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Seaweed Aquaculture for Human Foods, Land-Based

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Article Outline

Glossary

Algae A group of autotrophic organisms, containing chlorophyll a and sometimes other accessory pigments, which are able to convert solar energy into chemical energy via photosynthesis.

Aquaculture The farming of autotrophic and heterotrophic organisms in aquatic systems.

Bioextraction An environmental management strategy by which nutrients are removed from an aquatic ecosystem through the harvest of enhanced biological production, including the aquaculture of suspension-feeding shellfish and/or marine macroalgae.

Ecosystem Is the grouping of all living organisms occupying a particular unit of space and interacting with each other and their environment.

EPA Eicosapentaenoic acid is an omega-3 polyunsaturated fatty acid, sometimes presented with the chemical notation 20:5(n-3).

HDL High-density lipoprotein; composed of a high proportion of protein and relatively little cholesterol; high levels of HDL are thought to be associated with a decreased risk of coronary heart disease and atherosclerosis.

Heteromorphic Life Histories Life histories in which there are clear morphological differences between the different stages of the life cycle, i.e., individuals of the sporophyte and gametophyte stages are morphologically different and distinguishable. In some cases, such as the genus *Porphyra* and members of the kelps, there are macroscopic and microscopic stages alternating life cycle phases.

IMTA Integrated Multi-Trophic Aquaculture is a form of aquaculture in which organisms from different trophic levels, with complementary resource needs, are produced in the same system. Typically, these aquaculture systems integrate the production of a fed organism, such as fish or shrimp, with that of extractive organic aquaculture such as shellfish and the extractive inorganic aquaculture of seaweed.

Isomorphic Life Histories Life histories in which there are no distinguishing morphological differences between the different stages of the life cycle, i.e., the individuals of the sporophyte (diploid, 2n) and gametophyte (haploid, n) stages are morphologically identical and can be distinguished only when their respective, characteristic reproductive structures are present, e.g., *Chondrus crispus* and *Palmaria palmata.*

LDL Low-density lipoprotein; a lipoprotein that transports cholesterol in the blood, composed of

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a moderate amount of protein and a large amount of cholesterol; high levels of LDL are thought to be associated with an increased risk of coronary heart disease and atherosclerosis.

Macroalgae A group of macroscopic algae of which at least one part of their life history is multicellular and visible with unaided eye.

Mariculture Farming of autotrophic and heterotrophic organisms in marine systems, i.e., using seawater.

Polysaccharides Complex structural polymers. They have a structural function in the alga but may be extracted industrially to provide a range of polysaccharides used for their rheological properties, e.g., agar, carrageenan, and alginic acid.

Seaweed A group of macroscopic, marine autotrophic algae.

Sea-Vegetables A group of macroscopic, marine autotrophic algae, also called seaweeds, seaplants, or macroalgae; they may be used as vegetables for human consumption or raw materials for a range of industrial, commercially important extracts such as bioactives or polysaccharides.

Definition of the Subject and Its Importance

The production of seaweeds for human foods in land-based aquaculture, is an activity poorly presented by the scientific community. Of the thousands of seaweed species identified, a remarkably small subset is actually farmed in the marine environment (i.e., open water) and even fewer are grown in land-based aquaculture systems. Of those that are used in land-based systems, most are monocultures grown for specific high value uses. For instance, *C. crispus*, *P. palmata*, and *Saccharina latissima* are grown for human consumption; *Chondrocanthus* and the "*Trailiella*" stage of *Bonnemaisonia/Asparagopsis* for the cosmetic industry; and *Gracilaria* spp., *Palmaria* and *Ulva* spp. as feed for abalone). Given the many centuries history of terrestrial production of land plants for human and animal feed crops and the tremendous efforts given over to the selection and crossbreeding of these plants, by contrast, selection and improvement of seaweed crops is very much in its infancy. Even more so, of all the relatively small number of seaweeds which are domesticated for open water cultivation, even fewer species have actually been tested in land-based culture systems. This is in part due to the lack of reliable, domesticated species and their selected strains suitable for the rigors of on-land cultivation, and in part due to the complexities of life histories and the lack of understanding of the environmental regulation of growth. There is, therefore, a need to test other species since open water systems may not be appropriate for niche cultivation applications. The historical development of open water cultivation and multi-species pond cultivation may have originated in Asia (for discussion and references see later section); however, modern land-based aquaculture of seaweeds began with the work of John Ryther at Woods Hole Oceanographic Institute (WHOI) in the late 1960s through the mid-1970s [1]. Land-based Integrated Multi-Trophic Aquaculture systems (IMTA) may contribute to the development of sustainable fed aquaculture systems by minimizing environmental impacts (i.e., removing excess dissolved inorganic nutrients, *d*issolved *o*rganic *m*atter (DOM), and *p*articulate *o*rganic *m*atter (POM). Furthermore, while the systems may yet have to be optimized geographically and in relation to the species utilized, the controlled production of seaweed biomass in these systems may offer a reliable and safe source of food or ingredients for human consumption, fish feeds, as well as a source of valuable compounds for biotechnological applications. As a special focus, this entry will discuss the importance of land-based seaweed aquaculture systems and their global utilization.

