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The One-Health approach in seaweed food production

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ABSTRACT

Seaweeds are rich in macronutrients, micronutrients, and bioactive components and have great potential as sustainable resources in terms of both production and consumption of a desirable food. Still, the seaweed aquaculture industry's rapid growth points out challenges that need to be taken into consideration when assessing environmental integrity, animal, and human health. In this review, the seaweed aquaculture's potential impact on the wildlife and human welfare and the environmental integrity has been evaluated using the One Health approach, a principle in which human, animal, and environmental health outcomes are considered as strictly connected. This is the first effort to implement the One Health concept into the seaweed cultivation assessment, and it is meant to give new perspectives for the growth of this industry.

1. Introduction

The expansion of seaweed cultivations has the potential to positively impact local poverty and ecosystem management, and provide climate change mitigation (Hambrey, 2017). Using only sunlight and nutrients from the sea, while taking up CO_2, the seaweed farming will help meet the demand for food, animal feed, materials, chemicals, fuels, and nutraceutical products in the near future with a neutral carbon footprint.

Seaweeds could produce enough biomass and protein for a growing and possibly increasingly wealthy human population with no land and freshwater expropriation for agriculture. Moreover, seaweed farms could have a remarkable positive influence on the ecosystem since they can provide shelters to marine species, improve biodiversity, and provide a plethora of different ecosystem services to the environment (Kim et al., 2017).

In Europe for several decades, the seaweeds' cultivation has been sporadic and mainly focused on producing alginates or agricultural products from brown algae. Primarily, seaweeds have been farmed for their functional polysaccharide proprieties or mineral content (Stévant et al., 2017). In recent years, the consumption of Asian dishes (e.g., sushi) has enlarged the popularity of seaweed-based recipes and increased the interest in locally available natural ingredients (Stévant et al., 2017). Consequently, the number of research projects and industry activities tackling seaweed cultivation and production as food has increased. Several studies have highlighted the health benefits of the seaweed consumption given by many high-value nutrients such as phenols, carbohydrates, vitamins, minerals, and proteins (Brown et al., 2014; Padam and Chye, 2020; Wells et al., 2017; Cherry et al., 2019).

Despite the benefits provided in terms of public health, economic and social benefits, the seaweed industry's rapid growth might lead to unexpected ecological consequences (Campbell et al., 2019). In the expansion ecological and social aspects must be considered in order to balance economic growth and ocean health. To reach this objective, a holistic approach is required, in which different disciplines, including medicine, epidemiology, farming, ecology, chemistry, environmental science, and biology, work together.

As shown in Fig. 1, ecosystem services and potential adverse effects on the marine ecosystem are strictly linked, and every action in any of those compartments can influence the others. These inextricable interconnections can be summarized by visualizing the health of organisms and their environment as One Health. The One Health concept is a collaborative, multisectoral, and transdisciplinary approach to achieving beneficial health and well-being outcomes for people, non-human organisms, and their shared environments (Commission, 2019). The importance of this concept has been highlighted by the World Health Organization and the G20, and it is included in the United Nations Sustainable Development Goals (SDG) (Hambrey, 2017; Oosterveer and Sonnenfeld, 2012).

Implementing the One Health approach in the seaweed food production, as a principle in which human, animal, and environmental

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health outcomes are fully understood and considered, would lead to the development of practical tools useful to tackle broad societal challenges. Therefore, the One Health approach may become the preferable approach in which the food production industry can be designed and assessed, scientific evidence can be gathered, and policy and legislation applied.

The present review aims to provide an internationally applicable conceptual framework of the main ecological components linked to industrial seaweed productions that should be considered when using the One Health approach. Critiques have been highlighted and integrated into a risk assessment to measure aquaculture systems' conditions.

2. The One Health concept

The One Health concept was proposed as an extension of the One Medicine one. The One Medicine approach aims to recognize the close genomic relationship between animals and humans for disease prevention and better treatments (Zinsstag et al., 2011). In this context, the One Health concept extends this idea by including the ecosystem. Indeed, human well-being is inextricably linked to wildlife's welfare and the environment, in which humans live.

An increasing number of studies are now including the One Health concept (Rock et al., 2009; Zinsstag and Tanner, 2008; Gibbs, 2014; Lubroth, 2012; Jamwal and Phulia, 2021; Prata et al., 2021; Santos and Ramos, 2018; Stentiford et al., 2020). In aquaculture, it has been mainly used to describe the impact of pathogens on the environment, wildlife, and human conditions and set practical metrics that the industry has to follow to grant sustainability (Santos and Ramos, 2018; Stentiford et al., 2020). Implementing this framework in the seaweed aquaculture would help determining suboptimal conditions that could then be measured and the gathered data used to guide research, policy, and legislative changes (Stentiford et al., 2020).

Since the seaweed farming is still in its infancy, its exact impact is largely unknown. Different approaches have been used in other aquaculture sectors to minimize the impact on the environment and wildlife. Seaweed farms have been used to take up nutrients and coupled with other aquaculture activities. An example is the integrated multi-trophic aquaculture (IMTA), which represents a practical solution to managing the waste of fish farms by utilizing nutrients in excess as resources for the macroalgae farming (Chopin et al., 2008). Using this strategy, this cultivation benefits from fish waste with an overall increased biomass production and contributes to a better exploitation of the fish feed, reducing the environmental impact of waste (Chopin et al., 2001; Chopin et al., 2012). Kelp species are recognized as the most suitable species to get incorporated into IMTA systems in both temperate and cold water. Some experimental sites have already been successfully tested in Galicia and Norway, combining kelps and other species, e.g. *Saccharina latissima* (Stévant et al., 2017; Freitas et al., 2016).

Another example is the development of the Norwegian environmental regulation system "MOM" (Modelling-Ongrowing fish farms-Monitoring) (Ervik et al., 1997). The MOM is a management system, which includes environmental quality standards, where changes in the environment can be tracked closely. The MOM program was successfully used for the sustainable development of salmon farms in Norway. Even though this model does represent a viable tool to monitor the impact of fish aquaculture practices on the environment and the wildlife, it has

