution of benefits from industry growth, particularly in its contribution to fish consumption, resulting in mixed contributions to social and environmental sustainability. Differences in framing conditions and local contexts also mean sustainability outcomes can differ markedly from the growth of very similar systems in different regions. For example, Carrageenan seaweed farmers in Indonesia and Tanzania both employ off-bottom production strategies that are environmentally sub-optimal and lack onshore processing facilities, which limits domestic value addition and the benefits these industries could provide. Nonetheless, across Indonesia, seaweed farming has substantially raised living standards for many coastal communities through step changes in income, increasing women's access to financial resources, and supporting infrastructure development. These benefits have struggled to be realized in Tanzania where production in shallow waters has led to vulnerability to disease outbreaks and storm damage, compounding labor demands on a typically female-dominated industry with disproportionately low economic return. Diversified production systems which integrate and optimize resource use through co-culture or as part of a suite of livelihood activities aimed at maximizing contextualized local benefit (as in the case of Bangladeshi carp farming or US and Scandinavian oyster farming) seemingly minimize trade-offs across sustainability domains. By mapping specific SDG targets onto well-resolved sustainability indicators, the chosen methodology provides a measure of uncertainty in how any one or multiple aquaculture systems can inform the SDGs in different locations.

5.3 | Reporting progress on the SDGs—Indicators

The great diversity of aquaculture and its global extent are not only signs of its potential to contribute positively to the Agenda 2030, but also of a complexity that may challenge the capturing and reporting on its contribution to the different SDGs. The latter all the more so as indicators for specific goals are themselves spread across several custodian agencies. As aquaculture supports and connects to all the 17 SDGs, its evolution should be able to be measured, using most of the indicators developed by the UN General Assembly (2016). However, specific indicators to measure economic, social, and environmental sustainability of aquaculture systems have already to some extent been developed and are readily available (Boyd et al., 2007; Sustainability criteria for the blue economy, 2021; Valenti et al., 2018), and they would be useful for supporting the assessment of the evolution of the aquaculture sector towards the SDGs targets.

Within countries, the government, private sector, academia and research institutions, and civil society all have a responsibility to report on their activities for national statistics. The quality of the data is essential to obtain reliable progress from the indicators. However, statistics and government data are weak in developing countries because the institutions have low budgets, few technical specialists in analytics and limited access to governance infrastructure. As much of global aquaculture takes place in developing countries, these and other constraints make it challenging for obtaining good data on SDGs indicators, particularly evaluation of progress. As reported by the FAO

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(FAO, 2020a, 2020b), "A lack of reporting by 35%–40% of the producing countries, coupled with insufficient quality and completeness in reported data, hinders FAO's efforts to present an accurate and more detailed picture of world aquaculture development status and trends. Thus, the data validation process is important, and the results of indicators should be analysed with caution." The lack of genderized data, as in other food sectors, will also hamper aquaculture's contribution to attaining SDG objectives.

Efforts are currently underway to capture the extent to which enterprises in the agricultural sector—including aquaculture, as well as those engaged in food processing, wholesale and retail, contribute to the environmental, economic, social and institutional dimensions of the SDGs (FAO FSN, 2021). SDG Indicator 12.6.1 (the number of companies publishing sustainability reports) itself provides national governments with the possibility to collect relevant data on the private sector's contributions towards the SDGs. The data compiled by enterprises can then be used as an important source of data for the SDG monitoring framework, but also to design targeted approaches to promote change in corporate behavior regarding sustainability issues in the food sector. This is already happening and many seafood companies (including feed producers) now include performance reporting against the SDGs. This is a positive development but the format for reporting needs to be strengthened to fit better with the SDG indicators. One challenge with respect to reporting from the aquaculture sector remains, similarly within agriculture and capture fisheries, and this relates to the sector being dominated by the myriad of small-scale farmers with limited possibilities to collect data and absence of proficient reporting structures, i.e. owner operated small shrimp farms in Thailand. Lessons can be learned from the inshore fisheries sector where simple mechanisms are employed to enable individuals to record and share their catch data (Korda et al., 2021).

6 | UNDERSTANDING OF HOW AQUACULTURE CAN CONTRIBUTE TO ACHIEVING THE SDGs—CONTEXT SPECIFICITY AND TRADE-OFFS

Aquaculture's contribution to achieving the SDGs depends to a large extent on species/systems and the context, that is, being related to value chains, product markets (export/domestic), national economy, socioeconomic structures/fabric and governance at different spatiotemporal scales. Especially the importance of smaller scale actors in value chains is missing and given their importance and their comparative impacts on broader poverty alleviation this will be important to capture (Filipski & Belton, 2018; Kassam & Dorward, 2017). Thus, harnessing the diversity of small-scale actors is key to the future of aquatic food systems (Short et al., 2021). Without this understanding it will be difficult to make predictions of how any specific aquaculture development will play out and add value to particular policies, for example, circular economy, biodiversity conservation, climate emergency, transition to net zero and food security to mention a few relevant for the SDGs. To understand, project, and manage the different impact pathways through which different developments or innovations might operate and their potential effects on multiple SDGs (and possible trade-offs) has been subject of considerable research in sustainability transitions in multiple sectors (Dorninger et al., 2020; Gaitán-Cremaschi et al., 2019; Geels et al., 2016). Trade-offs related to aquaculture's contribution to (and negative impact on) the SDGs takes place at multiple scales (environment, social, geographical) and between different types of developments (e.g., type of food production systems), as well as between different types of aquaculture systems. Singh et al. (2018) investigated co-benefits and trade-offs across the goals of SDG 14 and the other SDGs, using an approach assessing compatibility requirement for fulfillment and context dependence of SDG targets. They suggested also that the framework could be used to explore relationships between other SDG targets (or similar multi-goal policies e.g., the Convention on Biological Diversity's Aichi Targets, etc.), and that it could be modified to increase its relevance in specific contexts (e.g., national/regional scales). Although they identified that the realization of all SDG 14 targets was, to various degrees, co-benefiting the realization of other SDG targets, the analyses missed aquaculture (e.g., in this case marine), because of the lack of aquaculture specificity in SDG 14 targets and indicators, and the fact that it is (implicitly) encompassed in so many other SDGs. It is important for aquaculture development to further develop its relationships with other production sectors, that is, agriculture and capture

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fisheries, especially related to resource utilization, environmental, economic, and social impacts. Thus, trade-offs related to how a particular production system contributes to the SDG is a reality for aquaculture development as well as for all other types of developments. Trade-offs occur in multiple dimensions so to help characterize those most relevant to aquaculture, a two-tier system is proposed. The contribution of how aquaculture relates to trade-offs can be characterized using the below two different "Tiers":

6.1 | Trade-offs "Tier1": Selecting and prioritizing a specific type of aquaculture

At the local level, consequential trade-offs may involve licensing or prioritization to access and use aquatic resources for aquaculture; at national level, decision-making about investments in aquaculture or fisheries or other aquatic sectors. At an international level, decisions about trade-agreements, for example, tariffs, are used in the Common Fisheries Policy (CFP) levels. Economic drivers, particularly when underpinning jobs and food security often prevail in negotiations over sector deals and are prioritized by governments. Thus, countries make trade-offs all the time and economic prosperity is often prioritized over social and environmental considerations. A general negative image of aquaculture has in many places (especially in the western world) resulted in weak political will to support development or expansion of the sector but this is now changing. The diversity within the sector offers potential as well as challenges and the potential for negative impacts need to be evaluated from a broader social–ecological system perspective. Figure 7 illustrates fed aquaculture's potential negative interaction with the environment and resources. In geographical regions where aquaculture is not part of the tradition or essential for local residents' food security or livelihoods, environmental concerns and recreational activities may override establishment of aquaculture. Even in situations where aquaculture has a long tradition and part of the culture it may be selected against when new alternatives develop—for example tourism (although under some contexts tourism and aquaculture have become positively linked). Social and cultural benefits of aquaculture such as the educational and networking opportunities that arise from capacity building of the sector are frequently overlooked or are invisible to policy advisers.

Constraints that can lead to prioritization unfavorably for aquaculture development and the opportunities for it to facilitate progress towards the SDGs include:

1. Equitable access to land and water—aquaculture is often underdeveloped in many countries' planning systems as commonly categorized under fisheries or agriculture. Thus, a need to improve aquaculture governance in planning and national strategic plans where they exist.
2. Market governance is weak—coordinated sector responses need to be developed that enhance rather than compete with other food-producing sectors such as fisheries.
3. Perceptions and attitudes impact behavioral responses and often when negative may account for the unwillingness of decision makers to support aquaculture.

6.2 | Trade-offs "Tier2": Selecting among different aquaculture systems

Understanding trade-offs across SDGs for different types of aquaculture, as well as ensuring an enabling or facilitating environment, are needed to deliver on the SDGs. No doubt any approach will be highly context specific (geographic and temporal) and must be assessed from likely short, medium- and long-term consequences (Hambrey, 2017). Identification of possible trade-offs between the different SDGs associated with different aquaculture development trajectories—that is, type of systems—pose a large challenge even if using an existing framework specifically targeting co-benefits and trade-offs across goals (e.g., Singh et al., 2018). This is not only because the need for detailed information about a systems general performance will be high, but because the additional need for local knowledge, experience, and perspectives is required for tailoring action likely to deliver positive impacts in the

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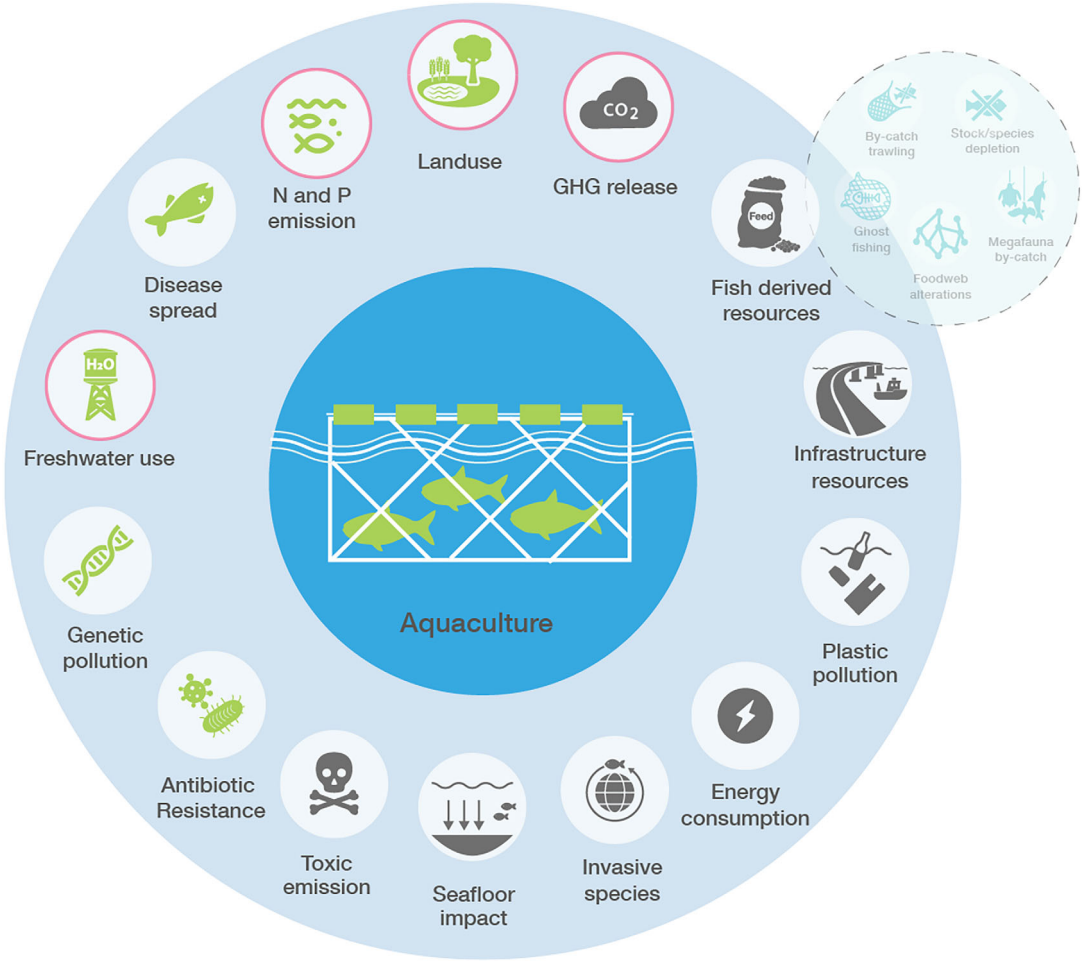

FIGURE 7 Overview of aquaculture's potential interaction with the environmental and resource systems for consideration in assessing Sustainable Development Goal outcomes. The small blue circle illustrates aquaculture feed linkages to capture fisheries. Rebuilt from Gephart et al. (2021).

specific context targeted (Hambrey, 2017). When developing aquaculture policies and deciding about investments and development in aquaculture it is important to have analyzed consequences from possible trade-offs and consider these separately from a broader system understanding (e.g., Brugere et al., 2021). Identification of key trade-offs enable understanding of how these may constitute barriers to upscaling or expansion. For aquaculture, this becomes even more challenging because of its absence in the SDG targets and indicators—which makes applying a method like that of Singh et al. (2018) very difficult in practice. Categorizing different types of aquaculture (archetypes, Table 2) to better align with various policies should enable the relationship between governance efficacy and management effectiveness to improve progress toward meeting the targets of the SDGs.

6.3 | Examples of trade-offs

- Salmon production in Chile has increased massively at a human cost because of infringements on human rights and health and safety standards on fish farms (Díaz, 2009; Riedemann Fuentes et al., 2020) and erosion of traditional

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culture (Barton & Román, 2016). However, perhaps the most important trade-off, from the local perspective, relates to the positive contribution of salmon farming to local employment, including more opportunities for women and reduction of local poverty (Cardenas-Retamal et al., 2021; Ceballos et al., 2018), versus environmental impacts (e.g., escapees, diseases, chemical use). Naylor et al (in review) identified how seafood consumption in Chile has been declining despite rising incomes and increased aquaculture production. Thus, produced salmon and mussels are to a large extent being exported and people are increasingly eating more terrestrial meat products. Thus, some of the benefits (health benefits) may occur far away (e.g., consumers in seafood importing countries) instead of locally. Rebalancing this would imply that there are mechanisms in place so that the revenues from exports fall back on the people and communities where production is generated in the first place, that is, through taxes (Soto et al., 2021).