Introduction

Seaweed is a popular term used to collectively describe marine macroalgae. Among this large and diverse assemblage of photosynthetic marine organisms are a number of species with a varied array of uses; when used for human consumption, they are more popularly known as "sea-vegetables." This collective of convenience includes the macroscopic, multicellular, red, green, and brown algae [2]. Seaweeds are often abundant and predominantly found in the near-shore marine ecosystems in all the oceans of the world. As a result of their diverse intercellular compounds including alginic acid, carrageenans, and agar, seaweeds have very important industrial applications [3, 4]. Being important primary producers in marine

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ecosystems, macroalgae are an integral component of near-shore environment and form a fundamental part of the basis of the photosynthetic food chains, playing a role similar to that of terrestrial plants [5]. In these natural environments, seaweeds often perform a large number of ecosystem services [6] (e.g., nurseries, nutrient cycling, and reduction of coastal erosion among others), which are neither fully costed nor often appreciated by the public or users of the marine environment. Humans have wild harvested (sometimes called "wild crafting") and cultivated seaweeds for several centuries for animal and human consumption as well as other applications including valuable sources of phycocolloids and most recently, researched as feedstock for biofuels and carbon sequestration [7–11].

Some seaweeds may attain lengths exceeding 90 m or more (e.g., the kelp *Macrocystis pyrifera*), while others may grow only a few centimeters per year. Many seaweeds have isomorphic life cycles (e.g., *C. crispus, P. palmata*, where the gametophyte and sporophyte generations are morphologically similar), while others have heteromorphic life histories (e.g., the genus *Porphyra* and many species of brown algae including the kelps, where the generations are morphologically distinct). The morphology of various seaweeds may include multicellular, highly differentiated kelp with their organs such as blades, complex stipes, and their anchoring structure referred to as haptera. Other multicellular seaweeds may be small and bushy with flat or cylindrical axes (*Gracilaria*), while others may form sheet-like specimens of one or two layers of cells thickness (*Porphyra*, *Ulva*, *Monostroma*). Some macroalgae may be encrusting forms, while yet others may have the ability to precipitate calcium carbonate to varying degrees and be lightly calcified yet remain flexible (e.g., *Padina*) or fully calcareous and occur as prostrate crusts (e.g., *Lithothamnion*, *Phymatolithon*) or fully articulated, e.g., many coralline species such as *Corallina* and *Jania*.

This entry will discuss the advantages for land-based aquaculture of seaweeds for human foods and animal consumption. The first section gives a brief introduction to seaweed uses, both past and present, followed by an introduction as to how seaweed aquaculture has been practiced more recently. Section 3 briefly explains the concept of integrated multi-trophic aquaculture (IMTA), since this can also be an integral component of land-based seaweed aquaculture systems. Section 4 presents some of the particularities of intensive, land-based seaweed production, which make it different from the more common extensive, open water seaweed mariculture. Section 5 presents success stories of land-based seaweed aquaculture. The entry concludes with a discussion of the potential impacts of the development of land-based seaweed aquaculture as well as future directions and perspectives of research in this area.

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Past and Present Uses of Seaweeds

Seaweeds have been used in the human diet since ancient times. Although Asian food culture has seen the most prominent use of seaweed for direct human consumption, there is also recent evidence of the use of seaweeds by prehistoric humans, in other parts of the world. Dillehay et al. [12], in an archeological study conducted in Monte Verde, southern Chile, identified remains of nine species of marine algae, including *Durvillaea antarctica* ("cochayuyo"), *Porphyra* sp. ("luche"), *Gracilaria* sp. ("pelillo"), and *Sargassum* sp. These authors also suggest that some algae may have been burned, suggesting that they had been dried to facilitate transportation and/or storage, or were even cooked and could have been used for their medicinal properties as well. Erlandson et al. [13] discussed the cold water, coastal fringing kelp beds on the Pacific Coast of the Americas as being a route, or a "highway," by which early travelers made their way in northerly and southerly migrations. In Asian and Pacific Island countries, the tradition is to consume seaweeds as raw or cooked sea vegetables [14–16]. In Western countries, the principal use of seaweeds has been as a source of phycocolloids (alginate, carrageenan, and agar) which are structural, thickening, and gelling agents for various industrial applications, including uses in textile, paper, food, toothpastes, shampoos, cosmetics, and pharmaceutical industries [3, 4].

There is presently an increasing interest by the general public regarding the impacts of the human diet in general health and the potential health benefits in the consumption of selective seaweeds in a varied human diet. In fact, the physiological or pharmacological functions of food factors were classified as the third function of food in addition to the nutritional and sensory roles as the primary and secondary function, respectively [17, 18]. Among the bioactive compounds known to have an impact in the human health, there are those described as prebiotic functional ingredients. These are defined as nondigestible, selectively fermented compounds that stimulate the growth and/or activity of beneficial gut microbiota which, in turn, confer health benefits on the host [19].

