Chapter 4
A Road to the Sustainable Seaweed Aquaculture

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4.1 Introduction

The seaweeds are common food supplement source from ancient times in the coastal areas mainly in the Oriental Asia. In the most recent times the seaweed are being exploited not only for the direct food consumption, but also, for other industries with a wide range of applications being the most prominent and commercial explored based in the unique seaweed polysaccharides (García-Poza et al. 2020). However, seaweeds synthesize many structural molecules, such as proteins, lipids and carbohydrates (primary metabolites) essential as food source. Furthermore they produce a wide range of bioacitive molecules that can be used in many industries (food, feed, agriculture, cosmetics, pharmaceutical and biotechnological) (Leandro et al. 2020b; Shama et al. 2019). This scenario provides a wide range of opportunites to mass produce the biomass and extract the valuable phycochemicals to meet

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the global demands (García-Poza et al. 2020). In addition, photosynthetic carbon accumulation Seawed cultivation provides additional advantage of carbon sequestration and address problems of climate change beside producing valuable feedstock to produce biofuels and raw materials (Hessami et al. 2019) for other industries Viz., food, feed, pharmaceuticals and fertilizers (Duarte et al. 2017).

Seaweeds are the basis of the ecological structure coastal area, supporting directly and indirectly a high number of aquatic species (Reisewitz et al. 2006).

Being autotrophic oranisms they offer support to a number of ecological resources, such as habitats, food and shelter to various trophic levels (herbivores, omnivorous and carnivorous, from invertebrates to vertebrates species) (Almanza and Buschmann 2013; Vásquez et al. 2014) and therefore, seaweeds are vital to support aquatic ecosystem.

Globally, the increasing demand for seaweeds and their sub-products have enhanced the interest in their production, rather than restricting only to wild collections. Harvesting of seaweeds from natural habitats is very dangerous from an ecological point of view, as uncontrolled wild collection can promote a negative impact in the ecosystems (Jung et al. 2013). This scenario supports industrial production of seaweeds hence attractive to many stakeholders to invest more in the production of different macroalgal species that can meet the needs of the economic sector (Ashkenazi et al. 2019). Moreover, it is extremely necessary to maximise the food production for feeding the rising human population on a planet through tapping of alternate renewable sources such as seaweed farming to supplement the limited production possibilities of food production through agricultural crops which demand fertile soil and water resources which are becoming scanty (Charrier et al. 2017).

In this chapter, the sustainable seaweed aquaculture is analyzed from seaweed economic point of view including the new cultivation technologies, sustainability and safety to meet the global industrial demands to support blue growth.

4.2 Seaweeds Economic Importance

Seaweeds are an exceptional source of raw material for industries such as food, feed, energy, biomolecules and livelihood for humans (Charrier et al. 2017; Mohammad et al. 2019). The use of seaweed biomass allows these industries to have alternative sources of raw material, with multiple advantages, such as lowering the production costs or increasing the value of the product. Seaweed can also be promoted as a specialty product for food uses. Today, it is estimated that more than 80% of the worldwide seaweed production and harvesting is destined for Human consumption, directly or as hydrocolloids (thickeners, gelling agents, etc.) (Rebours et al. 2014; Charrier et al. 2017). Seaweed are a rich source of natural compounds with multiple biological activities, namely as antioxidant and antibacterial. They are rich in vitamins (namely, A, B_1, B_2, B_{12}, C and E) and minerals, such as iodine. They also produce secondary metabolites of high commercial value and beneficial to human health. These characteristics turn seaweed in alternative food sources, since they can meet human nutritional needs and still be low on fat (Pereira 2010; Cardoso et al. 2014; Carvalho and Pereira 2014; Azevedo Fonseca 2016; Leandro et al. 2020a).

In recent years, we started to search for healthier ways of feeding ourselves. In addition, health care and life expectancy has increased. These facts boosted the studies on seaweed bioactive compounds (Plaza et al. 2008; 2009; Azevedo Fonseca 2016). Thus, seaweed represents a natural food with a high nutritional value, low in calories, and provide abundant biological activities supporting human health. All these characteristics are advantageous to the food industries to produce valuable products in a sustainable manner (Pereira 2010; Azevedo Fonseca 2016).