- Aquaculture can impact negatively on capture fisheries potential to deliver on many of the SDGs (Clavelle et al., 2019; Farmery, Allison, et al., 2021; Farmery, White, et al., 2021; Naylor et al., 2000) as a result of impacts on aquatic habitats and competition for fishery resources. However, again, the overall benefits from aquaculture need to be evaluated.
- In addition, fisheries and aquaculture interact through market competition indicating the need for integrated planning and management of the two sectors for understanding different SDG outcomes.
- Nutritional trade-offs can arise where increased consumption of farmed fish replaces more nutritious wild fish (Belton et al., 2014; Bogard et al., 2017) and also where nutrient profiles of fish are altered in response to different feed ingredients selected based on economic or environmental considerations. However, farmed fish still provides nutritional benefits and it is difficult to know to what extent increased availability may offset any changes in nutritional quality for people's health and well-being.
- Aquaculture companies often align themselves with SDG 14 (Life in Water) to highlight the role of farming large (medium to high value) fish in reducing depletion of wild fish stocks. A complication of this is that the use of fishmeal and oil in aquaculture feeds for some species limits the potential for smaller highly nutritious fish to be directly consumed, by humans and other predators alike. However, drastically reduced reliance on fishmeal and oil in farmed finfish such as salmon has shifted this link towards land (Tacon et al., 2021; Troell et al., 2014). This shift is an example of how new links bring different benefits and costs that need to be carefully considered. By connecting a greater fraction of feed nutrient supply to industrialized crops, we may end up sparing fish from the sea but inadvertently contribute to risks associated with agriculture-derived land-conversion, nutrients and pollutants entering aquatic waterways, and their potential effects on coastal ecosystems and fisheries.
- An example of trade-offs within SDGs resulting from aquaculture is remediation of regional eutrophication by mussel farming that potentially may cause local eutrophication that works against nature preservation objectives (Cranford et al., 2009). However, such trade-offs can largely be resolved through spatial planning (Aguilar-Manjarrez et al., 2017; Lacoste et al., 2020).

These examples of trade-offs serve to highlight the multi-faceted nature of aquaculture practices and emphasize the importance of identifying challenges and opportunities to enable the sector to better contribute towards progress in achieving the SDGs.

7 | INCREASING AQUACULTURE'S POSITIVE CONTRIBUTION TO THE SDGs—CHALLENGES AND OPPORTUNITIES FOR GOVERNANCE

Key challenges and opportunities, and also actions, for the aquaculture sector to continue contributing positively to Agenda 2030 are summarized in Table A2 (Appendix A) (Box 3). Below are some extended discussions of key selections.

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BOX 3 Private aquaculture sector engagement—incorporation and guidance by the SDGs.

More and more large seafood companies are engaging with the SDGs and presenting this engagement through their annual sustainability reporting. This also includes aquaculture feed companies that now map their current strategy and activities against the SDGs and align their established measurement criteria and focus areas with the SDGs identified as most relevant for their business. While industry engagement with SDGs is positive, the way in which companies measure progress towards contributing to the SDGs is not comprehensive, focusing on a limited range of SDGs. Environmental stewardship remains a key focus of aquaculture certification schemes (Osmundsen et al., 2020) and of companies seeking social license. Addressing a broader range of issues is not a priority for many companies or may not be feasible for medium and small-scale enterprises. Food security (SDG 2) remains one of the least commonly prioritized SDGs by large companies—but may be true also for small-scale producers. Large seafood companies based in the global north (not exclusively) also develop business partnerships (SDG 17) with smaller companies in the south—involving, for example, technology transfer and sometimes co-ownership.

Market-based tools such as eco-certification have been one of the main sustainability mechanisms used in the sustainable seafood movement and these relate to many of the SDGs. Environmental sustainability has been in focus but social performance is increasingly being considered. Today the volumes of certified farmed fish and shellfish constitute about 8% of global aquaculture production (76.7 million tons, 2015) (Jonell et al., 2019). Alongside the spread of private, global eco-certification schemes (e.g. ASC, Global GAP), state-initiated national certification programs for aquaculture have developed (e.g., GAP, CoC, GAP-7401, VietGAP, and IndoGAP, see Tlusty et al., 2016). Creating a metrics and evaluation framework that will encourage elucidation of the environmental and social gains made through certification will be important and here the effects on the SDGs may be useful as this provides for broader systemic insights (Jonell et al., 2019).

7.1 | Improvements for capturing/monitoring aquaculture's contribution to the SDGs: A gender perspective

Census data needs to better disaggregate household level and individual dependency on aquaculture so that socio-economic components can be better understood, particularly in relation to gender. This could involve:

- Collection of gender-disaggregated data in aquaculture which has long been called for and remains problematic. Gender data is often not detailed, especially regarding casual work, which is common in aquaculture and fisheries production/processing. It remains a challenge to show the visibility of women's participation in aquaculture (as a starting point to progressing towards gender equality in the sector) (Brugere & Williams, 2017).
- The biannual questionnaire sent by FAO to its member countries to monitor the implementation of the 1995 Code of Conduct for Responsible Fisheries (within which Article 9 is on aquaculture) does not include any questions on gender—which is not surprising given the Code itself is gender-blind (Williams, 2016).
- It is well known and documented that more women are present in the post-harvest sector (FAO, 2020a, 2020b), and although sex-disaggregated data is becoming more available, the products are not clearly disaggregated according to their source (farmed vs. caught), so tracking the contribution and benefits of women in aquaculture

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post-harvest value chains specifically is difficult—unless one looks at the products individual companies are transforming and their staff.

- Reporting against SDG 5 offers the sector an opportunity to do better at increasing the visibility of, and opportunities for, women in the sector, especially in relation to the reporting responsibilities of the private sector/companies (cf. point above, ex. Indicator 5.5.2 Proportion of women in managerial positions).
- Reporting also needs to enable capture of casual employment within the seafood sector, that is, especially within post-harvest activities where women play an important role.

7.2 | Climate change and emerging global stressors

Climate change has implications for aquatic systems, for example, increasing water temperature, sea level rise, acidification, changed precipitation patterns and freshwater availability (Dabbadie et al., 2018; Tigchelaar et al., 2021). Eutrophication is exacerbated, resulting in increasing incidences of algal blooms and hypoxia and pollution of bacteria and toxic compounds (Liu et al., 2017). The frequency of severe weather events is increasing and there are geographical species distribution shifts, including invasive species, pathogens and the incidence of diseases (Barange et al., 2018; De Silva & Soto, 2009). All of these changes may challenge the potential for aquaculture's future contribution to the SDGs. However, change is already happening with unevenly distributed effects across the world (De Silva & Soto, 2009; Soto et al., 2018).

Aquaculture production in low latitude countries will likely be most negatively affected from direct climate changes (Barange et al., 2018), while effects in northern latitudes may be both positive and/or negative. This creates challenges for existing farming to deliver on the SDGs but at the same time also creates opportunities for farms to be established in regions where farming conditions improve. Climate smart aquaculture may offer a proactive way for countries to build resilience in food security through, for example, selective breeding for traits able to evolve and withstand future predicted changes (Hoegh-Guldberg et al., 2019). In addition to direct impacts on farms environmental stressors also act on supporting systems providing the aquaculture industry with raw materials for feed. Climate projections indicate decline in production of some key crops and fish species (e.g., AgMIP, FishMIP, see Blanchard et al., 2017). General degradation of both terrestrial and aquatic ecosystems may also lead to more volatile crop and fish production, increasing risk of environmental shocks for raw material supplies (Cottrell et al., 2019; Froehlich et al., 2018; Gephart et al., 2017; Klinger et al., 2017).

Demands for space (land and sea) and freshwater will increase as well as competition with other users (Jouffray et al., 2020). Agriculture accounts for about 70% of the freshwater withdrawals in the world and is the main factor behind the increasing global scarcity of freshwater (Alexandratos, 2005; Bruinsma, 2009). A projected 55% increase in water demands for agriculture is expected by 2050 (Leflaive, 2012). Expansion of freshwater aquaculture on land may compete with agriculture for access to the same land and direct use of freshwater, but this competition may be reduced as intensification can occur within existing practices and efficient water management implemented (Beveridge et al., 2018, Belton et al., 2020; Zhang et al., 2022). For expansion in the sea both coastal areas and offshore areas offer opportunities for growth, although in some heavily populated coastal regions the competition for space may be intense and water qualities deteriorating (Liu et al., 2017; Troell et al., 2017). Expansion of ocean energy production from renewable sources may offer the potential for aquaculture to co-locate, integrating its production system with the logistics, power sources and human capacities of a larger industry as it moves offshore (Buck et al., 2018; Buck & Langan, 2017; Troell et al., 2009).

The impacts of aquaculture on climate through release of GHGs are largely determined by species, system, production methods, location and management (Barange et al., 2018; Gephart et al., 2021; Troell et al., 2014; Waite et al., 2014). Many studies have shown that aquaculture can have lower carbon footprint emission compared with terrestrial livestock—that is, in particular cattle (Gephart et al., 2021; Hallström et al., 2019; Hilborn

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et al., 2018; Poore & Nemecek, 2018). Henriksson et al. (2021) identified overlooked potential for implementing interventions to improve productivity and environmental performance of aquaculture species—in particular related to low-value, high-volume species that currently account for the majority share of aquatic food production.

Feed is the single largest contributor to GHGs from global aquaculture (MacLeod et al., 2020). Use of aquaculture feeds is increasing and much effort is going into production and utilization of feed resources that do not compete with demand for direct human consumption, such as fish processing by-products and other processing side streams, crops (soy, canola, maize, etc.), insect meals and single-cell organisms (Cottrell et al., 2020). There is a need for critical reflections about the various trade-offs with other SDGs in the use of these "noble feeds." Even though there is interest in ecological intensification of pond aquaculture, where underutilized and inexpensive agricultural products are used as feed ingredients and stimulate the production of natural food in the pond (Joffre & Verdegem, 2019) the trend is greater use of formulated diets. Technological innovations, combined with massive increases in production of solar and other renewable energy, enable aquaculture to decarbonize and have lowered prices to the point that in most parts of the world they offer the cheapest sources of energy, facilitating the transition. Efforts for reducing environmental impacts may come at high economic costs and risks (e.g., high tech. recirculation systems or offshore installations) and potential consequences related to different trade-offs need to be considered in future scenario planning.

Technological improvements, including genetic selection can also increase aquaculture contribution to SDGs. Reduction of feed conversion ratios in salmon farming is a good example, resulting in lower environmental footprints (including carbon footprint) through improved farming efficiency (Henriksson et al., 2021). If similar reductions could be achieved in other fed species, such as carps, tilapia, catfish it would further improve the sustainability of the sector (Hasan & Soto, 2017). Research to develop vaccines for major diseases and use of other environmentally friendly disease prevention and mitigation approaches such as probiotics, biofloc systems, etc., may also be important for improving growth performance (Box 4).

BOX 4 "Blue economic growth"—consideration of aquaculture's contribution to the SDGs.

The risks for inequalities resulting from aquaculture development and the overall seafood sector needs to be considered as this may threaten achieving sustainable aquaculture and meeting the SDGs more broadly. Applying an SDGs lens to aquaculture development enables a deeper understanding of social–ecological equity and food justice outcomes. For example, mariculture is considered to be a vital component of the "blue economy"—a concept in which ecosystem degradation is minimized and social benefits enhanced at the same time as revenues from the sustainable use of marine resources are optimized (FAO, 2015). The concept is interpreted differently by stakeholders and the scope and boundaries of the blue economy in line with the SDGs are vague (Lee et al., 2020). Costello et al. (2020) showed through modeling that mariculture (fish and shellfish) could increase significantly—although this has been challenged (Belton et al., 2020). This aquaculture sub-sector does, however, not currently produce as much food as freshwater aquaculture (73% of all farmed seafood—edible weight) originate from freshwater aquaculture (Edwards et al., 2019; Naylor, Hardy, et al., 2021; Naylor, Kishore, et al., 2021), and the products farmed are often destined for export markets. While generally having a lower environmental footprint than other animal proteins (Poore & Nemecek, 2018; Tilman & Clark, 2014), mariculture's contribution (fed systems) to local food security and livelihoods has been questioned (Belton et al., 2020; Farmery, Allison, et al., 2021; Farmery, White, et al., 2021). Better alignment of mariculture, and the blue economy more broadly, with the SDGs will help ensure the potential for growth and development, as well as protection of ocean resources, are realized.

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8 | CONCLUSIONS

Aquaculture holds huge potential to contribute positively to human and planetary well-being when outcomes are aligned with the Sustainable Development Goals. However, the evidence base remains variable but rather weak, further undermining policy change (Béné et al., 2016). The potential for the sector to further contribute to these aligned goals using frameworks such as that developed for the UN SDGs seems large. Aquaculture already contributes substantially to the many SDGs but the diversity of species/systems, in combination with different contexts, can result in different SDG outcomes not being fully realized or visible. This needs to be carefully evaluated. Our review concludes the UN SDG framework is a useful and needed lens for supporting sustainable transformation of aquaculture into the future on a global scale (Hambrey, 2017; Stead, 2019). But unless action can transform the political will to recognize the potential value of aquaculture across all the SDGs then this sector will remain uncoordinated and invisible to many national (food) policies. From a policy perspective aquaculture is governed differently depending on the country, for example, in some it comes under agriculture policy, in others it comes under fisheries or natural resources among others. This also only constitutes a partial part of governance, that is, that also is an outcome of private sector interactions, local cultural rights and norms, etc. The full potential of aquaculture to achieve targets of the SDGs may also only be realized if brought into broader food and natural resource systems decision-making. With the fundamental dependencies among aquatic and terrestrial food (and also other) sectors, there need to be clearer linkages among planning systems. One way to break down sector/policy silos is to use overarching themes like net zero or the triple challenge of people, planet, and climate. This requires integrated governance and systematic inclusion of aquaculture in policy development. A basic change in the way many think about aquaculture could be improved through narratives that better link the wider benefits using the SDG framing.

In addition, a deeper understanding of how aquaculture (systems and species) relates more broadly to the different SDGs, and also how existing indicators enable (or not) us to monitor change, are also needed to increase visibility of its potential to policy makers. The application of two assessment methodologies (i.e., impact pathway and Wheel of Sustainability) indicates ways to enable mapping of aquaculture linkages and contributions to the SDGs to be better understood and visualized by non-specialists. However, as pointed out in the paper, also indicated by the case studies, understanding about the specificity related to how contexts will shape aquaculture's contribution to the SDGs is imperative. Testing the methodologies described herein on other aquaculture systems and finding ways for simplifying the analysis should be a next step. Existing indicators that already to different degrees are reported should be evaluated and built upon (and the need for new ones be suggested). This would need careful review of the statistics that different nations collect and their efficacy evaluated to understand how they capture contribution to the SDGs (Box 5).

BOX 5 Summary of key messages.

1. Aquaculture contributes to all 17 SDGs but where data exists to evidence its impact are those related to (A) eliminating hunger and improving health (SDGs 2, 3); (B) increasing environmental sustainability of oceans, water, climate, and land through responsible production/consumption (SDGs 6, 12, 13, 14, and 15), and (C) reducing poverty, achieving gender equality, improving livelihoods, and reducing inequalities (SDGs 1, 5, 8, and 10).
2. Aquaculture is an important sector that contributes to human well-being, but better linkages between aquaculture, health, the broader food system, and natural resource management policy and practice need to be established for the sector to play a greater role in efforts to achieve the SDGs in this generation.