Due to their varied nutritional properties, seaweeds are the subject of research seeking new, natural sources of functional ingredients for food. Table 1 presents a summary of that information [20–22]. *Porphyra*, for instance, contains high levels of protein (25–50%), vitamins (higher vitamin C than in oranges), trace minerals, and dietary fibers [23]. This alga contains nearly 17 types of free amino acids, including taurine which controls blood cholesterol levels and is thought to prevent obesity [24, 25]. Several reviews have been published outlining the nutritional properties of seaweeds (e.g., [21, 22, 26]), the most recent of which include the comprehensive review of Holdt and Kraan [27] and another on antioxidants from macroalgae by Cornish and Garbary [28]. The review of Holdt and Kraan [27] is particularly valuable since it also details the regulatory environment affecting marketing and use of active compounds from seaweeds in human applications. On the other hand, Cornish and Garbary [28] consider the application of seaweed antioxidants in foods, food supplements, nutraceuticals, and medicine from the perspective of benefits to human health. The review provides examples not only from laboratory studies but also from clinical trials where antioxidants derived from seaweeds may provide major health benefits that warrant subsequent investigative studies and possible utilization. Furthermore, those authors advocate that the direct consumption of seaweed products for their antioxidant composition alone provides a useful alternative to nonnatural substances, while simultaneously providing worthwhile nutritional benefits. Finally, the review by Cornish and Garbay [28] includes a comprehensive listing of algal species evaluated for antioxidant activity and potential applications of detected compounds.

Burtin [26] elaborates upon the nutritional value of seaweeds as they are rich in polysaccharides and dietary fibers, minerals, proteins and amino acids, lipids and fatty acids, and micronutrients such as vitamins (vitamin B_{12}, C, and E) and polyphenols (phlorotannins). This author concludes that from a nutritional standpoint, the main beneficial properties of seaweeds are their high mineral (iodine, calcium) and soluble dietary fiber contents, the occurrence of vitamin B_{12} and specific components such as fucoxanthin, fucosterol, and phlorotannins. Burtin also states that seaweeds can be regarded as an underexploited source of health-promoting molecules for food processing and the increasingly important nutraceutical industries [26].

Kumar et al. [21] reviewed the presence and value of various bioactive substances which may be derived from certain seaweeds, namely, polysaccharides and related compounds; proteins and related substances; lipids and related compounds; minerals; vitamins and antioxidant compounds. These authors concluded that seaweeds are a low calorie food source, particularly from the nutritional point of view, since they have high concentrations of certain minerals, vitamins, proteins, and indigestible carbohydrates. Seaweeds also have low lipid content, but the lipids present are of a high quality in terms of their nutritional value. In fact, Blouin et al. [29] suggested that native, Atlantic species of *Porphyra* such as *Porphyra amplissima* and *Porphyra umbilicalis* have potential in foods for North American consumers. They analyzed the fatty acid content of freshly collected *P. umbilicalis* and reported that eicosapentaenoic acid [EPA; 20:5 (n-3)] and palmitic acid were the most common fatty acids. Those authors reported that the concentration of fatty acids found in wild collected *P. umbilicalis* (i.e., 3.2 mg EPA g dry wt^{-1} or 74 mg EPA 100 g fresh wt^{-1}) was not high enough to make this a primary source of daily omega-3 fatty acids, but the favorable n-3/n-6 ratio (2–3:1) in these species constituted an interesting nutritional value. In their review, Kumar et al. [21] concluded that the quality of protein and lipids in seaweeds generally is as acceptable as those present in other dietary vegetables due to high content of essential amino acids and relatively higher levels of unsaturated fatty acids. Furthermore, all of these authors suggested that seaweeds exhibit antioxidant, antimutagenic, anticoagulant, anticancer, and antitumor activity. In many cases, these properties were actually tested and proved in vivo and in vitro, as follows. Zhang et al. [30] showed that a sulfated polysaccharide fraction from *Porphyra*

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haitanensis could be used to compensate the decline in total antioxidant capacity and activities of antioxidant enzymes. The implications of these findings are that seaweeds and their extracts might play a role in retarding the aging process. In addition, unprocessed powder from the brown seaweed *Fucus vesiculosus* has proven to have strong antioxidant capacities [31]. The authors concluded that the polyphenol (phlorotannin) content of *F. vesiculosus* seemed to provide the main antioxidant properties. Other research using polysaccharides extracted from *Porphyra yezoensis* demonstrated anticoagulant [32] and immune-stimulating activities [33, 34]. Saito et al. [34] showed that *Porphyra* peptides induced a significant reduction in the blood pressure of hypertensive human patients. Various fucoidans, common sulfated polysaccharides of various commercially important brown algae, have been tested in several studies in rats and in humans, showing beneficial effects as an anticoagulant, antithrombotic, antiviral, and anticancer agent ([35, 36]; see also www.marinova.com). Anticancer properties of seaweeds are also reported in the studies of Teas et al. [37] and Yang et al. [38] among others. In particular, the results of Teas et al. [37] suggested that a diet containing 5% brown seaweed (i.e., *Laminaria*) was effective in delaying the time for chemically induced tumor development in rats. In turn, Yang et al. [38] investigated the association between the intake of *Porphyra* (red seaweed) and *Undaria* (brown seaweed) and the risk of breast cancer, in a case-control study. The authors concluded that the consumption of *Undaria pinnatifida* did not have any significant associations with the disease but the results also suggested that high intake of *Porphyra* may decrease the risk of breast cancer.