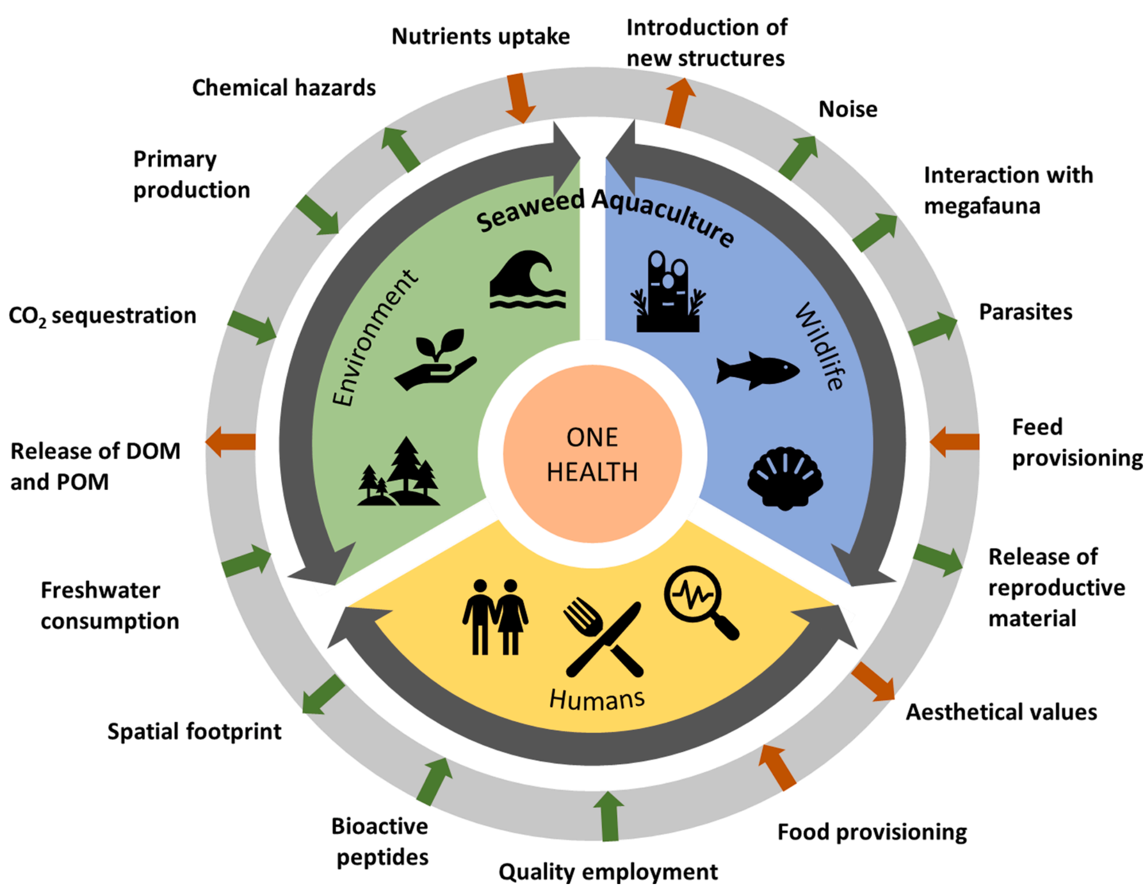

Fig. 1. Schematic representation of the One Health concept in relation to seaweed aquaculture. Seaweed cultivation can cause a variety of effects, as described in the outside circle. The arrows towards the center represent the benefits of seaweed aquaculture on each component. The arrows toward the outside are the downsides that each component has when seaweed cultivation occurs. Green and red arrows state the intensity of the effects (green: low impact, red: high impact). The same effect can be applied to more than one inner component. In the figure, the position of each effect is dependent on the component that they are affecting. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

limitations on the applicability to other aquaculture practices such as shellfish and seaweed (Zhang et al., 2009). Moreover, it only considers the interaction between the fish farms and the environment, without integrating the human aspect.

If adequately integrated into the development of seaweed farms, the One Health approach in seaweed production will encompass many SDGs' objectives. The ecosystem services given by seaweed cultivation, such as the eutrophication reduction, would help to achieve: i) the SDG 14, in particular, the indicator 14.1.1 that aims to prevent and significantly reduce marine pollution of all kinds; ii) the SDG 13, indicator 13.2.2, regarding climate change and reduction of greenhouse gas emissions; iii) the SDG 2, seaweed base healthy food products would contribute to indicator 2.1.2 that aims to end hunger, achieve food security and improved nutrition; iv) the SDG 12, seaweed biomass production would also help to reach the target 12.2 that aims to sustainable management and efficient use of natural resources; and v) the SDG 8, the social services given to the population would be consistent with indicators 8.3.1 and indicators 8.5.1 on achieving full and productive employment and decent work for all women and men (SDG, 2018).

3. Chemical composition of macroalgae

Macroalgae are a broad group of photosynthetic marine species commonly divided into three different phyla: green algae (Chlorophyte), brown algae (Phaeophyte), and red algae (Rhodophyte), each one with Pea unique chemical composition. They are a rich source of multiple valuable macro- and micronutrients, including proteins, carbohydrates, phenols, vitamins, and minerals, making them a desirable option for food production (Lafarga et al., 2020; Øverland et al., 2019). More than 70 species of algae have been approved for food consumption, each one with a different nutrient composition that varies according to species and abiotic factors, such as location, temperature, habitat, collection time, nutrient concentration in water, and salinity (Boderskov et al., 2016; Makkar et al., 2016; Schiener et al., 2015).

The seaweed protein content has gained particular emphasis due to the high amount that can be extract in some red and green algae. Indeed, this content can significantly vary between species. With some exceptions, brown algae usually contain a lower amount of proteins than red and green algae (Øverland et al., 2019; Lourenço et al., 2002). Green algae can contain proteins up to 26% of their dry weight (dw), even though the amount strongly depends on the harvesting season and the geographical area (Fleurence, 2016). The protein content of *Ulva lactuca,* for example, is known to be strictly linked to seasonal variations that can double the amount of extracted proteins during summer and winter (Biancarosa et al., 2017; Mæhre et al., 2014). Red algae have as average the highest protein content, with *Porphyra dioica* and *Porphyra umbelicalis* having up to 31.0 ± 0.2 and 24.0 ± 0.2 % of the total dw, respectively, reaching the same protein content as soybeans. (Biancarosa et al., 2017; Garcia-Vaquero and Hayes, 2016). Fig. 2 shows average protein contents of different algae classes, and Table 1 summarizes the amino acid content of several seaweeds used for food consumption. Overall, glutamic and aspartic acids are the most abundant amino acids responsible for the typical "umami" taste, commonly associated with seaweed. The amount of methionine, cysteine, and lysine is often limited