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3. Acknowledgement—and better identification—of aquaculture's present and future potential role in the global food system, for example, for rural and urban development (and redevelopment), for healthy and sustainable diets, for human health and wellness, will improve our understanding of its potential for positive contributions to many of the SDGs and influence effectiveness of policies and impact.
4. Integration of land and ocean-based aquaculture with emerging renewable energy systems, existing agricultural systems and other sectors of the economy (e.g., tourism) to accelerate aquaculture's contributions to the SDGs should be further explored to build cohesive strategies with common goals.
5. Key institutions at the global to local levels need to monitor aquaculture's contribution to the different SDG indicators through existing structures, while also continuing to build on these and to develop new tools that capture the wider benefits of aquaculture. Such monitoring is also essential to compare and demonstrate aquaculture impacts and trade-offs with respect to other food systems and livelihoods.
6. Having a broader value-chain perspective will be imperative for gaining deeper insights about aquaculture's overall contribution to the SDGs, for understanding outcomes from investments and transformation efforts especially in diversifying supply chains and livelihoods.
7. Understanding the specific contexts in which aquaculture development will be embedded is needed to realize how aquaculture can deliver on the SDGs (locally and globally). Different contexts determine how aquaculture production and value chains will generate benefits (and impacts) for society and the environment, framed by both local characteristics and global connections, that is, relationship to distant resource systems (e.g., feed ingredients) and markets (export benefiting consumers elsewhere, etc.). Identifying and considering trade-offs at local and global scale—that is, local negative impacts and more distant benefits—will be important for enhancing supportive governance processes.
8. Inequalities resulting from some aquaculture developments threaten achieving sustainable aquaculture and meeting the SDGs. Applying SDGs lens to aquaculture development enables a deeper understanding of social–ecological equity and food justice outcomes, thus enhancing self-regulatory operations.
9. Data representing values/benefits from the aquaculture sector need to be more detailed regarding gender. The specific role of aquaculture for the SDGs is generally not obvious because of lack of disaggregation of gendered data for livelihoods in the capture fishery and aquaculture sectors. Better disaggregation at various scales, including household level, enables quantification of specific aquaculture benefits and dependency. This information is commonly unavailable.
10. Improved ability to gain a social license to operate for ocean/aquatic food systems, especially aquaculture, will require accelerated education on wider benefits for local decision makers and the public to make informed choices. Consumers' understanding of aquaculture's role for achieving the SDGs is essential. New narratives that are evidence-based are needed to help combat the negative image of the sector which impacts political will.
11. Learning how global risks and emerging climate challenges relate to performance of various aquaculture systems is urgently needed to build resilient strategies able to combat faster recovery from the impacts of COVID-19 and other external global events such as the financial crisis in 2008. A nuanced understanding will be key in national and international development agendas (food, livelihoods, conservation and restoration aquaculture, etc.). Aquaculture strategies where past and future global shocks are built upon will be important, together with improved resilience for sustained businesses.

This paper highlights why a new narrative on the complexity of the diverse aquaculture sectors' direct and indirect benefits is needed to align with different contexts and policies aimed at achieving the SDGs in this generation. Such a narrative could facilitate expansion of the sector and improve governance on the best type of aquaculture

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that can meet the vast array of indicators and targets. Thus, this would enable delivering context-specific advice that improves the comprehensive and cohesive planning of aquaculture at a range of spatiotemporal scales. It is important to recognize that aquaculture is no panacea for global food security or for reaching the SDGs, but it can make important contributions if planned and executed well.

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DISCLAIMER

The views expressed in this publication are those of the author(s) and do not necessarily reflect the views or policies of the Food and Agriculture Organization of the United Nations.

ORCID

Khalid Salie https://orcid.org/0000-0001-8172-856X
Rodrigue Yossa https://orcid.org/0000-0003-4792-0173

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APPENDIX A

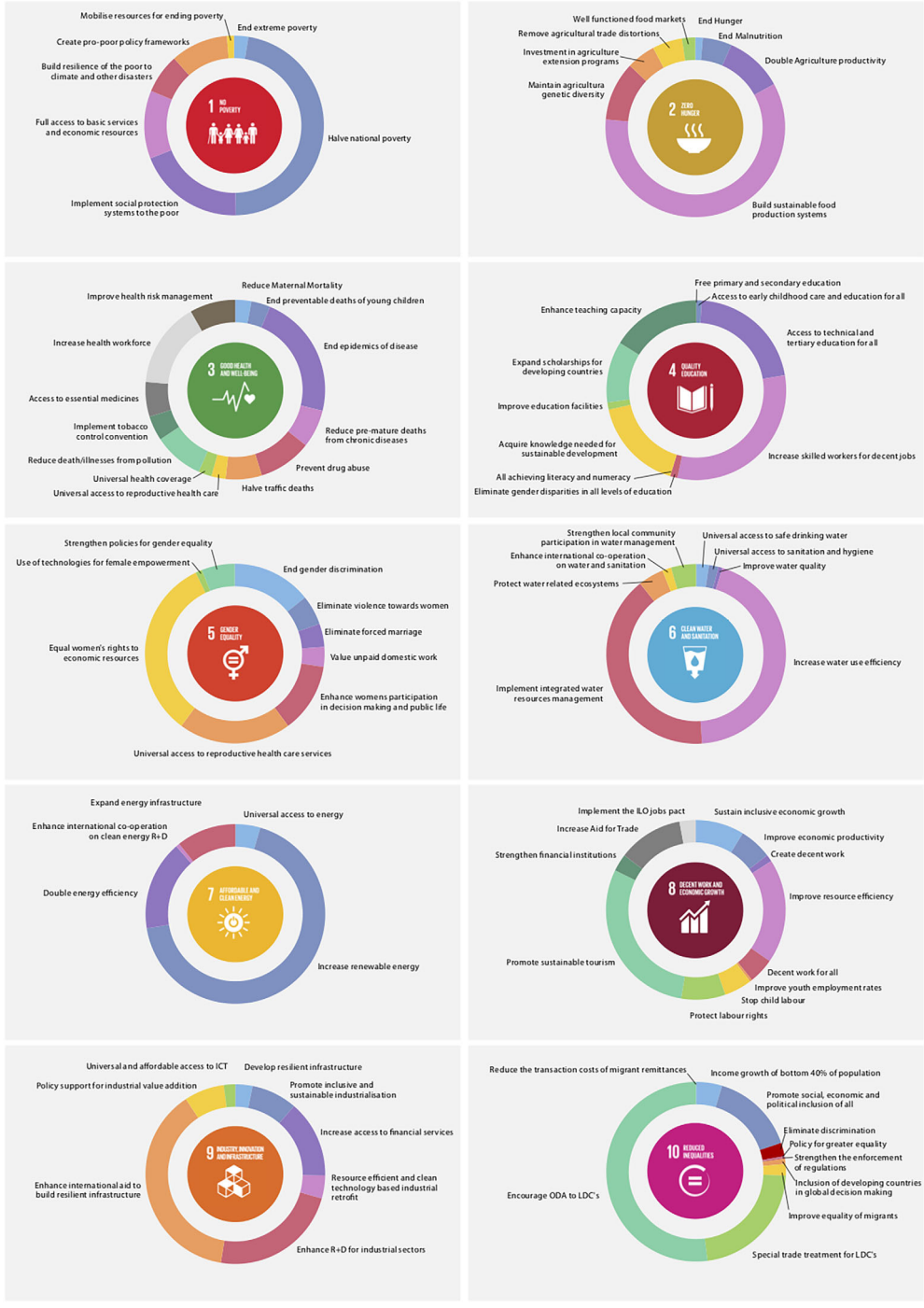

FIGURE A1 Higher resolution of results from literature search for each Sustainable Development Goal and its indicators.

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FIGURE A1 (Continued)

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TABLE A1 Mapping of Sustainable Development Goal (SDG) targets onto sustainability indices adapted from Osmundsen et al. (2020) and FAO core agricultural indicators of SDG contribution (https://www.fao.org/agrifood-economics/publications/detail/en/c/1507902/).

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
Economic	Labor and employment	2.3. "double agricultural productivity and incomes of small-scale producers… women, indigenous peoples, family farmers, pastoralists and fishers… through opportunities for value addition and non-farm employment"	Intensification of pond-based inland aquaculture has led to increases in daily labor rates for agricultural workers in areas where aquaculture is concentrated, for example, Mymensingh. benefits have occurred through both the upward and downward linkages within the value chain. For example those employed in the manufacture and trading of feeds, seed, and chemical inputs and those engaged in processing and or marketing products (++)	Lucrative activity for many farmers, when practiced alongside other coastal activities, for example, fishing, farming land crops. USD 5000 avg annual income (up to 15,000) to 20,000 farmers (++)	Productivity with current farming technology (peg and rope) very low. Zero value addition locally (nearly all production in Zanzibar is exported to Europe and the US), and derisorily low farm-gate prices for women producers (−−), (3, 1)	Often performed as small-scale side business or family farms, however, very little value adding and non-farm employment (0)	The salmon industry has had an important impact on employment and income in the regions where it has developed in southern Chile. There is specific evidence that it has contributed to reduce poverty in the rural coastal zones where salmon farms have been installed, which is basically households composed of small producers. Ceballos, Adams, Jorge David Dresdner-Cid, Miguel Ángel Quiroga-Suazo. 2018 (++)
		4.4. "increase the number of youths and adults who have relevant skills…for employment, decent jobs"	A large source of additional employment have been fishers/netsmen who work in teams to thin and harvest fish from overstocked; ponds through the production cycle Most of those examples involve younger people with limited access to formal training opportunities but that provide decent jobs that provide incomes that are considerably more than basic agricultural laboring jobs (++)	Largely conducted by many nuclear family members with share in farm benefits/ ownership (0)	Conducted at 90% by women, on a small, individual scale. Very low attractivity for youth in its current form (−−) (3)	Conducted mainly by adults except for in the case of family farming where youths are attracted to and engage in the activity. Know how is passed on from adults to the youth. Little formal training but increasing) (0)	The main impact of the salmon industry has been through the development of the service sector and through learning by doing. Notwithstanding, it is possible to reports special initiatives of the salmon industry to offer technical and vocational instruction to young workers (UN General Assembly, 2016) (++)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		8.2. "focus on high value labor-intensive sectors"	Value chains have diverse and often very specialized tasks such as individuals who specialize in removing pituitary glands from market sized carp to supply hatcheries or provide cleaning services for purchased fish in retail markets for a small fee (++)	Dominated by small-scale producers—need highly flexible labor, and requires only low capital and technology for startup. Also large number of agents and collectors have been able to establish within value chains. Farmers income equivalent of average degree qualified positions in cities (++)	In its current form, very labour intensive, in difficult work conditions, for little returns (−−) (1: Frocklin et al., 2012).	Short and simple value chains aiming at the high-end market, staff works with varying aspects during production and very little processing. Small-scale and labor-intensive (++)	There is evidence of the enormous impact that the advent of the salmon industry had on the regions were it installed. This develop several input–output linkages, economies of scale, competition, diversification, technological development and innovation (Perlman & Juarez-Rubio, 2010) (++)
		8.3. "development oriented policies, decent job creation… encourage growth of micro, small and medium-sized enterprises"	A high proportion of functionally landless households represent the major group of poor and ultra-poor in rural Bangladesh with limited access to productive assets reflecting highly skewed land ownership patterns. examples above demonstrate the "quiet revolution" (Hernandez et al., 2018) whereby quality employment throughout the value chain has occurred. But this is probably less related to "development oriented polices" and more about immanent development (Belton and Little, 2011) (++)	Dominated by small-scale producers—need highly flexible labor, and requires only low capital and technology for startup (+)	Seaweed farming should be, in principle, a good candidate for this (second export after cloves in Zanzibar), but currently is not a priority at policy level (–) (3)	Mostly small-scale farmers with high-value products, work conditions are generally good although the work can be physically tough, licensing procedures are in the process of being simplified and streamlined (+)	The salmon industry grew initially as a group of small independent firms with heavy reliance on foreign technology and production inputs. It developed to an integrated complex industrial composed of large amount of interdependent small, medium and large producers, processors, distributors, and service firms (Olson & Criddle, 2008) (++)