Bocanegra et al. [22] reviewed the major physicochemical properties of seaweed fiber, the nutritional properties of the seaweed, and their value as functional foods. In terms of physicochemical properties of the fiber, the authors highlighted the hydration properties and viscosity, the oil retention and fat absorption, the fermentability, and binding capacity (cation-exchange capacity responsible for heavy metal biosorption). As for the nutritional properties of the seaweed, Bocanegra et al. [22] pointed to numerous studies that demonstrated the chemical and nutritional importance of the seaweed, namely in relation to bioavailability, effect on growth and body weight, effects on digestion, excretion and gastrointestinal functions, effects on lowering cholesterol and blood pressure, antioxidant activities and effects on glucose metabolism. Those authors concluded, however, that although some antioxidant compounds are present in algae, other compounds that are also present, such as the arsenic (As), can induce a poor endogenous antioxidant status. Therefore, the use of marine algae in herbal medications or excessive consumption of some of these organisms requires some caution. As with all things, seaweeds should be consumed in moderation as part of a well-balanced diet. Bocanegra et al. [22] also highlighted that, at that point there were no data available on the changes that cooking (e.g., microwave oven, traditional oven, frying, boiling, etc.) might impact on the properties of algal constituents. It is clear that much more work remains to fully realize the full nutritional and health-promoting potential of the consumption of seaweeds. These authors also illustrated that although numerous beneficial health properties can be attributed to seaweed components and extracts, robust studies of potential functional foods containing seaweeds have yet to be carried out, namely, the determination of different matrices affecting their technological and nutritional properties. The points raised by Holdt and Kraan [27], regarding the requirements of various food regulatory agencies, particularly with regard to novel foods and ingredients, should also be carefully considered.

As marine organisms with unique structural and biochemical compositions, seaweeds could be responsibly exploited for their multifunctional properties in the form of food, energy, medicine and cosmetics, and as biotechnological tools. In recent times, the use of seaweeds in a wide variety of biotechnological applications has become more common. Sahoo et al. [39] and Gantt et al. [40] pointed out the advantages of the use of *Porphyra* as a model organism for both applied and basic research. In fact, part of the genome of *P. umbilicalis* and the transcriptome of *Porphyra purpurea* have been recently released by the Joint Genome Institute (U.S. Department of Energy, www.jgi.doe.gov/genome-projects/ Program CSP2008; see also www.porphyra.org) and made available to the public. The aforementioned authors specifically point to the possibility of establishing several pure lines. In

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particular, the small genome size, which is estimated to be 2.6×10^8 base pairs consisting of three chromosomes and also the short generation time (1–3 months) of the alga are suitable traits for genetic analysis. The "*Porphyra* Genome" project, currently underway, will be one of the first to sequence the full genome of a multicellular red seaweed species and provide valuable information for biotechnological applications [40]. Other macroalgal genome projects include that of *C. crispus*, likely to be published in early 2011 (Jonas Collén, personal communication) and *Ectocarpus* [102]. As has been experienced with microalgal research (see [41, 42] and references therein), such major advances allow for rapid implementation of genetic engineering techniques that may modify seaweeds, thereby increasing their biotechnology applications. Some caution however needs to be applied to applications of such techniques. Should these "modified" seaweeds be destined for food or food products, then the necessity to label them as GMO (*g*enetically *m*odified *o*rganisms) sources would actually reduce their market acceptance, particularly in Europe and even increasingly in North America.

Seaweed Aquaculture

The largest database reference for seaweed taxonomy (www.algaebase.org) currently has over 10,000 macroalgal species listed, the majority being seaweeds [43]. Despite the variety of life forms and the many thousands of seaweed species, seaweed aquaculture is presently based upon a relatively very small group of less than 100 species worldwide [7]. In fact, only five to seven genera alone (i.e., *Laminaria/Saccharina, Undaria, Porphyra, Eucheuma/Kappaphycus* and *Gracilaria*) account for about 83% of the world seaweed production (Table 2). The basic cultivation techniques of these genera are described in Yarish and Pereira [7] and Pereira and Yarish [44] and the references therein.

The use of seaweeds for food has strong roots in Asian countries such as China, Japan, and the Republic of Korea. For that reason, these are the primary areas where seaweed aquaculture was first developed and, furthermore, the species of seaweed most cultivated are the ones commonly found from those shores. Tseng [46] defined the commercial cultivation of seaweeds as: "the large scale production of macroscopic marine algae for commercial purposes." Doty [47] applied the term "marine agronomy" to define seaweed cultivation as a type of agricultural practice carried out in the sea.