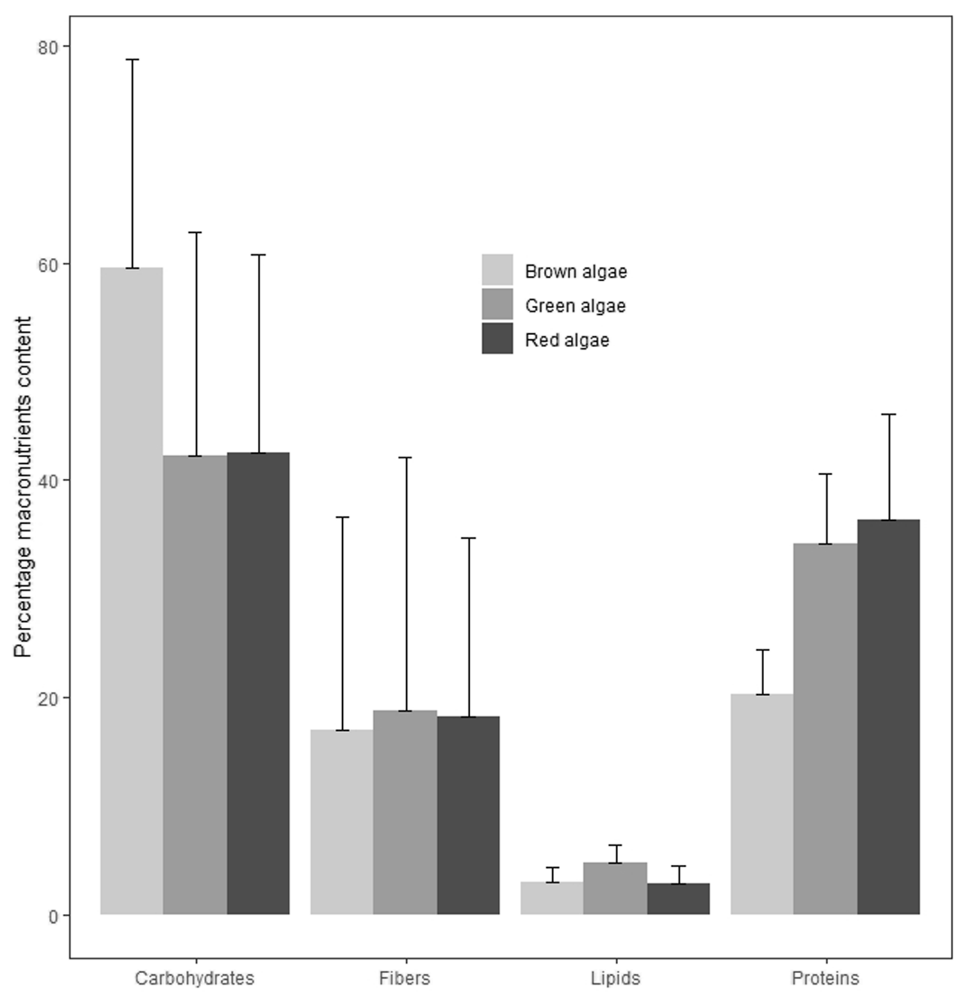

Fig. 2. Average percentage of macronutrient content in brown, green, and red algae. Data adapted from Cherry et al. (2019), analyzing the content found in 36 studies.

Table 1
Amino acid profiles of seaweed species approved for food consumption. Essential amino acids (EEAs) above and non-essential amino acids (NEEAs) below. The amino acid values are reported as g kg-1 of dry matter. Standard deviation was calculated from the data provided from the references. (n.a. = not available).

Species	Leucine	Valine	Lysine	Threonine	Isoleucine	Methionine	Tryptophan	Isoleucine	Phenylalanine	Total EAAs	References
Alaria esculenta	7.13 ± 0.66	5.77 ± 0.74	5.32 ± 0.62	5.2 ± 0.93	4.03 ± 0.4	1.87 ± 0.45	n.a.	1.65 ± 0.26	4.7 ± 0.52	35.7 ± 4.08	(Mæhre et al., 2014; Munda, 1977; Gaillard et al., 2018)
Ascophyllum nodosum	5.9 ± 0.25	4.98 ± 0.86	5.04 ± 0.86	4.55 ± 0.53	3.54 ± 0.41	1.96 ± 0	n.a.	1.73 ± 0.67	4.45 ± 0.78	32.1 ± 3.61	(Munda, 1977; Kadam et al., 2017)
Fucus vesciculus	4.08 ± 2.08	2.88 ± 1.56	3.09 ± 1.55	2.75 ± 1.1	2.2 ± 1.08	1.65 ± 0.15	n.a.	0.99 ± 0.36	2.66 ± 1.33	20.3 ± 7.9	(Mæhre et al., 2014; Munda, 1977; Munda and Gubenšek, 1976)
Himanthalia elongata	2.92 ± 0.87	3.69 ± 0.58	3.06 ± 0.16	2.92 ± 0.32	2.19 ± 0.08	1.63 ± 0.33	n.a.	1.5 ± 0.5	2.54 ± 0.25	20.4 ± 2.88	(Garcia-Vaquero and Hayes, 2016; Cofrades et al., 2010)
Laminaria digitata	4.9 ± 0.3	3.85 ± 0.25	3.45 ± 0.25	3.55 ± 0.25	2.9 ± 0.2	1.55 ± 0.25	n.a.	1.2 ± 0	3.25 ± 0.15	24.65 ± 1.5	(Munda, 1977; Munda and Gubenšek, 1976)
Saccharina latissima	37.2 ± 26.7	18.7 ± 14.6	51.6 ± 45.5	27.6 ± 23.3	18.5 ± 14.5	16.4 ± 12.8	3.4 ± 0.1	7.44 ± 6.3	25.5 ± 13.9	206.5 ± 144.1	(Boderskov et al., 2016; Bak et al., 2019; Marinho et al., 2015; Sharma et al., 2018)
Undaria pinnatifida	7.19 ± 1.07	6.14 ± 0.71	4.74 ± 1.4	4.19 ± 1.02	4.24 ± 0.5	2.31 ± 1.24	0.7 ± 0	4.78 ± 2.2	4.84 ± 0.48	39.1 ± 8.17	(Cofrades et al., 2010; Dawczynski et al., 2007; Taboada et al., 2013; Zhou et al., 2014)
Chondrus crispus	6.6	5.4	6.3	4.8	3.9	1.8	n.a.	2.1	5.2	36.1	(Parjikolaei et al., 2016)
Palmaria palmata	9.33 ± 2.05	8.73 ± 1.89	8.06 ± 0.79	6.73 ± 1.77	5.66 ± 1.32	3.03 ± 0.73	n.a.	2.06 ± 0.37	6.23 ± 1.22	49.8 ± 8.95	(Mæhre et al., 2014; Munda and Gubenšek, 1976; Parjikolaei et al., 2016)
Pyropia spp.	12.5 ± 9.09	11.7 ± 8.59	9.39 ± 6.6	10 ± 6.43	6.62 ± 4.23	3.01 ± 1.75	0.7 ± 0	3.38 ± 1.32	8.2 ± 4.94	65.6 ± 38	(Munda and Gubenšek, 1976; Cofrades et al., 2010; Dawczynski et al., 2007; Taboada et al., 2013)
Ulva spp.	20.5 ± 26.8	7.42 ± 4.33	6.66 ± 3.36	7.09 ± 4.01	5.5 ± 3.55	3.58 ± 2.97	0.7 ± 0	1.57 ± 0.93	6.76 ± 4.41	59.8 ± 45.9	(Mæhre et al., 2014; Munda and Gubenšek, 1976; Bikker et al., 2016; Ortiz et al., 2006; Tabarsa et al., 2012; Wong and Cheung, 2000; Yaich et al., 2011)
Mastocarpus stellatus	4.51	4.15	5.77	3.62	2.89	1.27	n.a.	1.6	3.82	27.63	(Gaillard et al., 2018)
Vertebrata lanosa	9.9	7.6	12.6	7.8	7.2	1.8	n.a.	2	8.2	57.1	(Mæhre et al., 2014)

Species	Alanine	Arginine	Cyst (e)in	Glysine	Proline	Tryptophan	Aspartic acid	Glutamic acid	Serine	Total NEAAs	References
Alaria esculenta	14.43 ± 3.3	4.79 ± 0.49	1.43 ± 0	5.61 ± 0.68	4.4 ± 0.66	3.45 ± 0.54	10.61 ± 2.19	16.4 ± 2.87	5.1 ± 0.61	66.2 ± 11.9	(Mæhre et al., 2014; Munda, 1977; Gaillard et al., 2018)
Ascophyllum nodosum	5.62 ± 0.42	4.07 ± 0.66	0.44 ± 0	4.96 ± 0.69	3.06 ± 0	2.33 ± 0.41	11.2 ± 2.79	18.65 ± 5.55	4.13 ± 0.36	54.4 ± 11.6	(Munda, 1977; Kadam et al., 2017)
Fucus vesciculus	4 ± 2	2.76 ± 1.53	n.a.	3.23 ± 1.32	2.35 ± 1.32	1.28 ± 0.57	6.51 ± 2.7	11.66 ± 6.68	2.78 ± 1.12	34.6 ± 18.6	(Mæhre et al., 2014; Munda, 1977; Munda and Gubenšek, 1976)
Himanthalia elongata	3.36 ± 0.04	2.82 ± 0.22	1.72 ± 1.41	2.84 ± 0.14	2.17 ± 0.37	2.05 ± 0.64	5.57 ± 0.37	7.16 ± 0.36	2.83 ± 0.06	30.5 ± 3.89	(Garcia-Vaquero and Hayes, 2016; Cofrades et al., 2010)
Laminaria digitata	4.4 ± 0.79	3.1 ± 0.3	n.a.	3.95 ± 0.15	3.35 ± 0.55	2.1 ± 0.3	6.9 ± 0.69	7.95 ± 0.55	3.15 ± 0.44	34.9 ± 3.94	(Munda, 1977; Munda and Gubenšek, 1976)
						18.2 ± 19.7					