(Continues)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		8.5. "productive employment and decent work for all women and men, incl. for young people and persons with disabilities"	The highly dispersed nature of aquaculture and the centrality of fish to diets means that aquaculture has spread to even disadvantaged groups such as the *Adivishi* (see Barman; (http://pubs.iclarm.net/resource_centre/WF_2484.pdf) (++)	Income from seaweeds is accessible to marginalized groups, for example, women and older communities (+)	Currently unproductive employment defying decent work conditions (−−) (1: Frocklin et al., 2012; http://marineagronomy.org/sites/default/files/Frocklin%20et%20al%202012.pdf)	Work available to both women and men as well as to young people, especially when also integrated with tourism activities and fisheries. Persons with disabilities are not often engaged because of the harsh conditions during production (+)	The salmon industry has generated much productive employment. There is an ongoing discussion about the type of work created. There are several complaints about working conditions. However, the evidence is not clear, because the relevant unit of comparison is still unclear. The Study Department of the Ministry of Labor in Chile has several studies about working conditions in the salmon industry (0)
		8.6. "reduce the proportion of youth not in employment, education or training"	See above-numerous employment niches with very few barriers to entry (+)	Income from seaweed farming has increased access to formal education and training for many farming families in Indonesia (+)	Not a very attractive option for employment for the youth, in its current form (−) (3)	Offers employment alternatives in rural areas, supplemental livelihoods for families and for youth with little formal training. Low effect because of small scale of sector (+)	The industry has generated opportunities for youth training, but we do not have figures (?)
		8.7. "Take immediate and effective measures to end forced labor… elimination of the worst forms of child labor"	Employment in aquaculture in general have increased incomes and choices for landless people, improving their negotiating power in what is a highly inequitable context. Child labor remains widespread throughout all sectors of the economy (−)	Given the family oriented business model, not clear to what extent children, women or other groups are coerced into labor (?)	Same as Indonesia (0)	This is inherent in the societal context of the CS (NA)	(NA)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		8.8. "protect labor rights and promote safe working environments"	Not particularly safe environments, although much kinship based employment, exploitation is the norm (−)	Management of rights and operations largely woven into cultural village fabric so unclear as to whether local customs uphold widely accepted human rights (?)	Same as Indonesia regarding labor rights. Current working environment is not entirely safe. Health and safety risks need to be addressed with both the traditional technology (peg and rope) and new tubular net technology (through swimming skills, safety at sea practices etc.) (−) (3)	Both North America and Scandinavia have a focus on safe working environments, labor rights are well developed in Scandinavia, less so in North America but still high compared with other regions. Yet this is not specific to the oyster culture sector (NA)	The salmon industry has generated much productive employment. There is an ongoing discussion about the type of work created. There are several complaints about working conditions. However, the evidence is not clear, because the relevant unit of comparison is still unclear. The Study Department of the Ministry of Labor in Chile has several studies about working conditions in the salmon industry (0)
		8.9. "promote local tourism that creates local jobs"	(NA)	Not a source of tourism in Indonesia and conducted in places usually more rural than main tourist areas (NA)	Seaweed is currently in conflict with hotel resort developments and tourist activities such as kite surfing (−−) (3)	Many small-scale farmers also engage in tourism activities, for example, "oyster safari" and/or gastronomic tourism with spin-off effects for the local community (++)	Impact on Magallanes and Argentina (Quiñones et al., 2019) (−)
		9.2. "promote inclusive and sustainable industrialization… and significantly raise industry's share of employment"	Most actors within aquaculture value chains remain family businesses but signs of diversification into value-added input products (feed, seed, chemicals) are common at the local level. Processors of shrimp and prawns and other larger employers are not known for inclusive norms. Innovation around intensification requires significant support if yield gaps are to closed and potential is to be realized (+)	Aquaculture could well become a strong platform for economic development in a blue economy framework, and seaweed aquaculture has proved valuable for rural development schemes. Carrageenan and agarophyte production have the scope to considerably increase. However, no value chain addition currently occurs in Indonesia but is exported to China (0)	Same as Indonesia but with increased emphasis on value addition locally (e.g., development of small processing units/factories). Currently however it is (−−) (3) since there is no processing, or sustainable industrialization of any form	Oyster culture provides significant environmental services during production and offers employment opportunities in rural areas. For the small-scale producers there is also an incentive to collaborate, for example, in forms of co-ops. Because of the small scale of the sector the impact is not significant (+)	The share of the salmon industry's employment in total employment (direct and indirect) in the regions where salmon production is located has increased significantly and in a permanent way (Resdner et al., 2017) (++)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		9.4. "upgrade infrastructure and retrofit industries… (for) increased resource efficiency and greater adoption of clean and environmentally sound technologies and industrial processes"	This remains a big gap and requires major innovation and investment (−)	Indonesia still relies on exporting to China for carrageenan because relevant skill sets are still insufficient (−)	New tubular net farming technology would be a good candidate/ contributor to this target, but currently it is in piloting phase. So (−) (3)	Oysters are extractive species and provide significant ecosystem services during production however all production will inevitably infer some environmental impact (e.g., littering from broken equipment, fuel used in boats and more). But relative to other animal food sources the production of bivalves has very low environmental impact (++)	This target is not clear! (?)
		9.5. "encouraging innovation and substantially increasing the number of research and development workers"	Bangladesh has a relatively strong academic/research infrastructure and dynamic NGO community but their links to private sector often remain undeveloped (+)	Several research organizations (academic, government and private) have grown to support seaweed farming in terms of business strategy, education, production, finance (+)	Several research institutions in Zanzibar dealing with seaweed and marine issues, idem NGOs (+) (3)	Significant collaboration between industry and academia in Scandinavia (++)	The salmon industry has developed rapidly to become a global player in the world market through catching up in technological innovations and the development of learning capabilities (Iizuka et al., 2016) (++)
	Wealth distribution	1.1. "eradicate extreme poverty for all people"	Bangladesh has made major strides in the last few decades in reducing extreme poverty and improved development across a large range of indicators. The rise and importance of aquaculture within the economy (unusally high % of GDP) suggest the significant role the aquaculture sector has played (++)	Growth has centered around small-scale producers which outcompeted larger vertically integrated companies in the 1970s—average income for Indonesian farmers is well above the poverty line (+)	Unequal outcomes currently. Seaweed farming is not getting families who farm out of poverty (−−) (1, 3)	Extreme poverty is not a big issue in the region and is mostly related to people not having access to the benefits offered by oyster culture (NA)	The industry has had a positive impact on reducing extreme poverty over the years specially in the Los Lagos region (Modrego et al., 2009) (+)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		1.2. "reduce by half the proportion of men, women, and children living in poverty"	The growth of aquaculture has already made a significant contribution but this is particularly the case in areas where commercial aquaculture has been geographically concentrated (+)	Growth has centered around small-scale producers which outcompeted larger vertically integrated companies in the 1970s—average income for Indonesian farmers is well above the poverty line and created education opportunities for children and income for women (+)	The farming needs to change, alongside policy attention and social norms for any progress towards this target to be made. So currently: (−−) (3)	Poverty is not a big issue in the region and is mostly related to people not having access to the benefits offered by oyster culture (NA)	The industry has had a positive impact on reducing poverty over the years in the Los Lagos region (Modrego et al., 2009) (+)
		1.4. "ensure that all men and women, in particular the poor and the vulnerable, have equal rights to economic resources, ..., ownership and control over land, ... natural resources"	This remains very difficult-access to and ownership of resources remains highly inequitable, BUT the rise of commercial aquaculture has spurred the rise in more dynamic markets for pond leasing that has allowed landless/poor people to become farmers-this is particularly the case for nursing juveniles (short production cycles/high cash flow) (+)	Women often have greater income than men from seaweed farming activities. While this can be a source of conflict, farmers surveys report significant improvements to living standards because of seaweed farming (+)	Not profitable in its current form (peg-and-rope technology). Virtually no value addition locally (Zanzibar)/nationally (Tz as whole). 80% of farmers are women and their earnings are not commensurate with their efforts and inputs. So: (−−) (3)	This is inherent in the societal context of the CS (NA)	(NA)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		1.5. "build the resilience of the poor and reduce their…vulnerability to…shocks."	Employment in freshwater aquaculture value chains build resilience even in flood prone environments compared with alternative livelihoods (+)	Income in Indonesia from carrageenan production is stable helps build assets to withstand shocks. Currently poor control of ice–ice outbreaks which cause production losses. Profitability of and reliance on seaweed farming has also meant that previous activities may be harder to resume when farming fails (0)	Very vulnerable to climate change in its current form (peg-and-rope technology). High dependence of women on this (meager) income. Vulnerable to international market prices, high dependence on exports (−−) (3)	Small-scale oyster aquaculture enhances the occupational diversity of actors in rural areas hence increases resilience and reduces vulnerability to changes. In North America systemic racism has limited opportunities for traditional oyster farmers to re-enter the industry (0)	The industry has contributed to reduce the vulnerability of the population to external shocks, through the building of infrastructure (roads, platforms), and communications. On the other hand they have not respected the resilience limits of the ecosystem. So the result is mixed (Soto et al., 2019) (0)
		5.a. "give women equal rights to economic resources, as well as access to ownership and control over land and other forms of property"	Gender norms mean that women may struggle for access/control of resources related to aquaculture, especially if commercially oriented; development of pond culture within the homeplot usually does fall under women's control (0)	Women often have greater income than men from seaweed farming activities. While this can be a source of conflict, farmers surveys report significant improvements to living standards because of seaweed farming (+)	Patriarchal and conservative society where men and women's rights (formal and informal) are not equal (−−) (3)	Women have equal rights to men in terms of ownership of resources and engage in oyster farming. This is inherent in the societal context of the CS (NA)	(NA)
		8.1."at least 7% gross domestic product growth per annum in least developed countries"	Aquaculture has contributed to the Bangladesh economic growth significantly but the data quality is suspect (?)	Indonesia is not a least developed country (NA)	(?)	The region is not a least developed country (NA)	The industry has contributed to high economic growth in the regions where it has located (United Nations, 2016) (++)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		8.3. "development oriented policies, decent job creation… encourage growth of micro, small and medium-sized enterprises"	Poor track record on effective government led policy (0)	Dominated by small-scale producers—need highly flexible labor, and requires only low capital and technology for startup (+)	Currently, seaweed farming is NOT a policy priority, although to a little extent integrated in MSP and "blue economy" talk (–) (2, 3)	Mostly small-scale farmers with high-value products, work conditions are generally good although the work can be physically tough, licensing procedures are in the process of being simplified and streamlined (+)	The industrial development has generated many new firms of different sizes in the service sector (Olson & Criddle, 2008) (++)
		8.5. "productive employment and decent work for all women and men, incl. for young people and persons with disabilities, and equal pay for equal work"	(+)	Income from seaweeds is accessible to marginalized groups, for example, women and older communities. Hard physical working conditions are inherent in farming but surveys suggest benefits outweigh the negatives (+)	Current dominant form of production (peg and rope) defies decent work conditions and is performed nearly only by women (so not possible to say about equal pay) (––) (3)	Work available to both women and men as wella s young people, especially when also integrated with tourism activities and fisheries. Persons with disabilities are not often engaged because of harsh conditions during production (+)	Productive employment has grown rapidly, but there is an ongoing discussion about the quality of the created work. The Study Department of the Ministry of Labor in Chile has several studies about working conditions in the salmon industry. The Study Department of the Ministry of Labor in Chile has several studies about working conditions in the salmon industry (0)
		10.1. "sustain income growth of the bottom 40% of the population at a rate higher than the national average"	(++)	Aquaculture could well become a strong platform for economic development in a blue economy framework, and seaweed aquaculture has proved valuable for rural development schemes. Carrageenan and agarophyte production have the scope to considerably increase (+)	Unless the current technology (peg and rope) changes, and value addition takes place locally, there is no chance to progress towards this target. But some initiatives are underway to simultaneously revolutionize the technology AND women's empowerment (–) (1, Brugere et al., 2020)	The bottom 40% of the population would not initiate oyster aquaculture because of the economic investments required (––)	Poverty reduction in the Los Lagos region, where the salmon industry first located, has been reduced more rapidly than in other regions. More specific, in the zones of the region where the industry is located, poverty has been more largely reduced (Modrego et al., 2009) (+)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		14.7 "increase the economic benefits to small island States and least developed countries from the sustainable use of marine resources, including through… aquaculture…"	(NA)	Indonesia is not a small island state or least developed country (NA)	If the production technology changes, potential is high to progress towards this target in Zanzibar. But currently (−) (3)	The region is not an island state or a least developed country (NA)	(NA)
	Financial performance (of the aquaculture system/ sector)	8.2. "Achieve higher levels of economic productivity through diversification, technological upgrading and innovation…"	(++)	Farmers able to grow Spinosum or other red algal galactan seaweeds when growing conditions for another are poor. Currently technological upgrading would enhance value adding within country but this remains lacking. Increased dependence on seaweed farming leaves communities open to market shocks and the livelihood benefits tend to reduce the diversity of livelihood practices such as copra production and fisheries (−)	Very low currently. Potential to increase profitability through different farming technology and spp (cotonii). And through value addition/ transformation locally (−) (3)	Significant levels of innovation ongoing to enhance cost efficiency of production and expand activities (++)	There is evidence of the enormous impact that the advent of the salmon industry had on the regions were it installed. This develop seevral input–output linkages, economies of scale, competition, diversification, technological development and innovation (Perlman & Juarez-Rubio, 2010) (++)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		8.3. "encourage growth of micro, small and medium-sized enterprises"	(++)	Dominated by small-scale producers—need highly flexible labor, and requires only low capital and technology for startup (+)	Small-scale, independent producers (+) (3)	Licensing procedures are in the process of being simplified and streamlined, startup funding available and research and innovation funding available to support startup. Local officials can be a large obstacle (+)	The salmon industry grew initially as a group of small independent firms with heavy reliance on foreign technology and production inputs. It developed to an integrated complex industrial composed of large amount of interdependent small, medium and large producers, processors, distributors, and service firms (Olson & Criddle, 2008) (++)
		8.4. "Improve…global resource efficiency"	Use of imported feed resources in semi-intensive aquaculture is an efficient food production strategy (+)	Value chain inefficiency adds costs to semi-refined carrageenan products and increases risks to trading games (−)	(?)	Oysters are extractive species and provide significant ecosystem services during production. Relative to other animal food sources the production of bivalves has very low environmental impact. Moreover the production has the potential to recapture finite resources that would otherwise get lost at sea, for example, P. This potential could however, be better utilized. Limited impact because of the small scale of operations (+)	We suspect contradictory effects, but we are not sure how to interpret the target (?)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		12.2. "…ensure efficient use of natural resources"	Most pond aquaculture is semi-intensive which is highly efficient in terms of natural resource use (+)	Typical 25% yield from dried seaweed to carrageenan and large amounts of biomass wasted rather than utilized (−)	(+)	Oysters are extractive species and provide significant ecosystem services during production. Relative to other animal food sources the production of bivalves has very low environmental impact. Moreover the production has the potential to recapture finite resources that would otherwise get lost at sea, for example, P (++)	We suspect contradictory effects, but we are not sure how to interpret the target (0)
		12.5. "substantially reduce waste generation through prevention, reduction, recycling and reuse"	Semi-intensive aquaculture commonly integrated within broader food systems (+)	Greater recovery of waste products for agricultural uses is necessary and value chain innovation and restructuring is needed (−)	Currently some seaweed is wasted while drying on the sand (−). This could be easily improved with simple infrastructure	Oysters are extractive species and provide significant ecosystem services during production. Relative to other animal food sources the production of bivalves has very low environmental impact. Moreover the production has the potential to recapture finite resources that would otherwise get lost at sea, for example, P. This potential could however, be better utilized. Limited global impact because of the small scale of operations but significant local impact (++)	Industry has improved significantly in the past 5 years and circular economy approaches are being implemented (Ibieta et al., 2017) (+)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
	Production costs	8.4. "Improve…global resource efficiency"	See above (+)	Value chain inefficiency adds costs to semi-refined carrageenan products and increases risks to trading games (−)	Very low production costs currently, and very low returns. Resource efficiency would increase with improved technology (−) (3)	Production costs manageable also at small scale farming operations (+)	We suspect contradictory effects, but we are not sure how to interpret the target (?)
		12.2. "…ensure efficient use of natural resources"	See above (+)	Typical 25% yield from dried seaweed to carrageenan and large amounts of biomass wasted rather than utilized (−)	(+)	Oysters are extractive species and provide significant ecosystem services during production. Relative to other animal food sources the production of bivalves has very low environmental impact. Moreover the production has the potential to recapture finite resources that would otherwise get lost at sea, for example, P. This potential could however, be better utilized. Limited impact because of the small scale of operations (++)	We suspect contradictory effects, but we are not sure how to interpret the target
	Indirect effects on economic activity	2.3. "double agricultural productivity and incomes of small-scale producers… women, indigenous peoples, family farmers, pastoralists and fishers… through opportunities for value addition and non-farm employment"	Intensified use of surface water for aquaculture may have disadvantaged fishers in certain contexts (0)	Survey and anecdotal evidence that seaweed has greatly improved the income of farmers, particularly women. Earnings typically equivalent to a university educated person in a government office and has contributed to establishment of electronic communication networks in remote communities (++)	Currently very few linkages with other economic activities (−−) (3)	Strong linkages between oyster culture and wild populations/fisheries, as well as tourism. Impact on economic activity important on local scale (++)	The salmon industry has had an important impact on employment and income in the regions where it has developed in southern Chile. There is specific evidence that it has contributed to reduce poverty in the rural coastal zones where salmon farms have been installed, which is basically households composed of small producers (Ceballos et al., 2018) (++)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		2.a. "Increase investment…in rural infrastructure, agricultural research and extension services"	(+)	Seaweed farming has generated sufficient revenue for most communities to allow greater connection to mobile networks (++)	Currently seaweed farming is a low priority for government but local universities and donor-funded researchers are working with seaweed farmers and communities (0) (3)	Significant increase in research and extension funds to low trophic aquaculture including oyster production (++)	The industry has contributed to the building of infrastructure (roads, platforms), and communications mainly directed to productive purposes (Aviles, 2015) (+)