Despite this analogy, marine agronomy is an activity in its infancy, when compared to the traditional terrestrial agronomy, with obvious differences when we compare the developmental status of both activities. While the origin of marine agronomy can be traced back to approximately 200 years ago, the birth of agriculture is still subject of debate among anthropologists but is thought to have happened approximately 10,000–12,000 years ago [48, 49]. In fact, the presently cultivated seaweeds were selected from local flora (i.e., from the wild) and limited "selection and breeding" techniques have been applied to develop domesticated strains, especially when compared to the efforts placed on staple terrestrial crops such as rice, potatoes, wheat, etc. For the latter, agronomic institutions have developed on various continents, which have specialized in their breeding, selection, and improvement, sometimes even using genetic manipulation.

In China, more than 200 years ago, the first methods to manage a seaweed crop, a species of the red marine alga *Porphyra*, consisted of simply cleaning rocky areas in early autumn. This was done just before the mass liberation of algal reproductive spores, so that they had more surface area for attachment and growth [50]. In Japan, a similar approach consisted of inserting bundles of bamboo twigs into sandy/muddy substrata before the spore release season. Net cultivation methods for mass production of "laver" were only introduced in the 1920s, resulting in some increase in productivity but still reliant on the collection of spores released from natural populations [46]. However, the substantive development of the aquaculture of this genus came with the description of the life cycle of *P. umbilicalis* by Katherine Drew (Baker), in 1949 [51]. Drew established that the filamentous red alga, "*Conchocelis rosea*," until then considered as a completely separate entity, was in fact the sporophyte phase of the life cycle *Porphyra*. This finding, together with subsequent research [51–54], allowed for the development of methods which could control the life cycle and also the artificial production and collection of spores. These were monumental findings allowing the

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aquaculture of *Porphyra* to move into a completely different phase of technological developments. Modern commercial cultivation methods were established in the 1960s which led to the very pronounced expansion of cultivation activities and economic development. China is currently the largest global producer of *Porphyra*, with more than 800,000 t, fresh weight, produced in 2008, followed by Japan – 337,000 t and the Republic of Korea – 224,000 t [45].

The brown, kelp species, *Saccharina japonica* (formerly known as *Laminaria japonica*), is presently the largest single species produced in aquaculture. It is grown as a monoculture and the volumes of production exceed any other marine species, including fish, crustacea, and molluscs. More than three million tons fresh weight (FW) are reported to be cultivated on ropes in open coastal waters. The cultivation of *Saccharina* was developed mainly during the second half of the twentieth century, initially using a stone planting technique. Since 1968, a method called "forced cultivation" led to a reduction of the previous 2-year cycle of production to 1 year; the shift to modern methods allowed for a tremendous increase in productivity and commercialization of the kelp and its products [46, 55].

The commercial cultivation of all other seaweed species is even more recent than that of *Porphyra* and *Saccharina*. For instance, the cultivation of the red alga *Gracilaria* probably began as recently as 1967 in Taiwan [46]. Seaweed aquaculture or marine agronomy is, therefore, an activity still in its relative infancy, especially when compared to traditional, terrestrial agriculture.

Despite being a recently developed activity, when compared with the traditional land agriculture sector, seaweed aquaculture has been developing steadily. According to the latest production data from FAO [45], in 2008, total seaweed aquaculture production was more than 15 million tons FW (fresh weight), valued at more than seven billion USD. This corresponds to 23% of the world's aquaculture production and approximately 7% of its global value. Besides the undeniable economic value of the biomass, seaweed aquaculture is nowadays also increasingly recognized for the significant ecosystems services it provides, namely through its extractive process of nutrient removal [56–58]. Chopin et al. [59] argued that evolving aquaculture practices will require a conceptual shift toward understanding the working of food production networks as opposed to simplistic and narrow focus on technological solutions. One of the innovative solutions promoted for environmental sustainability, as well as for economic stability and societal acceptability, is the system coined "IMTA" (or **I**ntegrated **M**ulti-**T**rophic **A**quaculture), which will be discussed in more detail in the next section.

Introduction of the IMTA Concept

In western countries, an interest in integrated aquaculture began toward the end of the twentieth century. After the initial work of Ryther et al. [1], interest in using algae as nutrient scrubbers in an integrated aquaculture system was renewed by a group of like-minded scientists including: Fujita et al. [60], Kautsky and Folke [61], Neori et al. [62], Krom et al. [63], Buschmann [64], Sphigel and Neori [65], Troell et al. [66], Chopin and Yarish [67], Neori and Shpigel [68], Yarish et al. [69], Chopin et al. [70] and Neori et al. [71], among others. In the last decade particularly, numerous papers continued to establish that the concept and implementation of Integrated Multi-Trophic Aquaculture (*sensu* [56, 71–73]) was and will increasingly be of paramount importance for the sustainable development of aquaculture. The advantages are not just important for a sustainable environment, as evidenced by Matos et al. [74], Msuya and Neori [75] and Abreu et al. [76], but also economic, as shown by Troell et al. [77], Whitmarsh et al. [78], Robertson-Andersson [79], Robertson-Andersson et al. [80], and Nobre et al. [58].