(continued on next page)

Table 1 (*continued*)

Species	Alanine	Arginine	Cyst (e)in	Glysine	Proline	Tryptophan	Aspartic acid	Glutamic acid	Serine	Total NEAAs	References
Saccharina latissima	36.5 ± 31.1	38.6 ± 31.6	2.93 ± 1.89	50.3 ± 46.1	24.8 ± 19.5		120.5 ± 102	119.2 ± 95.1	32.6 ± 24.8	443.9 ± 386.1	(Boderskov et al., 2016; Bak et al., 2019; Marinho et al., 2015; Sharma et al., 2018)
Undaria pinnatifida	8.26 ± 2.52	5.96 ± 1.6	0.68 ± 0.25	6.44 ± 0.82	4.27 ± 0.5	5.39 ± 2.8	9.76 ± 1.61	13.24 ± 0.78	5.05 ± 0.83	59 ± 12.2	(Cofrades et al., 2010; Dawczynski et al., 2007; Taboada et al., 2013; Zhou et al., 2014)
Chondrus crispus	6.7	9	3.4	6.7	5.8	2.4	11.2	11.7	5.7	62.6	(Parjikolaei et al., 2016)
Palmaria palmata	10.96 ± 2.48	6.93 ± 1.24	2 ± 1.5	8.7 ± 1.71	8.03 ± 2.35	3.73 ± 2.03	14.93 ± 2.45	15.76 ± 4.61	7.16 ± 1.22	78.2 ± 20.8	(Mæhre et al., 2014; Munda and Gubenšek, 1976; Parjikolaei et al., 2016)
Pyropia spp.	17.6 ± 14.4	12.1 ± 6.9	1.54 ± 1.01	11.1 ± 7.42	8.02 ± 5.56	7.32 ± 5.55	17.2 ± 12.2	20.3 ± 14.2	9.94 ± 7.51	105.2 ± 79.9	(Munda and Gubenšek, 1976; Cofrades et al., 2010; Dawczynski et al., 2007; Taboada et al., 2013)
Ulva spp.	10 ± 4.74	7.72 ± 4.12	1.25 ± 0.44	8 ± 3.98	6.22 ± 3.41	4.89 ± 2.73	13.93 ± 8.04	15.32 ± 9.64	7.15 ± 3.78	74.5 ± 45.3	(Mæhre et al., 2014; Munda and Gubenšek, 1976; Bikker et al., 2016; Ortiz et al., 2006; Tabarsa et al., 2012; Wong and Cheung, 2000; Yaich et al., 2011)
Mastocarpus stellatus	4.35	5.93	2.6	6.6	3.68	n.a.	8.6	8.02	4.25	44.0	(Gaillard et al., 2018)
Vertebrata lanosa	7.6	7	2.1	8.9	10.8	5.4	12.3	16.3	7.7	78.1	(Mæhre et al., 2014)

in brown algae, while leucine and isoleucine are less present in red algae proteins (Bleakley and Hayes, 2017). Lysine, in particular, is an essential amino acid present in limited quantities in terrestrial plant protein sources such as corn, rice, soy, and wheat. Thus, seaweed may represent a relevant source for the implementation of essential amino acids in healthy diets. In addition to proteins, seaweeds also contain fibers (20–30%), lipids (2%), and carbohydrates (up to 50%, as in the case of brown algae). Dietary fibers have been positively correlated to anti-obesogenic effects, including improved satiation, delayed nutrient absorption, and delayed gastric emptying (Brownlee et al., 2005).

3.1. Bioactive peptides

One of the main drivers for the recent increased interest in seaweed cultivation has been the potential production of nutritional components and the potential presence of bioactive peptides.

Bioactive properties are short amino acid sequences (i.e., 2–20 aa), encrypted in a protein, that can exert their beneficial effects once released through food processing, extraction, or digestion. Once available, these peptides have various biological effects, including antioxidant, antidiabetic, cholesterol-lowering, antihypertensive, antiobesity, anticancer, and antimicrobial (Admassu et al., 2018; Daliri et al., 2017). Due to the extraordinary seaweed diversity, a high variation of bioactive peptides from seaweed may be revealed and complement those already extracted from other sources such as meat, milk, cereals, and fish (Haque and Chand, 2008; Malaguti et al., 2014; Pampanin et al., 2012; Ryan et al., 2011). Hence, research on bioactive peptides could reveal nutritional benefits that may reduce the occurrence of severe human health challenges (Rüegg et al., 2018; Berry et al., 2015; Godfray et al., 2010). Bioactive peptides extracted from seaweed can, therefore, potentially be added as functional components in healthy diets and prevent and treat diseases (Brown et al., 2014).

Recently, many studies have reported a series of new seaweed-derived bioactive peptides, and more details related to their positive effects on human health can be found in the comprehensive review published by Lafarga et al. (Lafarga et al., 2020). Nevertheless, this is still a relatively new research field with a great potential to include many seaweed species and likely to increase in the coming years.

3.2. Proteins

Seaweeds have a low content of easily digestible proteins when eaten raw. Therefore, several studies have focused on finding efficient extraction methods to maximize the amount of proteins available during the consumption of seaweed products (Bleakley and Hayes, 2017; Cermeño et al., 2020). The protein extraction is a challenging step due to the complexity and the rigidity of the macroalgal cell wall and the presence of polysaccharides (e.g., alginates) and polyphenols. A protein extraction usually involves the disruption of the cell wall, using various approaches such as chemical treatment, enzymatic digestion, high-pressure disruption, or ultrasonication. The different types of physiological and biochemical characteristics of seaweeds usually affect the protein yield, and the extraction method applied can have a significant impact on the biological activity of the protein or peptides. Even though the literature is relatively limited regarding seaweeds' protein content compared to other crops, different extraction methods have been successfully proposed (Cermeño et al., 2020). Relevant information can be found in a comprehensive review published by Cermeño et al. (Cermeño et al., 2020). The authors evaluated extraction techniques applied for the discovery and the generation of bioactive peptides from seaweed, thereby providing vital information for pursuing the development of seaweed products.

4. Seaweed safety and daily intake

Effects, both beneficial and adverse, derived by seaweed consumption can be considered as average intake to provide useful information.

Roleda et al. (Roleda et al., 2019) carried out a health risk assessment on the human seaweed consumption, based on the average intake in China of 5.2 g per day of dw, corresponding to 26 g of fresh seaweed per capita. This is likely to be a conservative approach to estimate the average European seaweed daily consumption, due to the different eating culture in those areas. Based on these levels, for example, the seaweed's heavy metal concentration contribution would be below the EU Commission Regulation on contaminants in foodstuffs (CEVA, 2019). However, a regular intake of seaweed might lead to trace metals' bioaccumulation when the product is grown in contaminated areas, since macroalgae can accumulate trace metals several orders of magnitude higher than the surrounding waters (Bonanno and Orlando-Bonaca, 2018).