		7.a. "enhance…access to clean energy research and … promote investment in energy infrastructure and clean energy technology"	(NA)	(NA)	(NA)	Discussions about electrifying the boats, but nothing solid on this end yet (NA)	The industry has made efforts to increase the use of clean energies (+)
		9.1. "Develop quality, reliable, sustainable, and resilient infrastructure…"	Few data on this (?)	(NA)	(NA)	Little impact on infrastructure because of the small scale of activities (0)	The industry has contributed to the building of infrastructure (roads, platforms), and communications mainly directed to productive purposes (Aviles, 2015) (+)
		9.4. "upgrade infrastructure and retrofit industries to make them sustainable"	Few specific data on this (?)	(NA)	(?)	Discussions about electrifying the boats, but nothing solid on this end yet (NA)	This target is not clear! (?)
		9.a. "sustainable and resilient infrastructure development in developing countries"	Hatchery infrastructure investments through government/international projects have not proved resilient (0)	(NA)	(?)	The region is not a least developed country (NA)	The industry has contributed to the building of infrastructure (roads, platforms), and communications mainly directed to productive purposes (Aviles, 2015) (+)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
	Investments in technology and innovation	7.a. enhance…access to clean energy research and … promote investment in energy infrastructure and clean energy technology"	(NA)	(NA)	(NA)	Discussions about electrifying the boats, but nothing solid on this end yet (NA)	The industry has made efforts to increase the use of clean energies (+)
		8.2. "Achieve higher levels of economic productivity through diversification, technological upgrading and innovation…"	Diversification to pond aquaculture has increased opportunity cost for access to land and water (+)	Seaweed farming has augmented in some areas or replaced in others. Diversification has become hindered in some places, for example, Tanimbar Kei as people do not want to return to fishing/ cropping as a demographic shift has been felt (−)	Seaweed farming innovation pilots currently ongoing (Sea PoWer) (+)	Significant levels of innovation ongoing to enhance cost efficiency of production and expand activities (+)	There is evidence of the enormous impact that the advent of the salmon industry had on the regions were it installed. This develop seevral input–output linkages, economies of scale, competition, diversification, technological development and innovation (Perlman H, Juarez-Rubio F 2010) (++)
		8.3. "development oriented policies that support… creativity and innovation"	Often through NGO sector (+)	Seaweed farming in Indonesia has supported small community co-development of industry from internal initiatives that have generated strong market linkages (+)	Seaweed farming innovation in Zanzibar currently supported by non-state actors (foundations, research org, independent organizations) (+) (3)	Significant political will to enhance oyster (and other LTS culture) including a focus on innovations. Funding directed to innovations and sector development through research (++)	The salmon industry grew initially as a group of small independent firms with heavy reliance on foreign technology and production inputs. It developed to an integrated complex industrial composed of large amount of interdependent small, medium and large producers, processors, distributors, and service firms (Olson & Criddle, 2008) (++)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		9.5. "enhance scientific research, upgrade, the technological capabilities of industrial sectors… by…encouraging innovation	Significant investment in research and innovation has enhanced capabilities of private sector (+)	The benefits of seaweed farming for rural livelihood has fostered increased attention from aid agencies amd positive collaboration between NGO and governmental institutions for development of value-addition factories and farmer training (+) https://www.proquest.com/docview/1841301624/fulltext/5BE6F159B10A4BD6PQ/1?accountid=14522	Good collaboration between researchers (from the North and the South), seaweed farmers and foundations/donors to support the development of new farming technology (tubular nets) (++) (3)	Significant political will to enhance oyster (and other LTS culture) including a focus on innovations and well developed connections between industry and academia. Funding directed to innovations and sector development through research (++)	The salmon industry has developed rapidly to become a global player in the world market through catching up in technological innovations and the development of learning capabilities (Iizuka et al., 2016) (++)
		9.b. "support domestic technology development, research and innovation"	Quite limited but emergent (+)	As above (+)	See above (++)	Significant political will to enhance oyster (and other LTS culture) including a focus on innovations and well developed connections between industry and academia. Funding directed to innovations and sector development through research (++)	In the later phases domestic technological development is increasing (++)
		17.6. "Enhance North–South, South–South and triangular… cooperation on access to science, technology, and innovation"	(+)	As above (+)	See above (++)	Active engagement in research collaborations between north and south (++)	Cooperation and exchange with Norway and other salmon producing countries and capacity development and cooperation with LA countries (+)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
	License and permit conditions	16.3. "promote the rule of law at the national and international levels and ensure equal access to justice for all	(NA)	(NA)	(?)	This is inherent in the societal context of the CS (NA)	(?)
	(The conditions with which licenses and permits are issued—the transparency and clarity in the process)	16.5. "substantially reduce bribery and corruption all their forms"	Stocking programs in open water have increased corruption in some contexts (−−)	Local decisions about planning have typically overthrown government plans for spatial allocation but it is unclear how equitable or corruption free either approach is (?)	(?)	Very little corruption in the region (NA)	(?)
Institutional	Representation and negotiation	10.2. "empower, and promote, the social, economic and political inclusion of all"	development programs have focused on this with mixed results as prevailing power structures are difficult to challenge (0)	The development of seaweed farming and the decentralization of Indonesian government have encouraged local governance under adat rules (rather than federal mandates). But to what extent this leads to political inclusion of all is unclear—could be displaced mandates from local officials rather than federal (0)	Prevalence of discrimination on grounds on gender (−−) (1, 3)	Industry representatives included in governance work (e.g., strategies and action plans) (+)	Salmon industry was not very good at this in the past, yet they are now slowly improving (Chavez et al., 2019) (−)
		16.5. "substantially reduce bribery and corruption all their forms"	See above-mixed…has led to development of more open and equitable intuitions in some contexts (0)	Government allocations of tenure have largely gone unheeded, with local authorities being the primary decision makers so unclear (?)	(?)	Very little corruption in the region (NA)	(?)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		16.6. "Develop effective, accountable, and transparent institutions at all levels"	Has been a key focus of externally funded projects but mixed outcomes (0)	Local level decisions may be most equitable but transparent decisions and influence are not apparent, with trust among distributors and processors apparently key. This appears to be effective and accountable but not necessarily transparent (0)	Environmental planning policies and processes in place to regulate the siting of seaweed (and sea cucumber, etc.) farms in the lagoon (but it is not clear where the priorities for development lie, e.g., vs. tourism) (0) (3)	This is inherent in the societal context of the CS (NA)	Salmon farming sector and institutions are improving but yet there are concerns about it (for example providing numbers on AB use by company), there is need for more in-depth research (−)
		17.16 "Enhance the global partnerships for Sustainable complemented by multi-stakeholder partnerships…to support the achievement of the SDGs"	Bangladesh has been active in international partnerships (0)	There are many mutlistakeholder partnerships emerging in terms of farmer groups, government departments and microfinance companies investing in farmer training but few international partnerships are apparent (0)	Currently happening in case of promotion of new technology (partnership between researchers, consultants, foundations, farmers) (++) (3)	Highly relevant through project partnerships including the triple helix model and international projects, including the fulfillment of the Galaway and the Belem statements (++)	The Global Salmon Initiative is an interesting example of such partnerships, also promoting more transparency (https://globalsalmoninitiative.org/en/) (+)
		17.17. "encourage and promote effective public, public-private, and civil society partnerships"	Key development strategy for international development assistant to the sector (+)	Government oversight and interaction with local officials allows a more spatially explicit and appropriate form of governance in the intertidal zones used for seaweed farming around Indonesia (+)	None as such at present, although new project piloting tubular nets is exploring partnerships with foreign seaweed importers (−) (3)	Industry representatives included in governance work (e.g., strategies and action plans) and included in information and discussion forums between industry and governance actors. Partnerships including the triple helix model and international projects (++)	Public-private task forces. Good example during the Covid-19 (+)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
	Coordination of interests and activities	2.3. "double agricultural productivity and incomes of small-scale producers… women, indigenous peoples, family farmers, pastoralists and fishers… through opportunities for value addition and non-farm employment"	Depends on the specific context as to the level of benefit/disbenefit to poorer stakeholders (0)	Seaweed farming is complementary and compatible with other forms of livelihood activity. Whether or not this is realized dependence on how much alternate activities are maintained during seaweed farming and to what extent these can be revisited during decreased seaweed profitability (+)	Happening in case of promotion of new technology (partnership between researchers, consultants, foundations, farmers) (+) (3)	Farmers are engaged in producer and/or other types of sector associations but these organizations face issues with conflicting interests of participants and has limited impact on national level. Spatial planning processes becoming more sophisticated with modern GIS activities (0)	Impact on local income development (++)
	(wrt minimizing conflicts for space and resources among other users)	12.2. "…ensure efficient use of natural resources"	See above (0)	Very few inputs are needed for seaweed farming and thus minimizes resource conflict with other sectors (++)	Conflict with tourism development, threat of gas exploration and exploitation off the coast of Zanzibar (−−) (3)	Spatial planning processes implemented to a limited extent, conflicts with other maritime activities about space and with nature management objectives because of environmental effects of production (−)	We suspect contradictory effects, but we are not sure how to interpret the target (?)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		17.16 "Enhance the global partnerships for Sustainable complemented by multi-stakeholder partnerships…to support the achievement of the SDGs"	See above (+)	Relational governance structures have emerged out of problematic market and modular systems where farming cooperatives and enterprises trade with local entrepreneur collectors. These then feed into a local trading center where seaweeds are bagged shipped to local but also supranational (Chinese) processors. While the trade partnerships are global value addition on shore could be far more beneficial (0)	Currently happening (support from international donors) albeit on a small scale (+)	Highly relevant through project partnerships including the triple helix model and international projects, including the fulfillment of the Galaway and the Belem statements (++)	Global Salmon Initiative and others (+)
		17.17. "encourage and promote effective public, public-private, and civil society partnerships"	(+)	Relational governance structures have emerged out of problematic market and modular systems where farming cooperatives and enterprises trade with local entrepreneur collectors. These then feed into a local trading center where seaweeds are bagged shipped to local but also supranational (Chinese) processors (+)	Partnerships among non-state actors in support of women producers (+) currently ongoing	Industry representatives included in governance work (e.g., strategies and action plans) and included in information and discussion forums between industry and governance actors. Partnerships including the triple helix model and international projects (++)	Public-private task forces. Good example during the Covid-19 (+)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
	Siting	10.2. "empower, and promote, the social, economic and political inclusion of all"	This is mixed depending on context as elite capture has led to exclusion of the poor in some contexts from fishing whereas aquaculture value chains have generally led to opportunities (0)	The development of seaweed farming and the decentralization of Indonesian government have encouraged local governance under adat rules (rather than federal mandates). But to what extent this leads to political inclusion of all is unclear—could be displaced mandates from local officials rather than federal (0)	Currently farmers have very little voice against planned developments in the areas where they farm seaweed (−−). Current conflicts with kite surfers.	Oyster culture expansion is hindered by a focus on and priority on traditional maritime activities and nature management objectives (−)	(−)
	(How siting decisions are made and who is involved)						
		12.7. "Promote public procurement practices that are sustainable and in accordance with national policies and priorities"	Procurement of juveniles for public stocking has led to mixed outcomes (0)	(NA) the seaweed industry has seemingly evolved external to public procurement practices	(?)	This is inherent in the societal context of the CS (NA)	The question is not clear (?)
		16.3. "promote the rule of law at the national and international levels and ensure equal access to justice for all	Success of aquaculture and the increase in value of associated resources has led to greater inequity in some contexts (0)	Unclear to what extent seaweed farming is really promoting access to justice (?)	Outcomes of existing planning procedures may not always be in favor of seaweed farmers (when competing with high revenue generation tourist or urban developments for example) (0) (3)	This is inherent in the societal context of the CS (NA)	(?)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		16.5. "substantially reduce bribery and corruption all their forms"	See above (0)	Government allocations of tenure and enforcement have largely gone unheeded, with local authorities being the primary decision makers so unclear (?)	(?)	Very little corruption in the region (NA)	(?)
	Transparency and traceability	12.7. "Promote public procurement practices that are sustainable and in accordance with national policies and priorities"	See above (0)	Unclear as to the polarity—public procurement has not been the mechanism for accountability and enforcement, instead increasing public pressure for transparency, fair trade, and product standards is growing and to some extent enforced by processors (0)	(?)	This is inherent in the societal context of the CS (NA)	The question is not clear (?)
		16.6. "Develop effective, accountable, and transparent institutions at all levels"	See above (0)	Evidence that seaweed value chains are moving towards greater transparency because of relational links from local enterprises to centralized local trading venues which conduct the export process (+)	Mixed (0)	This is inherent in the societal context of the CS (NA)	Salmon farming sector and institutions are improving but yet there are concerns about it (e.g., providing numbers on AB use by company), there is need for more in-depth research. This is mixed (0)
		16.10. "Ensure public access to information and protect fundamental freedoms"	(NA)	(NA)	Mixed (0)	This is inherent in the societal context of the CS. Also a demand for traceability of food items (NA)	The industry does not show their information about antibiotic use at the farm level, it is shown however for each neighborhood or ACS therefore is mixed (0)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
	Accountability and enforcement	12.7. "Promote public procurement practices that are sustainable and in accordance with national policies and priorities"	See above (0)	Unclear as to the polarity—public procurement has not been the mechanism for accountability and enforcement, instead increasing public pressure for transparency, fair trade, and product standards is growing and to some extent enforced by processors (0)	(?)	This is inherent in the societal context of the CS (NA)	The question is not clear (?)
	Social assurance	8.5. "productive employment and decent work for all women and men, incl. for young people and persons with disabilities, and equal pay for equal work"	See above (+)	Income from seaweeds is accessible to marginalized groups, for example, women and older communities (+)	Current method of farming does not provide decent work conditions (−−). New farming technology is however improving work conditions of women but still on a very limited scale	Work available to both women and men as well as young people, especially when also integrated with tourism activities and fisheries. Persons with disabilities are not often engaged because of the harsh conditions during production (+)	Contradictory results (0)
	(employee rights and health and safety through equipment and training)	8.7. "Take immediate and effective measures to eradicate forced labor…"	Little data on this compared with export oriented brackish water (shrimp) vale chains (?)	Unclear to what extent this is evident in seaweed value chains and given the family oriented business model, not clear to what extent children, women or other groups are coerced into labor (?)	Labor is not "forced" as such, but it is not decent (0)	This is inherent in the societal context of the CS (NA)	(NA)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		8.8. "Protect labor rights and promote safe and secure working environments for all…"	See above (0)	An evaluation of 74 interviews in nine villages across South Sulawesi suggest that Seaweed farming had increase overall health had increased alongside seaweed farming in 5 years (Larson et al., 2021) (+)	Current farming conditions are not safe or decent for women (−−) New farming technology (tubular nets) is helping to redress this, through training and a gender-transformative approach, but still on a small scale	Both North America and Scandinavia have a focus on safe working environments, labor rights are well developed in Scandinavia, less so in North America but still high compared with other regions. Yet this is not specific to the oyster culture sector (0)	Contradictory results (0)
	Food safety	2.1. "end hunger and ensure access by all people to…safe, nutritious and sufficient food".	Most pond cultured fish marketed fresh and highly nutritious but some concerns around point of sal use of preservatives (e.g., formalin) to extend shelf life (0)	Carrageenan is typically exported as raw dried seaweed rather than used in semi-refined or refined carrageenan in country. Where processed carrageenan is used in food products, their use in as an additive into meat and dairy products. For some meat products that can allow for reduced fat content and thus greater health benefits—but it may also be used in dairy products such as ice cream with very little nutritional value. There also exists marginal controversy over the use of carrageenan in foods as inflammatory and carcinogenic products (see "The carrageenan controversy." Yet improved income in rural communities will have	Potential to increase local consumption of seaweed (very little currently) (−−) (2, 3)	Oysters cultured in this region are not important for food security but will offer nutritious food to the local population (+)	Salmon contributes to global nutrition, but at the local scale the contribution is limited (+)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
				increased people's financial access to stable food supplies (0)			
		12.3. "reduce food losses along production and supply chains"	Little known about this (?)	Little information on dangerous food waste potential but much of the biomass of seaweeds is wasted (70%–92%) rather than recovered and has implications for effluent (−−)	All production exported at present so there is little waste as such, apart from the seaweed that gets lost in the sand while drying) (+) (3)	Oysters are rarely wasted as a food item and supply chains are optimized to reduce losses. production targets local markets (++)	Reduction in food losses is big, but salmon escapees has also to be taken into account (+)
Environment	Abiotic effects	6.3. "improve water quality by reducing pollution"	Poor management can lead to poorly controlled eutrophication but in general aquaculture has improved surface water quality by giving value to better management (+)	Very little country specific information but the benefits of seaweed farming for improving water quality are some of the most well-established environmental benefits associated with seaweed farming globally (++)	(NA)	Oysters are extractive species and provide significant ecosystem services during production. Moreover the production has the potential to recapture finite resources that would otherwise get lost at sea, for example, P. This potential could however, be better utilized. Impact important on local scale despite the sector being small (++)	It is not clear whether this is referring to the fresh water phase or fresh water aquaculture. In any case processing plants use fresh water but in most cases have well managed outflows and are periodically controlled. There is only one company with a very small production in one lake (NA)
		6.4. "substantially increase water use efficiency"	On farm ponds have supported improved associated horticulture (++)	(NA)	(NA)	(NA)	No fresh water use in the fattening phase, except for the processing and in the feed production processes, there is water use for feeds but we do not know how efficient is its use. https://iopscience.iop.org/article/10.1088/1748-9326/9/10/109001/pdf (?)