The over-riding principle is that in IMTA systems the "wastes" or by-products of animal (fed) aquaculture are used as nutrient source for growth and development of the other trophic component of the system, such as macroalgae or other extractive, filter or detrital feeding organisms (e.g., bivalves, sea cucumbers, marine worms). The practical result is an added production of biomass which may have a direct economic value in addition to the ecosystem services which are provided by the extractive organisms. At the same time, the concentric alignment of the trophic levels provides substantial reduction of the load of inorganic nutrients in the effluents from intensive aquaculture systems,

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which in themselves can constitute a potential ecological problem leading to coastal eutrophication and harmful algal blooms (HABs).

Integrated mariculture has been practiced traditionally, although not necessarily intentionally, in China, Japan, and South Korea, where farms of fish net pens, shellfish, and seaweed have been situated in close proximity to one another [71, 81]. The arrangements and ultimate optimal integration of the trophic elements were largely achieved through trial and error and, as a consequence, traditional information regarding quantification and design has seldom been published (e.g., [82–84]). Nevertheless, in Asian countries, macroalgae are naturally considered as nutrient removers. For instance, the production of *S. japonica* (the Japanese kelp) was estimated as 4.765 million tons in 2008 [45]. Considering a very conservative N content of 2.79% DW (dry weight) and a wet to dry ratio of 5:1 [85], it can be estimated that approximately 5.58 kg of N are removed from the water with every ton FW of *Saccharina* produced. Therefore, the annual production of *S. japonica* removed approximately 26,588 metric tons of N from the surrounding seawater in 2008. In contrast, production of *Porphyra* and *Gracilaria*, while lower biomass volumes were produced, their N tissue content can exceed 7% DW for *Porphyra* [86] and 8% DW for *Gracilaria* [76].

On a global scale, the aquaculture of extractive organisms (e.g., seaweeds and shellfish) already removes a significant fraction of nutrients from the oceans [87]. According to Troell et al. [88], the harvests of those organisms already extract roughly 150,000 metric tons of N. However, as those authors also note, extractive and fed aquaculture are very often separated geographically, rarely balancing each other on a regional or local scale. An environmentally sustainable, balanced integrated aquaculture operation creates a mini-ecosystem in which the plant autotrophy balances the animal and microbial heterotrophy, not only in terms of nutrient removal (particularly C, N, and P) but also with respect to oxygen, pH, and carbon dioxide [87, 89]. It is unfortunate that, to date, there are only a few demonstration IMTA systems, in part due to the seasonality of the extractive seaweeds and the lack of "seed-stock." For instance, kelps for extraction of nutrients are only present for part of the cycle. The efficiency of dissolved nutrient removal will improve as alternation of extractive crop species is more clearly understood and refined.

As mentioned in the previous section, seaweed production is presently also recognized for its "ecosystem services" (see http://www.longislandsoundstudy.net/issues-actions/water-quality/nutrient-bioextraction/). Among these ecosystems services, the bioextraction capacity (through which the removal of biomass removes nutrients from the ecosystem) can be key for urban waterways that are not degraded by industrial pollution or don't have restrictions because they are away from sewage treatment facilities. However, as pointed out by Chopin et al. [59], these ecosystems services [90] have an economic benefit that is often ignored both by the industry and the regulators. A recent book sponsored by the World Conservation Monitoring Centre, in its chapter about Marine Systems, says very little about the role and direct economic value of algae in Marine Ecosystems [91]. Chopin et al. [59] argued that to improve the sustainability of anthropogenically derived nutrient-loading practices such as aquaculture, incentives such as nutrient trading credits (NTCs) are required. This would promote nutrient load reduction or nutrient recovery via a "polluter must pay" principle. The question can be posed that if carbon credits are now part of the internalized costs of some industries, why can the same process not be applied to nitrogen (N) and phosphorus (P), released through fed aquaculture, or point source pollution in the coastal marine environment. Neglecting the release of such nutrients in the marine environment can have quite striking consequences such as recently, when N released was associated with eutrophication of coastal waters resulting in massive algal blooms or "green tides" (see [92]). Also P has been discussed as "the next chemical element in global short supply"; therefore, its recovery makes considerable economic and ecological sense [93]. The land-based cultivation of seaweeds, particularly as part of an IMTA system, may also play an important role on the future recovery of these nutrient wastes.

A particularly interesting initiative, regarding the promotion of IMTA at a national level, was reported by the Australian government under the auspices of the Rural Industries Research and Development Corporation (RIRDC; [94]). The objective of that report was to clearly identify the potential for seaweeds to be cultured in Australia for domestic and export markets. The report identified an enormous potential for growth and development of this activity and defined that targeted markets should include the food and nutritional sectors. The associated health benefits of human consumption of a variety of seaweeds were also indicated in the report.

Following this initiative, the Australian RIRDC moved to support the formation of "Seaweed Australia" – a new organization for the emerging cultivated seaweed industry in that country. Under that context, a new report was prepared [95] to assist all industry and research groups involved in the production, processing, and marketing of seaweed products in a broad range of industries including health and nutrition, aquaculture, animal feeds, nutraceuticals, and pharmaceuticals. The report is the result not just of desktop research but of a series of meetings, workshops, and other forms of extensive consultation of the different stakeholders (for instance, industry and researchers). The conclusions include a clear identification of the priorities for the development of the cultivated seaweed industry in Australia in terms of: market focus; market research; higher value products; regulatory issues, and industry research.