In general, due to their absorption and bioaccumulation capacity, seaweed can be a direct source of ingestion of toxic chemicals such as cadmium, lead, mercury, arsenic, and micronutrients, such as iodine. Studies have highlighted the variability between species regarding the absorption of trace metals, micronutrients, and other pollutants (Phaneuf et al., 1999; Turner et al., 2008; Chalkley et al., 2019). Bonanno et al. (Bonanno et al., 2020) showed a high bioaccumulation of trace metals in *Posidonia oceanica* and *Ulva lactuca* collected in the Mediterranean Sea. Since *U. lactuca* is used as a feed source for animals, this might represent a challenge in the animal farming sector (Bonanno et al., 2020). A positive correlation between the fluctuation of salinity and temperature on trace metal accumulation has been demonstrated in laboratory experiments conducted using *Ulva* spp. (Turner et al., 2008; Haritonidis and Malea, 1999). The risk of reaching toxic levels is considerably low, even in heavily polluted areas (Phaneuf et al., 1999; Chalkley et al., 2019). However, these findings need to be confirmed by long-term evaluation in seaweed consumers.

One point of concern is the potentially dangerous high concentration of iodine and other trace metals due to the consumption of some seaweed species (Nanri et al., 2017). Iodine is a micronutrient essential for synthesizing thyroid hormones, and it is necessary for human growth and development, especially in the early stage of life (Delange, 2000; Zimmermann, 2009). A moderate intake of this nutrient could help the general iodine-deficient population in Europe to prevent thyroid disorders, even though excessive intake may be detrimental (Zimmermann and Andersson, 2011). In some algae, the iodine concentration can reach up to 624.5 ug / g dw (as for example in *Laminaria digitata),* while a total concentration of 150 μg per day has been suggested to avoid thyroid impairment (Desideri et al., 2016; Nitschke, 2016).

Another trace metal of possible concern is arsenic., which has been shown to resist cooking and *in vitro* digestion (Almela et al., 2005). While a high amount of arsenic can lead to DNA damage and potentially carcinogenesis, the majority of arsenic in seaweed is present as arsenosugar which is less toxic (Cherry et al., 2019; Ma et al., 2018; Holdt and Kraan, 2011). Taylor, Li (Taylor et al., 2017) showed that arsenic amounts in 23 different algae species in some commercial products were neglectable, except for Hijiki, where 87% of the extractable arsenic was present as inorganic arsenic (IARC Working Group on the Evaluation of Carcinogenic Risks to Humans, 2012). In addition, the inorganic arsenic was determined in 112 species of seaweed preparation sold in Spain, all of which within safe limits, with the exception of Hijiki in which the level of arsenic ranged from 41.6 to 117.0 mg/g (Almela et al., 2006).

While only a few studies have dealt with the possible microbiological contamination, they all agree that this type of contamination is not of concern (Wang et al., 2009; Bindu, 2011). The presence of *Escherichia coli* on algae harvested from heavily contaminated areas has been tested, showing that the bacteria were almost absent in every sample (Wang et al., 2009; Kumaran et al., 2010). Park, Jeong (Park et al., 2015) reported a norovirus outbreak associated with the green algae (*Enteromorpha spp*) consumption, and few other studies have been associated with foodborne intoxication associated with seaweeds (Haddock and Cruz, 1991; Yotsu-Yamashita et al., 2004). This highlights the necessity to further study the potential microbial contamination of seaweed, especially in the context of food production.

While most of the studies have focused on the health benefits associated with seaweed consumption, Cherry, O'Hara (Cherry et al., 2019) highlight the lack of human intervention trials in investigating the potential risks of consuming seaweed components. There is still a need to characterize each seaweed component and its effect on human health to discern which one positively or negatively affects individuals' health status. Even though observational studies could indicate potential benefits, these outcomes need to be taken with considerable caution. The specific grams of seaweeds needed to obtain a meaningful amount of protein, bioactive peptides, or dietary fibers also must be considered. Even more, with a higher intake of seaweed, there might be a following increased intake of toxic elements that need to be accounted for.

5. Benefits of eating seaweeds

The majority of data concerning seaweed and human health benefits are gathered through *in vitro* trials, as reviewed by Déléris et al. (Déléris et al., 2016). Most of these effect have also been substantiated by observational studies, as extensively summarized by Brown et al. (Brown et al., 2014) and Cherry et al. (Cherry et al., 2019), and are beneficial to human health in various aspects: increasing digestive efficiency, weight management, and preventing a wide range of diseases.

Several of these beneficial effects are due to the presence of unique bioactive compounds that are not present in terrestrial food sources. Some of these novel bioactive compounds such as phlorotannins and certain polysaccharides have a potential for treatments of chronic diseases as Alzheimer, as well as been used for their anticancer and antiviral potential (Bauer et al., 2021; Bilal and Iqbal, 2020; Shi et al., 2017).

The bioactivities reported in the literature, concerning peptides extracted from seaweed proteins, showed a wide range of beneficial effects. Bioactive peptides present in brown and red seaweeds have shown anti-tumorigenic effects, further indicating the potential for these compounds' utilization (Olivares-Bañuelos et al., 2019; Miranda-Delgado et al., 2018). These antitumoral effects of seaweed have been substantiated by a study conducted in Japan on stomach and colorectal cancer (Minami et al., 2020). *In vitro* trials with bioactive peptides extracted from seaweed have also highlighted the potential of seaweed as an energy regulator in obesity and type-2 diabetes (Bermano et al., 2020). Although studies on diabetes are mostly largely lacking, Kim et al. (Kim et al., 2008) showed that high fiber intake from *Ascophyllum nodosum* and *Saccharina japonica* led to a significant reduction of glucose level in blood in obese individuals after a four-week trial. There are also indications of potential benefits of bioactive peptides on preventing cardiovascular diseases, showing an inversed correlation between seaweed consumption and ischemic heart disease in Japanese adults (Murai et al., 2019). Another research deepens these results finding an inverse association with cardiovascular mortality among Japanese men and women, especially related to cerebral infarction (Kishida et al., 2020).

6. Bioavailability of seaweed components

Knowing seaweed's products ' bioavailability is of primary importance to systematically document and quantify seaweed consumption's biological benefits. Bioavailability can be described as the fraction of ingested food components available at the target site of action for utilization in physiological functions (Guerra et al., 2012). It entails the entire process from the first manipulation of food due to conventional processing techniques, such as heat treatment, drying, or freezing and, also, digestion and distribution of seaweed components in the human body. These processes can potentially change seaweed component proprieties, leading to a different metabolic fate in the human body, and therefore, every step needs to be evaluated and controlled (Bleakley and Hayes, 2017).

García-Sartal et al. (García-Sartal et al., 2013) showed that a water cooking procedure promoted the release of various metals into the boiling water, thus lowering the concentration of ingested metals. Another study carried out on eight different species of Indonesian seaweed showed a higher amount of macrominerals (i.e., Na, K, Ca, and Mg) and a lower trace-mineral content (i.e., Cu, Zn, and Fe), with high solubility of Mg and Ca (Santoso et al., 2006), after boiling. Pina et al. (Pina et al., 2014) determined the profile of the red seaweed, *Chondrus crispus*, based on four different factors: phycobiliproteins, volatile compounds, β-carotene and lutein, and antioxidant activity after different culinary treatments, showing a significant decrease in phycoerythrin content and an increase in β-carotene and lutein and an overall increase on the total antioxidant activity after boiling. Other studies have pointed out the adverse effects of processing seaweed with a loss of free amino acids and vitamins (Perry et al., 2019; Kazir et al., 2019). In particular, a study conducted on *P. palmata* and *A. esculenta* showed an increase of amino acid availability after heat treatment (either boiling for 15 or 30 min) by 86–109%, and further that the amount of free amino acid was 64–96% higher in treated samples compared to raw ones (Maehre et al., 2016).