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TABLE A1 (Continued)

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		6.5. "integrated water resources management at all levels"	(++)	(NA)	(NA)	(NA)	No direct freshwater use except in processing (0)
		6.6. "protect and restore water-related ecosystems"	See above—some loss of wetlands associated with aquaculture development (0)	Depends heavily on the gear used. Off-bottom lines can denude intertidal zones of seagrass beds and coral bommies with fewer impacts reported for floating gears (−)	Current farming technology (pegs and ropes) uses mangrove wood (−) New tech (tubular net) does not require pegs, so helps reduce pressure on local mangrove ecosystems, but only on a pilot scale at present (3)	Oysters are extractive species and provide significant ecosystem services during production, e.g. remediation of eutrophication and shoreline protection (++)	(NA)
		12.7. "Promote public procurement practices that are sustainable and in accordance with national policies and priorities"	See above (0)	Seaweed industry has largely evolved outside of public procurement practices. However, local authorities (adat) where impacts are felt determine siting and resource use (+)	(?)	This is inherent in the societal context of the CS (NA)	Limited information but in general there has been a trend to use clean providers (often included in certification schemes). On the other hand feed companies are increasingly offering certified inputs (Wurmann et al., 2022) (+)
		14.1. "prevent and significantly reduce marine pollution"	little mariculture:coastal aquaculture systems are probably nutrient sinks improving (0)	Ropes and pegs have little potential for marine pollution, plastic waste bottles for marker buoys are common but pose little threat relative to other food systems (+)	Currently peg and ropes cause little pollution (++) but this could be an issue for the tubular net technology when they are used on a larger scale (pvc nets and ropes are used, but likelihood of breakage is relatively low) (3)	Oysters are extractive species and has the potential to recapture finite resources that would otherwise get lost at sea, for example, P. Culture equipment can contribute to littering. No toxic chemicals are used during production. Significant impact on local scale (+)	Farms follow the norm to reduce impacts on sediments under cages but there is no evaluation of farside effects and ecosystem impacts (Quiñones et al., 2019; Soto et al., 2021) (−)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		14.2. "sustainably manage and protect marine and coastal ecosystem to avoid significant adverse impacts"	(NA)	Depends heavily on the gear used. Off-bottom lines can denude intertidal zones of seagrass beds and coral bommies, and increase siltation in adjacent reefs with fewer impacts reported for floating gears (−)	Negative impact of seaweed plots (using peg and rope tech) on seagrass beds. Demonstrated potential of few environmental impact of deep water farming technology using tubular nets) (−) (1–3)	Oysters are extractive species and provide significant ecosystem services during production, for example, remediation of eutrophication and shoreline protection. Harvest techniques (dredging) can be damaging to the bottom substrates (0)	Norms and regulations focus on individual farms but not enough attention is paid to ecosystem level impacts and carrying capacity (Quiñones et al., 2019; Soto et al., 2021) (− −)
		14.3. "minimize and address ocean acidification"	(NA)	Very poor empirical evidence of any relationship seaweed farming and ocean acidification (NA)	(NA)	(NA)	It may be reducing the capacity of fiords to trap carbon by increasing the nutrient inputs (Farias et al., 2019; Soto et al., 2021) (−)
		14.5. "conserve at least 10% of coastal and marine areas"	(NA)	Seaweed farms have been shown to elevate number of fish and invertebrates in farming areas (Theuerkauf et al., 2021) but it is unclear whether on balance this is displaced from elsewhere, or whether that is relative to seagrass beds or taking into account of mangrove trees that are felled for materials or the benefits of seaweed farming reduced dependence on fishing (0)	Currently seaweed farming takes place in officially designated marine conservation areas (++) Seaweed farming can be considered as a nature-based solution	(NA)	We need clarification on this target since it may not be a resort of the aquaculture sector (−)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		15.1. "ensure the conservation, restoration, and sustainable use of terrestrial and freshwater ecosystems and their services"	See above (0)	Possible that seaweed products could displace burden from stressed terrestrial systems for crops but this is yet to play out (?)	New tech (tubular nets) limits damage to seagrass beds and creates a defacto protected area for fish (biodiversity). However currently pegs and ropes do not provide much of this in the lagoon (−) (2, 3)	(NA)	This target could be addressed indirectly through feeds and we suspect there are some impacts, however most feed companies are introducing certification to ensure sustainable use of feed inputs. https://www.nature.com/articles/s41598-020-68231-8.pdf (?)
		15.3. "…restore degraded land and soil"	(NA)	Seaweeds can be effectively used as a fertilizer but given the widespread use of synthetic fertilizer whether any benefit has been realized lacks evidence (?)	(NA)	(NA)	We do not enough information on the production of feed ingredients although we suspect feed industry is undergoing sustainable improvements (?)
		15.5. "Take action to… reduce the degradation of natural habitats"	(NA)	Seaweed farming does provide a means to reduce degradation from nutrient pollution and has witnessed as such in many area, especially China. There are trade-offs and many of the benefits depend on the context (species, scale, etc.) but on balance seaweed farming can be used for positive change (++)	New tech (tubular nets) limits damage to seagrass beds and creates a defacto protected area for fish (biodiversity). However there is currently little government support to use seaweed to reduce habitat degradation (−) (2, 3)	Oysters are extractive species and provide significant ecosystem services during production, for example, remediation of eutrophication and shoreline protection. Significant impact on local scale (++)	Industry has taken some actions but not enough, to protect benthic biodiversity, mammals, birds and ecosystems in general (Quiñones et al, 2019) (−)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
	Biotic effects	14.2. "sustainably manage and protect marine and coastal ecosystem to avoid significant adverse impacts"	(NA)	For the reasons I list it can be a source of impact and variable impacts on biodiversity (0)	As above (−)	Oysters are extractive species and provide significant ecosystem services during production, for example, increased biodiversity and remediation of eutrophication. Oyster aquaculture can also support re-establishment of wild oyster populations through larvae spillover and can support restoration and stock enhancement projects. Harvest techniques can sometimes be detrimental to substrates, and bottom culture may impact marine vegetation negatively by shading and trampling. Possible depletion of food resources by exceeding carrying capacity of limited importance because of small scale operations (0)	Norms and regulations focus on individual farms but not enough attention is paid to ecosystem level impacts and carrying capacity (Quiñones et al., 2019; Soto et al., 2019, 2021) (−−)
		14.4. "effectively regulate harvesting and end overfishing, IUU fishing and destructive fishing practices"	Efficient aquaculture has reduced fish prices for consumers potentially reducing pressures to overfish (?)	Many in Indonesia have transitioned from fishing-based livelihoods to that of seaweed farming and this has allowed conservation measures to be put in place to help rebuild stocks (++)	(NA)	Oyster aquaculture may support establishment of wild populations through larvae spillover and restoration efforts. Harvest techniques can sometimes be damaging to the bottom substrates (+).	Replacement of fish oil and fish meal by other ingredients and certification (Naylor, Hardy, et al., 2021, Naylor, Kishore, et al., 2021) (+)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		15.2. "promote the sustainable management of all types of forests"	(NA)	Mangrove poles in widespread use throughout Indonesia (−−)	Currently pegs are made of mangrove wood (−) New tech reduces pressure on mangrove wood for pegs	(NA)	Possibly salmon farming has provided alternative livelihoods to cutting forest for firewood and other LCU in Chiloe and in other places (?)
		15.5. "Take action to… reduce the degradation of natural habitats, halt biodiversity loss, and… threatened species"	Ponds can have both positive and negative impacts on conservation see above (0)	For the reasons I list above it can be a source of impact and variable impacts on biodiversity in Indonesia (0)	New tech (tubular nets) limits damage to seagrass beds and creates a defacto protected area for fish (biodiversity). However there is currently little government support to use seaweed to reduce habitat degradation (−) (2, 3)	Oysters are extractive species and provide significant ecosystem services during production, for example, increased biodiversity and remediation of eutrophication. Oyster aquaculture can also support re-establishment of wild oyster populations through larvae spillover and can support restoration and stock enhancement projects. Harvest techniques can sometimes be detrimental to substrates, and bottom culture may impact marine vegetation negatively by shading and trampling. Possible depletion of food resources by exceeding carrying capacity (of limited importance because of small scale operations) (0)	During the 5 past years they have taken action to reduce plastic pollution and other (Quiñones et al., 2019) (0)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		15.8. "introduce measures to prevent the introduction and significantly reduce the impact of invasive species on land and water ecosystems"	Both introduced and native species are farmed but no major issues with invasiveness (0)	Indigenous species of euchuematoid seaweeds farmed in Indonesia but does not actively create or prevents threats (NA)	(NA)	One of the most cultured oyster species is the invasive Pacific oyster. In the context in this CS, target organisms are native oyster species, hence reducing the market demand of the non-native species (0)	Considering the increase in production there are comparatively less escapes today, also industry has worked better with fishermen to recapture escapees but it is not enough (Quiñones et al., 2019; Soto et al., 2022) (−)
	Emissions and waste	6.3. "improve water quality by reducing pollution"	see above-poorly managed pond aquaculture can be polluting but otherwise acts as a treatment in situ approach (0)	Well-established benefit of seaweed farming (++) Spillias et al in review	Seaweed farming causes little pollution in itself, but some of the equipment can be lost in the sea (0)	Oysters are extractive species and has the potential to recapture finite resources that would otherwise get lost at sea, for example, P and may remediate eutrophication. Impact significant on local scale (++)	It is not clear whether this is referring to the fresh water phase or fresh water aquaculture. In any case processing plants use fresh water but in most cases have well managed outflows and are periodically controlled. There is only one company with a very small production in one lake (NA)
		12.4. "environmentally sound management of chemicals and all wastes"	See cell above (0)	Uncertain of the fate concerned with seaweed farming but much of the biomass is wasted with implications for nutrient pollution (−)	(NA)	No toxic chemicals are used during production (++)	industry uses antimicrobials and pesticides, although there have been efforts to reduce use and some environmentally friendly solutions (Quiñones et al., 2019) (−)
		12.5. "substantially reduce waste generation through prevention, reduction, recycling and reuse"	See above (0)	Greater resource efficiency in processing is required and the use of wastes (−)	Mixed (0)	Oysters are extractive species and has the potential to recapture finite resources that would otherwise get lost at sea, for example, P and may remediate eutrophication. Impact significant on local scale (++)	Industry has improved significantly in the past 5 years and circular economy approaches are being implemented (Ibieta et al., 2017) (+)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		14.1. "prevent and significantly reduce marine pollution"	Freshwater ponds likely to reduce nutrient inflows into marine waters (+)	Positive influence on nutrient pollution with very little threat from production (++)	Seaweed farming causes little marine pollution (+)	Oysters are extractive species and has the potential to recapture finite resources that would otherwise get lost at sea, for example, P and can remediate eutrophication. Culture equipment can contribute to littering. No toxic chemicals are used during production. Significant impact on local scale (+)	Farms follow the norm to reduce impacts on sediments under cages but there is no evaluation of farside effects and ecosystem impacts (Quiñones et al., 2019; Soto et al., 2021) (−)
	Feed	6.3. "improve water quality by reducing pollution"	(+)	(NA)	Seaweed farming uses no feed (++)	Oysters are extractive species and no feed is used (NA)	Feed producing companies have improved sustainability of their inputs (0)
		14.2. "sustainably manage and protect marine and coastal ecosystem to avoid significant adverse impacts"	(NA)	(NA)	Environmental impacts of seaweed farming are minimal but seagrass beds can be trampled (+) with traditional peg-and-rope technology	(NA)	Norms and regulations focus on individual farms but not enough attention is paid to ecosystem level impacts and carrying capacity (Quiñones et al., 2019; Soto et al., 2021) (−−)
		14.4. "effectively regulate harvesting and end overfishing, IUU fishing and destructive fishing practices"	See above (0)	(NA)	(NA)	(NA)	Replacement of fish oil and fish meal by other ingredients and certification (Naylor, Hardy, et al., 2021, Naylor, Kishore, et al., 2021) (+)
		15.1. "ensure the conservation, restoration, and sustainable use of terrestrial and freshwater ecosystems and their services"	Growth of aquaculture has led to greater awareness of importance of sustainable resource use (0)	(NA)	Seaweed farming uses no feed (++)	(NA)	This target could be addressed indirectly through feeds and we suspect there are some impacts, however most feed companies are introducing certification to ensure sustainable use of feed inputs (?)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		15.5. "Take action to… reduce the degradation of natural habitats, halt biodiversity loss, and… threatened species"	Increasing value of indigenous fish species has led to greater awareness of their importance and efforts to integrate into farming systems and conserve natural stocks (0)	(NA)	Currently mangrove wood is used for pegs (−)	(NA)	Industry has taken some actions but not enough, to protect benthic biodiversity, mammals, birds and ecosystems in general (Quiñones et al. 2019) (−)
		15.7. "Take urgent action to end… the trafficking of protected species of flora and fauna"	(NA)	(NA)	(NA)	(NA)	(NA)
	Energy consumption and GHG emissions	13.3. "improve… institutional capacity on climate change mitigation, adaptation, impact reduction"	(NA)	Seaweed farming often cited for carbon draw down effects but with uncertain implications for longevity of mineralization or responsible disposal in marine environments (0) (Costa Pierce & Chopin, 2021)	Mixed (0)	Oysters sequent large amounts of carbon in their shells and if treated properly the shells can thus act as a carbon sink (+)	This is a target difficult to judge because is addressing different objectives. Industry is learning and improving on this subject, mitigation actions and moving to carbon neutral is one of their goals. This has been achieved through FCR reduction and certification of feed components. However industry is still ignoring emissions potential related to eutrophication and also they are not taking enough actions regarding adaptation. On the other hand fishery institutions are strengthening their capacity to build adaptation to climate change (Soto et al., 2021) (0)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
	Fish health and welfare	12.6. "Encourage companies…to adopt sustainable practices"—seems pretty general but	Some efforts from feed/pharma companies (+)	(NA)	(?)	(NA)	After ISA companies have managed to reduce fish loses and improve fish welathfare but we do not know how much, probably improved with the neighborhood management, AM use have also decline but not enough (+)
	Mitigation measures	2.4. "ensure sustainable food production systems and implement resilient agricultural practices…that help maintain ecosystems and strengthen capacity for climate change… and other disasters"	See above (+)	Relative to many other food production systems seaweed farming have the capacity to have more positive effects on ecosystem maintenance. Strengthening capacity for disasters depends on the degree of dependence on the industry, coupling with volatile global markets and prevalence of disease (while Kappaphycus striatum has been deemed less volatile to ice–ice and temperature changes than cottonii) (0)	Mixed (0)	Relative to other animal food sources the production of bivalves has very low environmental impact. Moreover the production has the potential to recapture finite resources that would otherwise get lost at sea, for example, P. This potential could however, be better utilized. Limited impact on global scale because of the small scale of operations (+)	Companies are learning but it is not enough (Soto et al., 2021) (−)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
	(as it pertains to clean-ups, contingency and emergency plans)						
		12.5. "substantially reduce waste generation through prevention, reduction, recycling and reuse"	See above (+)	There is much potential to increase resource efficiency and utilize unused biomass from seaweed aquaculture as a resource but this is not yet widespread (−)	Mixed (0)	Oysters are extractive species and has the potential to recapture finite resources that would otherwise get lost at sea, for example, P and may remediate eutrophication. Impact significant on local scale (++)	Industry has improved significantly in the past 5 years and circular economy approaches are being implemented (Ibieta et al., 2017) (+)
		12.6. "Encourage companies…to adopt sustainable practices"	(+)	During times of crises farming cooperatives tend to dissolve and this reduces negotiating power, but farming cooperatives may be a more sustainable livelihood approach than many other alternatives that helps build assets between shocks (+)	Mixed (0)	Strong support expressed in governance documents to increase mussel and oyster aquaculture but sometimes not implemented on local level. Funding available to develop more sustainable practices and to support innovation (+)	Is this regarding reduction of GHG??? If it is companies are indicating to be improving in several areas to become carbon neutral but not in others, for example, Eutrophication (0)
		13.1. "Strengthen resilience and adaptive capacity to climate related hazards and natural disasters"	(+)	Can help build assets between shock events but can reduce diversification too so positives and negatives (0)	Mixed (0)	Culture structures can act as breakwaters (+)	Companies and farmers are improving but need to do much more, also understanding their responsibility (Soto et al., 2018, 2021) (−)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		14.1. "prevent and significantly reduce marine pollution of all kinds"	(NA)	Beneficial for nutrient pollution and little other pollution from production (++)	Mixed (0)	Oysters are extractive species and has the potential to recapture finite resources that would otherwise get lost at sea, for example, P and can remediate eutrophication. Culture equipment can contribute to littering. No toxic chemicals are used during production. Concerns on over-reliance on plastic technologies (0)	Farms follow the norm to reduce impacts on sediments under cages but there is no evaluation of farside effects and ecosystem impacts (Quiñones et al., 2019; Soto et al., 2021) (−)