Physiological Considerations for the Production of Seaweeds in Land-Based Cultivation Systems

The physicochemical parameters that affect seaweed physiology in land-based systems are essentially the same as those that affect these organisms in natural populations and in open water aquaculture systems. Factors such as temperature, light and nutrient availability, pH and salinity are always critical for seaweed growth. The work of Craigie and Shacklock in particular was essential for the development of the cultivation of the red seaweed, Irish Moss (*C. crispus*) and that information is a primer for any land-based seaweed aquaculture facility [96]. These authors described the importance of appropriate site selection as a fundamental requirement for the success of any aquaculture undertaking. Craigie and Shacklock [96] confirmed that seawater in the vicinity of the potential site must be of the highest quality, i.e., low sediment and particulate matter, free of agricultural runoff and pollutants from other activities such as industrial, mining, and urban sources. The authors also briefly presented the requirements of the target cultivated species in terms of temperature, pH, salinity, nutrient requirements (i.e., carbon and nitrogen supply), seawater exchange, plant agitation, and interactions with other species. All of this information was the result of integrated basic research conducted for each one of those factors.

The traditional phycological literature, from the past 3–4 decades, contains considerable fundamental research on the physiology of seaweeds in general. However, this research was mainly conducted under laboratory conditions and much less practical work was undertaken in tank systems at scales relevant for economically viable commercial purposes. As with many other organisms, different algal species have different physiological requirements and optima [97]. As pointed out by Troell et al. [88], after reviewing 28 studies on various IMTA systems, where the majority included tank systems, there is a need to:

1. Understand in detail the important biological/biochemical processes in closed recirculating and open seaweed culture systems
2. Conduct research into these advanced aquaculture technologies at scales relevant to commercial implementation or suitable for extrapolation
3. Broaden the focus to include factors affecting seaweed growth and uptake capacity
4. Improve experimental design for statistical calculations
5. Understand the temporal variability in seaweed-filtered mariculture systems
6. Define numerical design parameters critical for engineers in designing commercial recirculation systems with seaweed filters
7. Study the influences of location-specific parameters, such as latitude, climate, and local seaweed strains/species, on seaweed filter performance
8. Include economic components, considering the added value of seaweeds, their products, and feasibility aspects
9. Analyze the role and function of integrated aquaculture practices for improved environmental, economic, and social acceptability within the broader perspective of integrated coastal management initiatives

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10. Develop educational, training, and financial incentive approaches to transfer these novel and somewhat complex technologies of integrated mariculture from the scientists to an industrial scale

Despite the potential benefits for seaweed aquaculture as part of land-based IMTA systems, little progress has been made during the most recent decades, in terms of solving the needs as raised by Troell et al. [88]. The only published and, therefore, known exceptions are the work by Abreu et al. [76] taking into account an appropriate experimental design and scale (Figs. 1 and 2), and the research of Robertson-Anderson [79], Robertson-Anderson et al. [80] and Nobre et al. [58]. The differentiating factor is that Robertsson-Anderson and Nobre et al. performed economic and ecological assessments of a commercial, abalone-seaweed farm in South Africa.

Another less commonly applied method of land-based seaweed production is that of spray cultivation. This method has not been tested extensively on many species, but *Ascophyllum nodosum* [98] and *Gracilaria chilensis* [99] have been grown in such systems with some success. In the spray method, the seaweeds are not fully immersed in seawater but instead are held in adequate containers (often inside a modified greenhouse) and seawater is sprayed continuously or periodically over the target seaweeds. As referred to by Msuya and Neori [75], the documented benefits of seaweed spray culture included: construction and pumping costs, temperature control, gas (CO_2 and O_2) exchange, irradiance, nutrient uptake, and control of pests and epiphytes. Although the reported growth rates for these systems were usually low, Msuya and Neori [75] showed that the performance of *Ulva lactuca* in a spray system was in fact close to that of a standard, air-agitated tank culture system. In that work, *U. lactuca* was spray cultured in a “mattress-like layer,” held in air on slanted boards by plastic netting. Fish mariculture effluents were applied by being sprayed onto the algal mattresses. The growth rate, yield, and ammonia-N removal rates were 11.8% day^{-1}, 171 g fresh weight (FW) m^2 day^{-1}, and 5 g N m^2 day^{-1}, respectively, by the spray cultured *U. lactuca*, and 16.9% day^{-1}, 283 g fresh weight (FW) m^2 day^{-1}, and 7 g N m^2 day^{-1}, respectively, by traditional tank, immersed cultivated materials.