Seaweeds are also used both as fertilizers and as animal feed, hence an important alternative raw material for agricultural and livestock industries (Makkar et al. 2016; Charrier et al. 2017). Seaweed are being increasingly considered as beneficial for world agriculture, since they represent an organic, healthy, and nutritious raw material. They can be used by direct application of the biomass or in extracts. There is evidence that using extracts of brown seaweeds (*Ascophyllum nodosum* and *Sargassum muticum*, for instance) in lower concentrations (diluted extracts) improve agricultural crops (Silva 2001). In that way, it is advantageous for the enhancement of agricultural productivities, making the crops more efficient, healthier and reduce dependence on the conventional fertilizers and also supporting organic farming (Sousa et al. 2020).

There are research and published bibliography advocating for the use of seaweed in as livestock feeds. Research shows that seaweed should be used as feed additive and not be applied as a substitute of the typical feed, since the beneficial effects are registered when is usually used under 10% of the total concentration. Seaweed represents a strong alternative animal feed due to the present search for alternatives to the typical feed supplements and antibiotics, which are being highly regulated at a world level. Macroalgae are rich in protein, dietary fibers and phytochemicals which can be used not only to enhance the nutritional quality of animal feed, but to act as a substitute of antibiotics (Morais et al. 2020). The actual demand for renewable and sustainable energy sources that will not compromise on food and land resources can also be fulfilled by seaweeds. This is possible as seaweeds are fast growing, show high biomass yielding with elevated and free of charge productivity, when compared to other conventional biomass feedstock, as corn or soybean for example. However, there are questions related with the biosafety of the use of such biomass could not have a quality guarantee due to variations of nutritional values and risks of heavy metals accumulation (Morais et al. 2020).

In addition, the industrial sector uses seaweed biomass for nutraceuticals, cosmetics, biotechnological and pharmaceutical applications, thus propelling the growth of seaweed biotechnology (Mazarrasa et al. 2013; Morais et al. 2021). Seaweed's extracts and purified compounds demonstrate high potential to be incorporated in cosmetic formulae and pharmaceutical products, with various functions fortifying with natural ingredients as a substitute for the synthetic ones (Carvalho and Pereira 2014; L. Pereira 2018; Morais et al. 2021). There are diverse companies that already use seaweed extracts and compounds in their formulas. However, the monitoring of seaweed biochemical profile is a problem that seaweed-based cosmetic products must overcome. The development of seaweed cultivation and green extraction methods are the major questions for this subject, with the latest research showing promising results (Morais et al. 2021).

Currently, around 32.4 million tons of seaweeds per year (wet weight) are produced worldwide and, as a signal for the growth of the biotechnology market of seaweed products, seaweed-related patent applications have increased at 11%/year since 1990 (Mazarrasa et al. 2013; Charrier et al. 2017; FAO 2020). The production capacity value presents itself as the triple of almost 20 years ago, back to 2000. Asia leads the way in cultivation of seaweed, despite harvesting natural stock (as is current practice in non-Asian countries), with 99% of its production coming from aquaculture (Charrier et al. 2017; FAO 2020). As an example, in the European seaweed market, aquaculture only accounts for 32% of the production (Araújo et al. 2021).

There is still a problem of sustainable production technologies and profitability associated with seaweed economics which needs to be addressed (Steneck et al. 2002; Charrier et al. 2017; Araújo et al. 2021).

The major advantage in promoting seaweed cultivation is its ability to sequester carbndioxide at far exceeding levels compared to coastal vegetation and land plants. CO_2 Sequestration abilities of seaweed are higher up to 1.5 times that of seagrass meadows, salt marshes and mangroves (Krause-Jensen and Duarte 2016; Charrier et al. 2017) Seaweed also help in the removal of dissolved nutrients from coastal waters and coastal protection from erosion (Arkema et al. 2013; Charrier et al. 2017; Araújo et al. 2021). These bioremediation actions have an economic value, furthermore in the Green Deal Era. De Groot et al. (2012) estimated the value of coastal Ecosystem services provided by macroalgae to be over 28,000 $/ha/year, thereby providing opportunities in the global market (de Groot et al. 2012; Charrier et al. 2017).