In addition to processing, another critical factor is the transfer of components from the food to the organism. Digestion processes, release from the food matrix, and the behavior of algal food components in the gut affect the absorption and the bioavailability of macroalgae components (Bleakley and Hayes, 2017). In general, nutrient bioavailability in seaweed is lower than that of animal products (Barbier et al., 2019). This difference has been attributed to human guts' minor ability to degrade complex polysaccharides, impeding proteins' accessibility and other components to gastrointestinal enzymes (Lopez-Santamarina et al., 2020; Mæhre et al., 2016). Therefore, a legitimate strategy to create added-value products would be the selective extraction of individual components from the seaweed matrix, such as bioactive peptides. *In vivo* studies regarding the bioavailability of seaweed components are therefore required and deserve further research.

7. Seaweed industrial production

Seaweeds have traditionally been an essential ingredient in Asian countries, leading the market, with 98% of the total biomass production (FAO, 2018). In Japan, consumers have an average intake of 1.6 Kg dw per year per capita (Makkar et al., 2016). In Western countries, macroalgae are not a significant food source yet, and industrial applications have been limited mainly to the production of phycocolloids (alginate, agar, carrageenan) (Fleurence, 2016). However, the seaweed production is now receiving growing interest due to its recognition as a sustainable source of renewable biomass, the zero-footprint impact in cultivation, and its health-promoting characteristic (Desideri et al., 2016). Data regarding macroalgae's perspective, in terms of future utilization possibility, is lacking as the industry is still at the beginning of its potential. A limited seaweed supply also constrains the food production market. Today the demand for many seaweed species such as *P. palmata* is outstripping the supply (Barbier et al., 2019).

Wild seaweed species harvesting accounts only for less than 2% of the worldwide supply. This approach is currently used in Europe and Asia for economically attractive species for which cultivation techniques are not yet established (FAO, 2018; FAO, 2018). Wild harvesting can lead to the depletion of those natural resources (Fenberg and Roy, 2008), and the use of mechanical harvesting gears has also raised concerns about the sustainability of these practices and their adverse effects on the marine ecosystem (Skjermo et al., 2014). An additional research effort is needed to develop new protocols for cost-efficient production and potential valuable products. According to Barbier et al. (Barbier et al., 2019), macroalgae products' development increased by 147% from 2011 to 2015, which can be reflected by increased market demand for seaweed biomass. To fulfill this demand for products with environmentally sustainable and responsible production, there is the need for guidelines for future ventures. As previously described, seaweeds can represent a source of intake of toxic chemicals. Therefore, the possibility for seaweeds to represent a safe food requires the development of legislative measures, which will ensure monitoring and labeling of products to safeguard, for example, against excessive intakes of salt, iodine, and heavy metals.

In general, guidelines to support stakeholders to develop seaweed products are lacking and ventures needs to comply with each country's specific regulations. For instance, a company that wishes to sell those products has to deal with the Food and Drug Administration (FDA) regulatory body in the USA and with the Food safety commission (MAFF) in Japan (Holdt and Kraan, 2011), making a profitable international business harder to approach.

In Europe, a harmonized legislation for evaluation of seaweed product safety and standardised procedures for the development of novel foods and food additives would support the development of the seaweed industry (Lähteenmäki-Uutela et al., 2021). As pointed out by Holdt and Kraan (Holdt and Kraan, 2011), the European legislation is currently complicated and is changing continuously, making the market of seaweed challenging. Recently, Barbier et al. (Barbier et al., 2019) shed light on the current situation in terms of food security and legislation in main producing countries with a special focus on the European market. At present, an effort to standardize the European legislation on the commercialization of seaweed has been undertaken by the European Food Safety Authority (EFSA). Some preliminary results have been already published regarding the risk associated to seaweed consumption (Institute, 2019). However, it is important to highlight that there is a need for more data to perform robust risk assessments in the coming time.

Here we present a risk assessment based on the One Health concept that could be used as a foundation for developing universal guidelines for sustainable seaweed cultivation and production.

For sustainable products and responsible productions, a process development requires an environmentally sustainable foundation, linking industrial-economic prosperity and social interests. Therefore, to evaluate foundation sufficiency, a risk assessment based on the One Health concepts could provide the necessary guidelines.

8. Risk assessment

A hypothetical risk assessment on each part of the One Health concept (humans, environment, and wildlife) is presented in Table 2. The table summarizes the potential benefits and negative impacts of increased seaweed production, considering the direct and indirect influence of these activities on the environment, human health, and animal health. The critical point presented serves for reference, and hopefully, they can be updated as new data are gathered following the expansion of the seaweed industry. Furthermore, as mentioned above, every stressor is strongly dependent on geographical area and seasonality; hence, the risk assessment should also be weighed for each specific farm on a case by case basis.

8.1. Human health challenges related to seaweed production

Besides the direct effects derived by seaweed consumption described above, seaweed aquaculture can provide a range of positive public health effects, with economic and social advantages. Seaweed farming has already generated substantial socio-economic benefits to marginalized coastal communities in developing countries. In some of these communities, seaweed farming resulted rapidly the primary source of income (FAO, 2018). According to the 2018 FAO report, seaweed farming takes place in more than 50 countries, and thanks to the low initial capital investment required and the safe accessibility of seaweed plots, it can gives a vital income opportunity to a community (FAO, 2018). Seaweed cultivation may result in a significant opportunity to earn some income, especially for women in developing countries, giving direct benefit to societal equality (FAO, 2018; Larson et al., 2020). Carrageenan seaweed farms have shown similar socio-economic benefits in countries such as Mexico, Tanzania, India, and Indonesia (Valderrama et al., 2013).

A study conducted in Sweden highlighted the potential of seaweed cultivation to become a highly profitable industry in which negative externalities are relatively small compared to the financial value generated (Hasselström et al., 2018). The positive externalities derived by seaweed aquaculture, such as habitat generation, carbon sequestration, and bioremediation through nutrient uptake, described below in this review, will likely impact society positively. Another positive effect, often overlooked, is the freshwater savings when comparing mariculture

Table 2
Benefits and negative impact of seaweed cultivation and industrial seaweed production on humans, wildlife, and the environment.