		15.1. "ensure the conservation, restoration, and sustainable use of terrestrial and freshwater ecosystems and their services"	(+)	Possible that seaweed products could displace burden from stressed terrestrial systems for crops but this is yet to play out (?)	Mixed (0)	(NA)	This target could be addressed indirectly through feeds and we suspect there are some impacts, however most feed companies are introducing certification to ensure sustainable use of feed inputs (?)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
Social	Food and nutrition security	2.1. "end hunger and ensure access by all people to…safe, nutritious and sufficient food."	(++)	Carrageenan is typically exported as raw dried seaweed rather than used in semi-refined or refined carrageenan in country. Where processed carrageenan is used in food products, their use in as an additive into meat and dairy products. For some meat products that can allow for reduced fat content and thus greater health benefits—but it may also be used in dairy products such as ice cream with very little nutritional value. There also exists marginal controversy over the use of carrageenan in foods as inflammatory and carcinogenic products (see 'The carrageenan controversy." Yet improved income in rural communities will have increased people's financial access to stable food supplies (0)	Currently seaweed is not consumed locally. Processing into juices is embryonic but nutrient potential exists if demand can be created (0)	Oysters cultured in this region are not important for food security but will offer nutritious food to the local population (+)	Salmon contributes to global nutrition, but at the local scale the contribution is limited (+)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		2.3. "double agricultural productivity and incomes of small-scale producers… women, indigenous peoples, family farmers, pastoralists and fishers… through opportunities for value addition and non-farm employment"	(+)	Positive livelihood impacts around household income, expenditure are most widely reported from Indonesian surveys (++)	Currently seaweed production is badly affected by climate change: sea water temperature and salinity variations negatively impact on growth and quality (epiphytes). There is no (or embryonic) opportunities for value addition locally. This could be reversed with improved farming technology and capacity to process (–)	Oyster culture in this region will support incomes of small-scale producers and family farmers as well as support fishers (+)	The salmon industry has had an important impact on employment and income in the regions where it has developed in southern Chile. There is specific evidence that it has contributed to reduce poverty in the rural coastal zones where salmon farms have been installed, which is basically households composed of small producers (Ceballos et al., 2018) (++)
		2.4. "ensure sustainable food production systems and implement resilient agricultural practices that increase production and productivity that help maintain ecosystems"	(++)	Relative to many other food production systems seaweed farming have the capacity to have more positive effects on ecosystem maintenance. Strengthening capacity for disasters depends on the degree of dependence on the industry, coupling with volatile global markets and prevalence of disease (while Kappaphycus striatum has been deemed less volatile to ice–ice and temperature changes than cottonii) (0)	Currently seaweed farming yields are low (effects of climate change). It also negatively impacts seagrass beds (trampling) and mangrove forest (cutting of wood to make pegs to hold the seaweed) (––)	Being an extractive species, oyster culture in general, and in this context with eutrohicated waters in particular, is an environmental sustainable activity, especially compared with many other food production systems. The activity also enhances biodiversity and promotes ecosystem restoration (++)	Companies are learning but it is not enough (Soto et al., 2021) (–)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		12.3. "halve per capita food waste at the retail and consumer levels and reduce food losses along production and supply chain	Limited wastes in the system (+)	Still considerable biomass waste through the value chain (−)	Some of the harvests is lost or damaged while drying in the sand (?)	Oysters are rarely wasted as a food item and supply chains are optimized to reduce losses. Production is aimed at local markets (++)	Reduction in food losses is big, but salmon escapees has also to be taken into account (+)
		14.b. "provide access to small-scale fishers to marine resources"	(NA)	While seaweed farming can compete for space, it is still compatible with other coastal livelihoods including artisanal fishing and can even help garner more conservative fisheries protection measures (+)	(NA)	Often oyster farming is combined with wild harvest through e.g. live storage of oysters harvested from wild populations and with tourism activities. Also produced seed is used to enhance wild populations, inferring an ecological service to fisheries (++)	The development of the salmon industry reduced fishing grounds for some fish species (Ramirez et al., 2009) (−)
	Enquiry and Learning	4.3. "ensure equal access for all women and men to affordable and quality technical, vocational, and tertiary education"	Targeted development efforts towards this aim (+)	Seaweed farming has been a key driver in an increased in education for rural populations throughout Indonesia (++)	(?) There is little training in seaweed farming provided as such. Equal access opportunities would need to be checked, but may be skewed in favor of men.	This is inherent in the societal context of the CS (NA)	(+)
	(engagement in research development, education)	4.4. "substantially increase number of youths and adults who have relevant skills…for employment…jobs… entrepreneurship"	(+)	Seaweed farming has been a key driver in an increased in education for rural populations throughout Indonesia (++)	(+) Local, independent seaweed initiatives (e.g., Sea PoWer) are supporting the development of skills for women seaweed farmers, who also engage with the research community through farming trials.	The local farmers are often engaged in research projects, and students (all university levels) get training in collaboration with the industry (+)	The main impact of the salmon industry has been through the development of the service sector and through learning by doing. Notwithstanding, it is possible to reports special initiatives of the salmon industry to offer technical and vocational instruction to young workers (UN General Assembly, 2016) (++)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		4.5. "eliminate gender disparities and ensure equal access to all all levels of education and vocational training for the vulnerable, including persons with disabilities, indigenous peoples, and children…"	See above (0)	Income from seaweeds is accessible to marginalized groups e.g. women and older communities however, Indonesia remains a patriarchal society so it is uncertain to what extent gender and disability inequity in training is minimized (?)	(+) Current small-scale initiatives (e.g., Sea PoWer) is working to improve training and empowerment of women seaweed farmers	This is inherent in the societal context of the CS. Growing oyster industry in the first nations (0)	Impacts of different sign. Equalitarian access to education has happened, but gender disparities persist (0)
		4.a. "substantially expand…the number of scholarships available to developing countries …for enrolment in higher education, including vocational training and…technical… programmes"	Increasing opportunities for formal qualifications in aquaculture (+)	Seaweed farming has been a key driver in an increased in education for rural populations throughout Indonesia (++)	(NA)	The CS is not in a developing country. Some collaboration and educational exchanges are ongoing but nothing specifically related to the oyster industry. Funding available for research scholarships (0)	Local scholarships for youth technical training. 18.pdf (ongcanales.cl) (+)
	Respect for native culture and the value of indigenous knowledge and intangible heritage (in aquaculture)	2.3. "double agricultural productivity and incomes of small-scale producers… women, indigenous peoples, family farmers, pastoralists and fishers through opportunities for value addition and non-farm employment"	(+)	Locally led farming cooperatives but there are reports of migrants seeking opportunities changing local cultural conditions in farming communities (0)	(NA)	Mariculture in general in this area supports traditional fishing communities and maintain their cultural identity, for the oyster sector through a combination of culture activities, tourism and fishing. Growing oyster industry in the first nations (++)	The salmon industry has had an important impact on employment and income in the regions where it has developed in southern Chile. There is specific evidence that it has contributed to reduce poverty in the rural coastal zones where salmon farms have been installed, which is basically households composed of small producers (Ceballos et al., 2018) (++)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		8.9. "promote sustainable tourism that…promotes local culture and products"	Efforts to raise awareness of cultural and nutritional significance (+)	Not a source of tourism in Indonesia and conducted in places usually more rural than main tourist areas (NA)	Potential if local processing and transformation of seaweed was established. Potential high demand from tourism sector for seaweed based products (which would also convey identify and culture). However, current tourism development is in conflict with seaweed farming (and other forms of coastal aquaculture) (−)	Mariculture in general in this area supports traditional fishing communities and maintain their cultural identity, for the oyster sector through a combination of culture activities, tourism and fishing. Growing oyster industry in the first nations (++)	Impact on Magallanes and Argentina. https://www.researchgate.net/publication/337033246_Servicios_ecosistemicos_Marino-Costeros_en_la_Region_de_Magallanes_y_la_Antartica_Chilena_Reporte_regional_preparado_por_el_Centro_de_Investigacion_Dinamica_de_Ecosistemas_Marinos_de_Altas_Latitudes_I (−)
		11.4. "Strengthen efforts to protect… the world's cultural and natural heritage"	(+)	Allows communities to maintain coastal livelihoods with better living conditions while reducing reliance on fisheries resources. But in migration for those wanting to be involved in farming has changed community composition and culture in some areas (0)	See above about seaweed products. In addition, currently seaweed farming is not perceived by authorities as a form of intangible cultural heritage worth preserving (−)	Mariculture in general in this area supports traditional fishing communities and maintain their cultural identity, for the oyster sector through a combination of culture activities, tourism and fishing. Growing oyster industry in the first nations (++)	https://www.researchgate.net/publication/337033246_Servicios_ecosistemicos_Marino-Costeros_en_la_Region_de_Magallanes_y_la_Antartica_Chilena_Reporte_regional_preparado_por_el_Centro_de_Investigacion_Dinamica_de_Ecosistemas_Marinos_de_Altas_Latitudes_I (−)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
	Employee interests and well-being	8.8. "Protect labor rights and promote safe working environments"	See above (0)	An evaluation of 74 interviews in nine villages across South Sulawesi suggest that Seaweed farming had increase overall health had increased alongside seaweed farming in 5 years (Larson et al., 2021) (+)	Current working conditions for women farming seaweed (using the traditional peg-and-rope technology) are unsafe (−−) (Frocklin et al.)	This is inherent in the societal context of the CS (NA)	The salmon industry has generated much productive employment. There is an ongoing discussion about the type of work created. There are several complaints about working conditions. However, the evidence is not clear, because the relevant unit of comparison is still unclear. The Study Department of the Ministry of Labor in Chile has several studies about working conditions in the salmon industry (0)
		10.2. "empower and promote the social, economic, and political inclusion of all"	See above (0)	Unclear to what extent people involved in farming are empowered and that division of assets is inclusive (?)	In its current form, seaweed does not empower women (−−). There is however demonstrated potential of women's empowerment with new tubular net technology, but it is still at a pilot scale (cf. Sea PoWer)	This is inherent in the societal context of the CS (NA)	Efforts have not been visible (0)
		10.3. "Ensure equal opportunity and reduce inequalities of outcome	See above (0)	High earnings for women relative to poor time points, increased education opportunities for children (+)	As above (−−)	This is inherent in the societal context of the CS (NA)	Non-equal wages by gender (−)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		10.4. "Adopt policies, especially fiscal, wage, and social protection policies"	(NA)	Increasing reliance on seaweed farming has undermined diversification in some areas and leaves communities vulnerable to market shocks without social protection measures. But these policies are to be adopted by the government not industry (NA)	Currently the seaweed farming sector is not the subject of such policies (if they exist) (−−)	This is inherent in the societal context of the CS (NA)	These policies are aimed to be adopted by governments, not the industry. Different firms may have wage and social policies, but not as an industry (NA)
	Social capital of local community	10.2. "empower and promote the social, economic, and political inclusion of all"	See above-mixed (0)	Unclear to what extent people involved in farming are empowered and that division of assets is inclusive (0) despite local communities being afforded greater control over governance	Currently seaweed farming provides few opportunities for social capital building as it is carried out on individual plots (−). However, the tubular net technology has shown potential for building social capital (Brugere et al. 2020)	Empowers the local community by maintaining the traditional connection to the sea and fisheries/culture/tourism based incomes. Limited effect because of small scale (0)	Efforts have not been visible (0)
	(feedbacks into social fabric of community, elements can be expressed as social license)	11.3. "enhance inclusive and sustainable urbanization and capacity for participatory integrated and sustainable human settlement planning"	(NA)	(NA)	(NA)	Social license for oyster aquaculture is high on policy level but also in a local context because of small-scale activities. Oysters are more attractive to the community because of the perception of the product (e.g., compared with mussels) (+)	(NA)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		11.4. "Strengthen efforts to protect… the world's cultural and natural heritage"	Positive in terms of strengthening cultural heritage around diet (+)	Allows communities to maintain coastal livelihoods with better living conditions while reducing reliance on fisheries resources. But in migration for those wanting to be involved in farming has changed community composition and culture in some areas (+). In terms of social capital, overall positive	Seaweed farming is currently not linked to these efforts (0)	Empowers the local community by maintaining the traditional connection to the sea and fisheries/ culture/tourism based incomes (+)	Impact on Magallanes and Argentina. https://www.researchgate.net/publication/337033246_Servicios_ecosistemicos_Marino-Costeros_en_la_Region_de_Magallanes_y_la_Antartica_Chilena_Reporte_regional_preparado_por_el_Centro_de_Investigacion_Dinamica_de_Ecosistemas_Marinos_de_Altas_Latitudes_I (−)
	Equity and gender equality	1.4. "ensure that all men and women, in particular the poor and the vulnerable, have equal rights to economic resources, …, ownership and control over land, … natural resources"	See above (0)	Women often have greater income than men from seaweed farming activities. While this can be a source of conflict, farmers surveys report significant improvements to living standards because of seaweed farming (+)	Despite women constituting the main workforce in the seaweed industry, their control over their production, and returns obtained from their farming, are not commensurate with their involvement (−−)	This is inherent in the societal context of the CS (NA)	(NA)
		2.3. "double agricultural productivity and incomes of small-scale producers… women, indigenous peoples, family farmers, pastoralists and fishers through opportunities for value addition and non-farm employment"	See above (+)	As above (+)	(−-)	Women and men are both represented within the oyster sector as business owners (+)	The salmon industry has had an important impact on employment and income in the regions where it has developed in southern Chile. There is specific evidence that it has contributed to reduce poverty in the rural coastal zones where salmon farms have been installed, which is basically households composed of small producers (Ceballos et al., 2018) (++)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		5.1. "End all forms of discrimination against all women and girls everywhere"	(?)	Uncertain that is achieved despite income benefits (?)	(?)	Women and men are both represented within the oyster sector as business owners however the traditional "mansplaining" persists in many situations and women are still not promoted in the same way as men (–)	There is evidence of segregation of women to certain jobs in the processing industry, which generates wages on average superior for men than women (Arengo et al., 2010) (–)
		5.5 "Ensure women's full and effective participation and equal opportunities for leadership at all levels of decision-making in political, economic and public life"	(?)	As above (?)	Currently: (––) This could be changed with the scaling out of improved farming technology and pursuit of women's empowerment (e.g., Sea PoWer)	Women and men are both represented within the oyster sector as business owners however women are still not promoted in the same way as men (–)	
		5.a. "give women equal rights to economic resources, as well as access to ownership and control over land and other forms of property"	See above (0)	Women often have greater income than men from seaweed farming activities. While this can be a source of conflict, farmers surveys report significant improvements to living standards because of seaweed farming (+)	(––) Currently	This is inherent in the societal context of the CS (NA)	Not applicable. To review
		10.2. "empower and promote the social, economic, and political inclusion of all"	See above (0)	Unclear to what extent women involved in farming are truly empowered and that division of assets is inclusive (0)	(––) Currently	This is inherent in the societal context of the CS (NA)	(–)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
		10.3. "Ensure equal opportunity and reduce inequalities of outcome	See above (0)	Inequalities of outcome are uncertain as all that is known well is that women have greater earning potential (?)	(−−) Currently	This is inherent in the societal context of the CS (NA)	(−)
	Community integration	8.8. "Protect labor rights and promote safe working environments"	See above (0)	The farming community is deeply integrated into the community (++)	(−−) Currently	This is inherent in the societal context of the CS (NA)	The salmon industry has generated much productive employment. There is an ongoing discussion about the type of work created. There are several complaints about working conditions. However, the evidence is not clear, because the relevant unit of comparison is still unclear. The Study Department of the Ministry of Labor in Chile has several studies about working conditions in the salmon industry (0)
		10.2. "empower and promote the social, economic, and political inclusion of all"	Aquaculture can sometimes be divisive (0)	Unclear as to whether decisions about development are truly inclusive but farming activities have been adopted in a widespread fashion because of community benefits rather than mandated (+)	(−−)	Social license for oyster aquaculture is high and maintained within the community structures (+)	(−)