4.3 Seaweed Aquaculture: The Development of a Millennial Technique into the Industry

Seaweed aquaculture technologic development have been growing dramatically in Asia over the past century and, more recently, have also developed a strong presence in the Americas and Europe (Kim et al. 2017; Ferdouse et al. 2018; García-Poza et al. 2020). Historical records demonstrates large-scale seaweed production have been operating in Asia for decades, mainly in nearshore cultivation techniques (Cheng 1969). Most of the seaweed production occurs in China, Indonesia, and other Asian countries (47.9%, 38.7%, and 12.8%, respectively, in 2016), mostly for human food and food additives (Goecke et al. 2020).

Still, the increasing global effort to develop these farms differs from country to country in terms of seaweed production and its marketing strategies. There is a higher demand for edible seaweed as a direct food product in the East, which generates farmer incomes higher than the resources obtained from the application of seaweed in the polysaccharide industry in Western countries (Hafting et al. 2015).

The nearshore cultivation technique is used by near-coastal population and it is the most common cultivation system to cultivate seaweeds, being a low cost and low productivity cultivation system. Although, this cultivation system is used by Asiatic population by centuries (Soto and Wurmann 2019). Considering the seaweed cultivation, it only need nutrients, seawater and light to initiate the seaweed cultivation (García-Poza et al. 2020).

However, it has been developed more cultivation methods, for example:

– Offshore, this cultivation is used along the times (similar to the nearshore cultivation) which seaweed can be cultivated on the sea floor (attached to hard substrate) or on long-lines (anchored lines or nets that are either seeded or have individuals tied to them for grow-out). The advantage is the installation and maintenance costs are very low, however, there is need of a land laboratory to do the long lines preparation (García-Poza et al. 2020).
– Inshore, this type of seaweed cultivation started in the 1970s–1980s. The advantage is the scope of observing and rapidly modify based on the cultivation conditions. However, a disadvantage of this type of cultivation are the high cost of construction and maintenance (García-Poza et al. 2020).

This seaweed cultivation can be also grouped with other aquatic species cultivation (for example, oysters, fish, shrimp) forming a multitrophic aquaculture (IMTA), which try to mimic the natural ecosystem to produce more than one species, and lowering the production costs ratio when compared to single species aquaculture (Granada et al. 2016; Knowler et al. 2020).

The global need to produce large quantities of seaweed will rise in the coming years, however, there is still a continuous optimization of the cultivation method to satisfy this increasing need, a sustainable and safe output of seaweed and its compounds until today (Buschmann et al. 2017; Camus et al. 2018). This thematics demands an integrative collaboration between academia and the aquaculture industry through research and development (R&D) centers, which has contributed to the joint development of research projects to enhance the profitability and sustainability of the seaweed cultivation industry (Hafting et al. 2012). Presently in most places the new onshore and offshore cultivation processes are not yet total environmentally viable and are economically unsustainable, due to the influence of abiotic and biotic factors (Peteiro et al. 2016; Buschmann et al. 2017). Inorder to address this issue there is need to enhance innovation in production for the benefit of farmers and industrial partners to develop globally acceptable quality biomass for international trade(García-Poza et al. 2020). This is the basis to the Aquaculture 4.0, which relates the seaweed cultivation systems coupled to a multidisciplinary engineering including computer aided automation thus leading to increased competitiveness and performance of aquaculture, minimizing total costs (García-Poza et al. 2020). Moreover, this new technological advancement reduces the costs and pollution in the aquaculture systems, with the advantage that permit to obtain higher yields of biomass with a known quality (Behroozi and Couturier 2019). These innovation in the aquaculture is a long step for the sustainability of the aquaculture system and biomass production.

4.4 Aquaculture Sustainability and Safety

Nowadays, with the blue and circular economy mindset, there is a need to guarantee the safety and sustainability of the seaweed aquaculture from an ecological and economic point of view.