Target	Characteristic	Benefits	Negative Impact	Reference
Human	Food provisioning	Food produced by seaweed farms is nutritious and has beneficial effects associated with the presence of bioactive compounds.	Possible risk of exposure to harmful microbial and chemical contaminants by human consumers	(Brown et al., 2014; Wells et al., 2017; Cherry et al., 2019)
Human	Aesthetical value	Increased interest in the marine environment through scientific and educational programs.	Farm installation can reduce the land value.	(Skjermo et al., 2014; Hasselström et al., 2018; Ullmann and Grimm, 2021)
Human	Income generation	Poverty alleviation and wealth generation, especially in developing countries. Access to high-quality food and other opportunities.	None.	(FAO, 2018; Skjermo et al., 2014; Ullmann and Grimm, 2021)
Human	Quality employment	Enhanced employment opportunities. Gender equality and technical knowledge and skills generations.	Working in a risky environment.	(FAO, 2018; FAO, 2018; Ullmann and Grimm, 2021; Msuya, 2012)
Environment Human	Spatial footprint	The spatial footprint for sea-based production systems is minimum relatively to yield compared to other production systems.	Less space for recreational activity, possible presence of litter, and wastes from seaweed farms.	(Hasselström et al., 2018; Ullmann and Grimm, 2021; Ottinger et al., 2016)
Environment Human	Freshwater consumption	The freshwater consumption is limited compared to other food production techniques.	None.	(Barbier et al., 2019; Radulovich, 2011; Duarte et al., 2017)
Environment	CO2 sequestration	Seaweeds account for almost 50% of all carbon fixed in marine sediments. The carbon footprint is negative thanks to carbon uptake by seaweeds.	Increased releasing of DOM and POM can negatively affect the seafloor leading to anoxia or hypoxia, directly impacting the ecosystem living underneath.	(Froehlich et al., 2019; Capron et al., 2020; Hendriks et al., 2014; Chung et al., 2013; Xiao et al., 2021)
Environment Wildlife	Nutrient uptake	No addition of nutrients needed. Seaweed can minimize the impact of eutrophication on impacted areas.	Local reduction of nutrients leading to a change in the composition of wild phytoplankton and zooplankton.	(Ullmann and Grimm, 2021; Viaroli et al., 2008; Visch et al., 2020; Xiao et al., 2017)
Environment Wildlife	Primary production	Seaweed farms contribute to a significant part of primary production.	None.	(Duarte et al., 2017; Jupp and Drew, 1974; Wu et al., 2016)
Environment Wildlife	Introduction of new structures	Increased local habitat biodiversity and productivity.	Absorption of kinetic energy. Change on the natural course of coastline erosion. On a large scale, change in local hydrodynamics.	(Campbell et al., 2019; Visch et al., 2020; Grant and Bacher, 2001; Smale et al., 2013)
Environment Wildlife Human	Chemical hazards	Farm management procedures use a minimal amount of chemicals and pesticides. Chemical impact on the surrounding environment and wildlife is minimal.	Accumulation of pollutants from the surrounding environment	(Bonanno and Orlando-Bonaca, 2018; Bonanno et al., 2020; Visch et al., 2020; Brinkhuis et al., 1987)
Environment Wildlife Human	Release of reproductive material and non-native species	None.	Loss of habitat fitness with possible ecosystem shifts. Spread of non-native species leading to direct effects on farmers.	(Valiela et al., 1997; Valero et al., 2017; Loureiro et al., 2015)
Wildlife	Interaction with megafauna	Increase possibility of entanglement and other problems related to the presence of farms to megafauna.	Provision of species refugee.	(Campbell et al., 2019; Poonian and Lopez, 2016; Norderhaug et al., 2005)

to land based cultivation. Water scarcity may be the most limiting factor to increasing world food production (Radulovich, 2011; Duarte et al., 2017). When being compared to land crops, seaweed production could help save up to 1000 L of freshwater per kilogram of biomass (Radulovich, 2011).

A research work, appointed by Innovation Norway in collaboration with the Norwegian Ministry of Fisheries and Coastal Affairs, reported the social-economic benefits of seaweed cultivation in Norway (Skjermo et al., 2014). Macroalgae cultivation, which uses only sunlight and nutrients from the sea while taking up CO_2, may provide a zero CO_2 footprint industry and significantly contribute to meet the demand for food, feed, materials, chemicals, fuels, and nutraceutical in the near future. Leading the way to a steady replacement of fossil resources, the cultivation of macroalgae in Norway would establish a future feedstock bypassing the competition with land-based agricultural resources.

8.2. Environmental impact

Environmental conditions required for the growth of different species of seaweed vary. In general, seaweeds need areas with enough nutrients, optimal light, and specific temperature ranges. Depending on these factors, the environmental impact of a seaweed farm can be diverse. The establishment of universal guidelines could be incomplete and would not consider specific site characteristics, species selected (concerning the use of alien and locally absent species in aquaculture), or biosecurity measures to control the spread of diseases. These specific site considerations must be taken into account to minimize the industry's impact on the environment.

While there is still a lack of data regarding extensive cultivations in western countries, several studies have highlighted the potential benefits of seaweed farms on the marine environment. Direct impacts, due to farming operations, are mainly localized and site-specific, and, by contrast, there is increasing evidence that seaweed aquaculture could significantly mitigate small-scale environmental impacts. Seaweed cultivations do not need pesticides and fertilizers and instead remove inorganic nutrients (Campbell et al., 2019; Marinho et al., 2015). If co-located in areas with high anthropogenic nitrogen input, seaweed cultivation could substantially reduce the excess of nitrogen, phosphorus and organic pollutants (Seghetta et al., 2016; Arumugam et al., 2018). Seghetta et al. (Seghetta et al., 2016) assessed the nutrient uptake of extensive offshore cultivation of *S. latissima*, resulting in an uptake of at least 10% of anthropogenic phosphorus output. A comprehensive study performed on the Chinese coast on a large scale seaweed cultivation system, showed that seaweed cultivation already plays a central role on mitigating coastal eutrophication (Xiao et al., 2017). The seawater nutrient concentration reduction efficiency of the seaweed farm was found of 47% ± 3% for phosphorus and 53% ± 7% for nitrate depending on the location and species used (Xiao et al., 2017).

On a larger scale, seaweed cultivations could also contribute to climate change mitigation (Duarte et al., 2017; Froehlich et al., 2019). Fast-growing brown kelps (i.e. *S. latissima*; *Laminaria hyperborea, Undaria pinnatifida)* are some of the most productive vegetation systems on Earth, accounting for almost 10% of the total ocean-based primary production and 50% of all carbon fixed in marine sediment (Jupp and Drew, 1974; Smale et al., 2013; Pedersen et al., 2012; Smale et al., 2020). Although this enhanced primary production and CO_2 sequestration are likely to play a small role, they would still be a positive contribution (Ortiz et al., 2006) The potential of seaweed species to locally increase the seawater pH has been recently studied. The highlighted mechanism could potentially provide an ecologically important way to improve seawater conditions and counteract the ongoing acidification process (Hendriks et al., 2014; Chung et al., 2013; Pettit et al., 2015). Xiao et al. (Xiao et al., 2021) have shown the capacity of seaweed farms to remove CO_2 from the seawater in a large scale setting, with the species *Saccharina japonica* raising the seawater pH by 0.100 within the farm area. Even though evidence are still limited, this display the potential of seaweed farming in buffering the ocean acidification.

Long-term data on the effects of seaweed farms on the environment is still lacking and therefore needed. Despite that, a recent study carried out on Sungo Bay (China) assessed that the sediment status beneath a bivalve and seaweed farm, over ten years, was in “best conditions,” and the environmental impact was low (Zhang et al., 2020). Zhang et al. (Zhang et al., 2020) have also observed significant macrofauna changes compared to previous assessments, meaning an increased total environmental health. Even though impacts are strongly dependent on specific sites characteristic, these data show a low impact on the seafloor due to the enhanced biomass production. Nevertheless, anoxia and hypoxia events due to macroalgae bloom have been described (Valiela et al., 1997). Dissolved and particulate organic matter released from seaweed farms in sites without current or in shallow areas could lead to these anoxia and hypoxia events potentially damaging the ecosystem (Viaroli et al., 2008).