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TABLE A1 (Continued)

Subdomain	Indicator	Relevant SDG targets	Bangladesh freshwater pond aquaculture	Indonesia Carrageenan	Tanzania Carrageenan.	Small-scale oyster culture in Scandinavia and USA east coast	Chile salmon
	Community contributions	2.a. "Increase investment…in rural infrastructure, agricultural research and extension services"	(+)	Highly beneficial for rural investment (++)	(−) There is no investment in the seaweed farming industry currently. However researchers are working with communities of seaweed farmers.	Beneficial for rural investments but not highly beneficial because of the small-scale nature of the operations (+)	The industry has contributed to the building of infrastructure (roads, platforms), and communications mainly directed to productive purposes (Avilés, 2015) (−)
		8.2. "Achieve higher levels of economic productivity through diversification, technological upgrading and innovation…"	(++)	Adoption of seaweed farming can be diversified to adjust for shocks through farming different species but may also reduce livelihood diversification through high dependence on single crops highlighting vulnerability (0)	As above (−)	The sector is highly innovative and works intensively to find solutions better adapted to local conditions to enhance economic return on production and diversify production (++)	There is evidence of the enormous impact that the advent of the salmon industry had on the regions were it installed. This develop several input–output linkages, economies of scale, competition, diversification, technological development and innovation (Perlman & Juarez-Rubio, 2010) (++)
		8.6. "reduce the proportion of youth not in employment, education or training"	(+)	Huge increases in education opportunities for children in many locations as a results of seaweed farming (++)	There is little potential currently for the youth being interested in being involved in seaweed farming (−). This could be changed with a more attractive technology.	Young people with little formal training are often employed at the farms. Contribution is positive but limited because of the small scale of activities (+)	The industry has generated opportunities for youth training, but we do not have figures (?)
		9.1. "Develop quality, reliable, sustainable, and resilient infrastructure…"	0	The spread of physical and electronic infrastructure has been enabled by seaweed farming. Value adding infrastructure is still lacking (+)	There is no processing facilities, drying facilities currently (−−)	Little impact on infrastructure because of the small scale of activities (0)	The industry has contributed to the building of infrastructure (roads, platforms), and communications mainly directed to productive purposes (Aviles, 2015) (+)

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TABLE A2 Key challenges and opportunities, and actions, for the aquaculture sector to continue contributing positively to Agenda 2030.

Outline of a few key challenges	
A broader food system perspective	Aquaculture needs to be better acknowledged in the food system and become an integral part together with agriculture/livestock production in policy, planning and governance. Science policy silos which exist in food systems need to be broken and food systems planning need to move from in large terrestrial focused. Even if this is now beginning to change and aquatic food, in particular aquaculture, is becoming more visible in global food discussions, more efforts are needed. Identifying the barriers to integrating aquaculture across policies and the solutions for co-developing cohesive strategies where aquaculture is given equitable consideration to other sectors and activities will only happen if better framing to policy priorities can be demonstrated
Cohesive regulatory framework and planning for aquaculture at local, national, regional and international levels	Aquaculture has no cohesive voice nor strategy compared with commercial fisheries, thus, action is needed to improve integration between sub-sectors of aquaculture and between other sectors to produce comprehensive and evidence-led policy
Better aligned and more coherent aquaculture policies	Policy incoherence is a big hurdle (cf. Brugere et al., 2021). If aquaculture is to contribute to a number of SDGs (poverty, gender equality, etc.) aquaculture policy needs to be attuned to social and other policies and vice-versa, for example, re. safety nets, land rights and access to resources, gender and other forms of discrimination
Limited functional understanding of aquaculture system/species	To narrow views of aquaculture mainly contributing to food security and income generation may miss out opportunities for other contributions, for example, environmental benefits (e.g., nutrient assimilation through seaweed farming, restoration aquaculture, etc.). Most planners and policy makers have little to no experience of aquatic ecosystems therefore education on the pros and cons of aquaculture requires effective engagement strategies of targeted audiences, for example, managers, planners and policy advisers
Aquaculture as an alternative for sustainable expansion of food	There has traditionally been a lack of political will for expansion of aquaculture at both local and national levels—it has not been a priority in many countries. However, there has been a shift and now governments in many countries are keen to develop their aquaculture sectors, even in quite challenging places (e.g., UAE, Pakistan, Morocco, Djibouti, etc). So, the will is there but the will is yet to be implemented in local governance structures and thought throughout from a SDG perspective. Seeing is believing (Slater et al., 2013) - where local communities are actively involved in choosing pilot aquaculture projects and thereafter involved in development where demonstrable outcomes are seen requires better understanding of local cultures. This if communities are going to support and demand investment in this activity thus pushing governments to invest in exploratory and extension projects that adequately consider the social and cultural context of aquaculture. Many aquaculture development projects focus on the environmental and economic dimensions yet without the social context management and associated policies for development will fail
Knowledge and consumer demand	Market forces driving demand for species which may mainly optimize for a few SDGs and therefore missing opportunity for broader positive contribution to other SDGs. How to make production more sustainable for those species in demand or change/shift demand towards other species being more sustainable will be key. A focus on consumer education is needed as this could generate a relevant breakthrough to focus more on aquaculture food and services—that is, informing consumers on the comparative aspects of aquaculture facing SDGs

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TABLE A2 (Continued)

Examples of opportunities	
Aquaculture's general contribution to the SDGs	Marine spatial planning that gives equitable consideration to access and use of marine resources by mariculture could improve comprehensive and cohesive planning that enables aquaculture to realize its full potential in contributing towards achieving the SDGs. Aquaculture as a new sector in many parts of the world can be planned considering optimization of SDGs. Spatial planning of aquaculture under the ecosystem approach provides an opportunity to balance the different objectives; economic, social and environmental (Aguilar-Manjarrez et al., 2017)
Blue growth building on SDGs performance	Blue economic growth involves promotion of aquaculture and using a SDG framework may enable broader sustainability thinking and creating incentives for producers to look beyond profits. Also, expanding beyond marine environments—that is, "blue" encompassing also freshwater aquaculture will be important for identifying global prospects of aquatic production. Global aquaculture companies provide opportunities for bidirectional benefits (i.e., aquaculture forging partnerships not just benefitting from them). SDGs could contribute to/support sustainable and equitable aquaculture development instead of the other way round
Aquaculture for resilience	Aquaculture can play a role in building a resilient food system—but different species/system properties need to be carefully identified as well as how the aquaculture sector provides resilience at the food system scale (diversity, etc.). Rewriting the narrative about aquaculture's wider benefits such as conservation, climate smart production through breeding of more resilient species etc. is needed
Energy and urban farming	Aquaculture's potential for radical transformation through energy production (e.g., biomass) and food production in cities (e.g., vertical farming, aquaponics, community farming) for example, may hold potential which can be realized through context-specific technology development and partnerships (local to global)
Increased importance for sustainable diets	There is a general push for diets to include greater part of fish/seafood rather than meat. Arguments are built on both nutritional and environmental qualities
Introduction to traditional farming systems	In "new geographies" for aquaculture, where there is a lack of tradition of aquaculture and low level of knowledge/expertise, other more traditional activities may be prioritized over aquaculture. Here there may be opportunity to establish traditional systems with particular focus on local indigenous groups
Suggestions for actions	
	To more explicitly consider aquaculture's role for 2030 Agenda's 17 goals, 169 targets and 230 indicators
	Identify aquaculture's role in the global food system, in rural and urban redevelopment, in diets, and overall, in human health and wellness, and recognize the value of indigenous knowledge and traditional aquaculture farming systems as an integral part of intangible heritage and foundation for future sustainability
	National aquaculture policies should better integrate aquaculture in national food strategies and sustainable livelihood programs

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TABLE A2 (Continued)

	Influence government long-term strategic plans so that the narrative about aquaculture explains economic prosperity in context of environmental and social responsibility
	Incorporate the changing roles of international seafood trade into future contributions of regional aquaculture developments (identifying and acknowledging trade-offs related to the many SDGs)
	Establish greater transparency and cooperation between countries under bilateral aid projects involving aquaculture and build on existing experience and knowledge. Different partnerships could make aquaculture's contributions to the SDGs more clear, particularly around addressing displacing impacts
	Facilitate for broader integrative thinking/planning: Integrate land and ocean-based aquaculture with emerging renewable energy systems, existing agricultural systems, and other sectors of the economy (e.g., fisheries, tourism)
	Develop aquaculture sustainability credits to incentivize investments (e.g., Ferreira et al., 2020) and participation and incorporate ecosystem services more broadly into the "aquaculture discussion"
	Better linkages/integration between coastal aquaculture development and broader marine management, and development of tools such as carrying capacity modeling to help assess these through integrated use of indicators (Ferreira & Ramos, 2013)
	Better use/implementation of the Ecosystem Approach to Aquaculture; as done with "The Code of Conduct for Responsible Fisheries"—that is, making it more operational
	Involving key stakeholders when monitoring aquaculture's progress towards the SDGs—thus enabling broad stakeholder participation and also developing tools and mapping of SDGs to localized or downscaled meaningful indicators for tracking/monitoring progress
	Enhance/incentivize aquatic farming's role for conservation of biodiversity—policy/industry integration, adoption of ecological aquaculture (novel investment like blue bonds of greener finance and natural capital approaches
	Accelerated education for local decision makers and the public related to aquacultures potential role for achieving the SDGs, such as Ireland's Aquaculture Remote Classroom
	Making the SDGs more visible in the private aquaculture sectors sustainability reporting and improve our understanding about what's in the SDGs for private companies/aquaculture producers and how they deal with trade-offs in their SDG reporting
	Embed social and environmental responsibility into economic goals for the industry to better link to the SDGs
	Highlight often neglected cultural and social values in aquaculture and explore opportunities for synergies

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