4.4.1 Aquaculture Sustainability

For sustainable aquaculture, there is a need of a study from the beginning of the process to understand the economic and ecological impact in the ecosystem of the seaweed cultivation up to the seaweed biomass production phase, reducing the wastes and ecological impact.

At the beginning, there is a need an authorization of licensing by the local country authorities and also study the aspects of social and economic impacts and risk managements (García-Poza et al. 2020).

Wood et al. (2017) studied the installation of a seaweed aquaculture farm in the United Kingdom, according to licensing and environmental conditions. Based in this study, there is a need of lease the seabed and obtain a Maritime License from the national regulator. There are no impacts related to existing populations in the cultivation environments. It is unlikely that a small farm alone will have a major effect on the marine environment, in contrast very large farms or several small farms next to each other can have a more noticeable effect.

Pereira et al. (2021) evaluated the sustainability of the cultivation of the red macroalga *Hypnea pseudomusciformis* and its use in human food with the Association of Algae Producers of Flecheiras and Guajiru, in Ceará, Brazil. The authors found that the environmental indicators showed an efficient use of energy, nitrogen, and phosphorus, which impacted the algae biomass production by 383, 894 and 1860%, respectively. In addition, algae absorb carbon, do not pollute, and present a low risk to local biodiversity because they are native. The social indicators revealed that 51% of the investment is in the local community and the distribution of income is equal among workers. The farm has a high demand for labor, which is socially inclusive. Finally, the farm was highly profitable, with an Internal Rate of Return (IRR) of 119%, capital recovery in 1.2 years and positive externalities, generating an additional income of US$ 262.00 t^{-1}. This assay demonstrates that this project was excellent to develop into a commercial seaweed aquaculture, very well supported by the sustainability data.

However, when talking in the production of biomass, there is a need to guarantee that the biomass is fully exploited. The best opportunities to fully exploit the seaweed produced is as food industry (as food supplement) or in the biorefinery processes. This Biorefinery concept aims to fully use the biomass to produce several products and/or compounds together.

The step-by-step extraction of pigments, mannitol, phlorotannins, carbohydrates and residues of four species of brown algae *Ecklonia radiata* and *Undaria pinnatifida* was investigated by Zhang et al. (2020). The authors obtained yields, calculated based on the dry weight of each product in each species of seaweed, of 3.4–9.8% (pigments), 22.2–30.7% (mannitol), 0.1–5.1% (phlorotannins), 5.2–15.5% (alginates), 12.2–18.5% (other carbohydrates) and 13.5–19.5% (residual algae). The results indicated that brown seaweeds are potential candidates to be used in biorefineries in order to produce biomaterials, adding value and bioenergy.

Furthermore, Rudke et al. (2020) cite that in the future, it is expected that the extraction of carrageenan from the red macroalgae *Kappaphycus alvarezii*, in the biorefinery process, should be expanded to obtain ethanol, fertilizers, pigments, protein concentrates, among other products that can be obtained from the biomass of this species, which has a large volume of cultivation around the world.

4.4.2 Aquaculture Safety

The aquaculture has an important factor that is very dynamic, and most importantly the monitoring of quality of seawater and ensuring the safety levels needed for the biomass production free from contaminants(Lin et al. 2019; Ngajilo and Jeebhay 2019; Nuwansi et al. 2019 (Kumararaja et al. 2019). The anthropological actvities have enhanced the pollution levels in the marine ecosystem whieh is a matter of serious concern throughout the world (Shah and Shah 2020). They also add potential organic an inorganic components.

(Mawi et al. 2020). Moreover, the seaweeds can absorb heavy metals, incorporating them into the cell wall (López Losada et al. 2020) and some toxic organic compounds such as organo-halogenated (Leri et al. 2019), which are very dangerous to the exploitation of the biomass. There should be sufficient supportive regulations regarding the quality monitoring of the seawater to ensure the safety for seaweed cultivation. Only then that a reasonably safe product can be obtained by the farmers and producers.

4.5 Conclusions and Future Perspectives

Seaweeds have been gaining a high interest from diverse industries to be exploited as natural source of food, fuel, fertilizer and biochemicals.

The monitoring of the aquaculture system is essential to guarantee the biomass quality and safety for further exploitation.

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