If not correctly managed, scaling up industrial cultivation will not be without consequences. Potential adverse effects on the environment are still poorly studied, and long-term data that might enhance or resize the ecosystem services given by seaweed farms to the environment are lacking. It is conceivable that industry’s growth may lead to an inevitable modification of the environment for introducing new structures in the water and the biotic consequences linked to the introduction of new biomass. The physical interaction of seaweed cultivation deployed into the sea, near the coastline, could cause a breakdown of swells, theoretically changing coastline erosion’s natural course (Campbell et al., 2019; Smale et al., 2013). This absorption of kinetic energy, on a large scale, would lead to changes in local hydrodynamics. Indeed, a circulation model of flow in a site of dense cultivation of macroalgae and bivalves displayed a significant reduction of the total flow, reaching a decrease of 54 % in the middle of the cultivations compared to control (Grant and Bacher, 2001). This lower flow rate could significantly decrease the exchange rate of nutrients that may change the seawater body’s chemical properties. This problem could be avoided with a careful selection of the site and careful management to avoid negative consequences for protected or vulnerable species.

8.3. Wildlife impact

Seaweed ecosystems are diverse and structurally complex systems that have highly heterogeneous biodiversity (Steneck et al., 2002). Cultivated seaweed plots have been shown to rapidly attract biodiversity, including many fish species in tropical areas (Radulovich et al., 2015). The addition of artificial facilities may provide a healthy habitat and nursery zones to marine species, resulting in a positive effect on marine biodiversity (Bernard et al., 2019; Diana, 2009). Chai et al. (Chai et al., 2018) showed enhanced biodiversity associated with a *Gracilaria lemaneiformis* cultivation, providing further support for using this species as a practical approach to increasing the ecosystem’s health. There is still a limited knowledge of whether macrofauna would be attracted to seaweed farms due to cultivation practices. Cultivations may enhance foraging opportunities for some species, and, although this might be a positive interaction, could lead to a greater risk of entanglement (Poonian and Lopez, 2016). A careful location selection and specific cultivation system could minimize these risks. (Campbell et al., 2019). On the other hand, artificial facilities could also increase the marine environment’s disturbance due to collecting procedures like pollution caused by loss of material and noise production (Radford and Slater, 2019).

Seaweed farms could also pose a threat to benthic habitats due to the release of particulate and dissolved organic matter that can alter the local marine chemistry. The high abundance of seaweed could lead to increased nutrients uptake and rapid oxygen depletion due to organic matter decomposition (Viaroli et al., 2008). These two factors would result in a phytoplankton community compositional change, especially for large-scale farms. These compositional changes can disturb essential ecosystem functions and the flow of goods and services (Eklöf et al., 2005; Aldridge et al., 2012). Another challenge related to extensive cultivation could be the increased competition for light with benthic communities that might suppress the abundance of phytoplankton in those areas (Campbell et al., 2019). The cultivation of seaweed on surface water may shade the underlying habitats competing with autotrophic species. The effects of shading on the biomass production underneath a seaweed farm showed a potential reduction of up to 40% in biomass production (Eklöf et al., 2006; Zhou, 2012). Scaling up the cultivations needs to consider this factor when selecting a site, avoiding protected or vulnerable communities.

The domestication of wild seaweeds will be an unavoidable practice in large farming systems (Valero et al., 2017). Cultivated species will most likely be characterized by human-imposed shifts to improve biomass production and reproductive efficiency. This release of reproductive material could introduce a genetic bottleneck that may narrow the genetic pool of wild species, potentially making them more susceptible to environmental changes and diseases. A genetic material release could lead to a crop to wild gene flow that could depress natural populations (Campbell et al., 2019; Valero et al., 2017). Loureiro et al. (Loureiro et al., 2015) showed that reducing the gene pool in farmed species could make them less resilient to abiotic or biotic stresses, such as pathogens and diseases. However, the consequences of this reduced gene pool are still poorly studied. Researches will be required to assess both the variability of natural population and cultivated species’ effects on surrounding population fitness and associated ecosystem (Campbell et al., 2019; Valero et al., 2017).

The introduction of non-native species may also threaten the genetic diversity of wild stocks. Williams and Smith (Williams and Smith, 2007) found that from 277 macroalgae species introduced in non-native habitats, 121 were somehow linked to aquaculture or shellfish farms. There is a rising awareness that non-indigenous species’ introduction may lead to unwanted and sometimes severe ecological effects (Williams and Smith, 2007; Klein and Verlaque, 2008). Introduced macroalgae species can impact the environment in several ways, such as reducing the cover, productivity, and diversity of native seaweed, triggering an ecosystem shift (Klein and Verlaque, 2008; Britton-Simmons, 2004). Massive ecosystem alterations have already happened with *Caulerpa taxifoglia* in the Mediterranean sea and *U. pinnatifida* to the French Atlantic coast (Casas et al., 2004; Meinesz et al., 2001). In some cases, these alterations have occurred even on sites in which seaweed farming has never been carried out due to marine currents’ spores’ transportation (Tano et al., 2015).

The thrive of non-native species could pave the way for the introduction of new pathogens, parasites, and epiphytes linked to those species (Loureiro et al., 2015). Knowledge of these organisms’ effects on native species lacks, even though some studies have reported effects directly on cultured species (Mulyaningrum et al., 2019; Zhang et al., 2019; Vairappan et al., 2008). Tsiresy et al. (Tsiresy et al., 2016) reported the drastic decline in production of *Kappaphycus alvarezii* due to an alien epiphytic parasite's appearance. Further on, an incident of filamentous algae, *Polysiphonia spp,* became rapidly invasive in various regions in Madagascar, leading to dramatic consequences to the local farmers (Tsiresy et al., 2016). Therefore, these non-native species would directly impact local farmers due to reduced seaweed farms' productivity.

9. Conclusions

Implementing the One Health approach in seaweed food production, which involves experts in human, animal, environmental health, and other relevant disciplines, can support the development of the seaweed cultivation industry in the most sustainable way. This collaborative, multisectoral, and transdisciplinary approach can represent the fundament to set practical metrics that the industry has to follow for granting sustainability.

Seaweed cultivation can, if properly managed, have several positive externalities while providing healthy food for the society. Current data, from both *in vivo* and *in vitro* studies, have proven the potential of this unexploited resource that could, for instance, help combat chronic diseases, lack of iodine, and, in general, improve the quality of life. The high nutritional value of seaweed for human consumption and the development of bioactive peptides seaweed-based products are two essential elements for this new industry to flourish. Further research could help to enable the exploitation of macroalgae in the development of functional food or nutraceutical.

As pointed out, there are potential adverse effects on ecosystem, biodiversity, and human health that are important to consider while supporting the seaweed production industry's development. The industry needs to rely on the scientific community's data to improve the knowledge of less productive or more fragile species that are more challenging to cultivate. Indeed, many species are highly interesting as feedstock for high-value products or attractive in healthy human seafood production, and for that, clear guidelines are not yet established and therefore highly needed.

The one-health principles will facilitate the production increase while ensuring sustainable and healthy food. This would help measure and mitigate the drawbacks of seaweed cultivation. Overall, The seaweed aquaculture can provide a solution for the increasing food demand for the incoming years, while complying with the UN SDGs and having a zero environmental impact.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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