Examples of Successful On-Land Cultivation Enterprises

Acadian Seaplants Limited (www.acadianseaplants.com) is a Canadian company founded in 1981 and is probably the foremost example of an economically successful, land-based seaweed aquaculture enterprise. The company initially began with the collection of wild harvested *C. crispus* (Irish Moss) and progressed to the manual harvesting and processing of Rockweed (*Ascophyllum nodosum*). In particular, harvesting of the rockweed can be regarded as a positive case study for stewardship and successful, sustainable management of a wild resource (see [100, 101]). With respect to *C. crispus*, the company continues to successfully manage wild harvested materials in South West Nova Scotia and Prince Edward Island and also progressed to the land-based production of a specific strain of *Chondrus.*

While the *Chondrus* cultivation enterprise was initially planned to be a source of high-grade carrageenan, the production of *C. crispus* became more sophisticated to produce a value-added, salad product for the Japanese food market. Over the years, this enterprise has grown to become the world’s largest, land-based seaweed cultivation system for the production of human food (Fig. 3). The production operation occupies a large site in south-western Nova Scotia, and the seaweeds are grown for the Asian food market and to conduct fundamental and applied research on seaweed extracts.

Spurred on by the needs created by design and construction of the land-based cultivation tanks and the challenges of cultivation of carragenophytes, the company was able to succeed and expand production facilities. The basis for this success was a strong R&D and market development strategies to diversify the company and its products. Presently, the company exports its diversified products to over 70 countries. More than 95% of its products are exported. According to the company managers, the cultivation division of the company has been gaining momentum and future plans include domestication of new species for additional target markets, plus enhancements to the existing edible seaweed product line, new product formats, and additional colors (Fig. 4).

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Another example of a land-based seaweed production company is the Sylter Algenfarm GmbH & Co.KG (SAF), founded in 2006 by the marine botanist, Prof. Dr. Klaus Lüning. He spent most of his professional life unraveling the complexities of the environmental and internal control of seaweed growth and reproduction [2]. SAF cultivates seaweeds in a land-based seaweed farm at the North Sea island of Sylt, using a seawater source flowing from the oyster tanks of Dittmeyer's Austern-Compagnie. The two main seaweed species cultivated by SAF are young sporophytes of the brown alga *S. latissima* (formerly known as *Laminaria saccharina*) harvested in May, at a blade length of approximately 0.8 m, for the human food sector (Fig. 5) and the red alga *P. palmata* for the cosmetics industry. The niche in the *Laminaria* market occupied by SAF is a result of an opportunity due to the fact that the iodine content of imported *Laminaria* (kombu) from the Far East or from France, with concentrations of 3,000–6,000 mg iodine/kg algal dry weight, is considered too high for safe consumption. In contrast to the imported red alga *Porpyhra* (nori) for European Sushi restaurants, which contains very little iodine, imported kombu from Asia cannot pass the German "veterinary barrier" for human food, while the "young *Laminaria*" produced by SAF contains only 600 mg iodine/kg algal dry weight, probably because of the young age of the thin blades: This has enabled SAF to occupy that niche market and gives *Laminaria* the position as an innovative, marine vegetable in German restaurants.

In order to meet the growing demands for "young *Laminaria*" in Germany, in 2008, SAF began a cooperation with two sea farms in the Northern Baltic Sea (Kattegat Sea area), where *S. latissima* is grown on ropes, in the sea, either together with blue mussels (*Mytilus edulis*), or fish (rainbow trout). Harvesting of the young, thin kelp blades in May secures the low iodine content. Moreover, this co-cultivation of kelp with marine animals provides a further example of integrated multi-trophic aquaculture (IMTA). For the fish cultivators in Denmark, this is important since the Danish state urges them to employ countermeasures against the uncontrolled release of ammonium, nitrate, and phosphate from the fish cages into coastal waters. The total N of 6% kelp dry weight assists the fish cultivators to demonstrate that for each ton of fresh harvested kelp (dry weight is $\approx$ 10% of fresh weight), 6 kg of N are removed from the system. This is yet another advantage of the local production of the kelp. Naturally, this ecosystem service (nutrient removal) would not be performed in the direct vicinity of Danish fish farms if the *Laminaria* or *Saccharina* was imported from Asia. On the other hand, for SAF, the harvested kelp biomass in the Kattegat provides the sufficient biomass for the German food market.

Another example, although not producing seaweeds directly for human food, is the Big Island Abalone Company, in Hawai. This company cultivates a proprietary strain of *Palmaria mollis* on a significant scale as feed for abalone cultivation. More details are available at their Web site (www.bigislandabalone.com).

Future Directions

Land-based cultivation of seaweeds reduces the pressure on wild harvest of seaplants, particularly those which are difficult to access in time or space or their harvest would be unsustainable and perhaps ecologically damaging. Furthermore, land-based seaweed production allows for the evaluation of numerous species that, due to their size, morphology, and/or particular physiological needs might not necessarily be good candidates for traditional, open water systems, such as those routinely used for *Porphyra*, kelp, and the major phycocolloid-producing seaweeds (i.e., *Kappaphycus* and *Eucheuma*). Another important feature of seaweed production in land-based systems is that they allow for much greater environmental and input controls than would ever be possible in open water seaweed aquaculture. Such high levels of control, or intensive production, is critical to provide the necessary traceability, security of supply, high-quality standards and safety, not just for human consumption as food but especially for nutraceutical and pharmacological applications. Furthermore, the control of some environmental parameters (as well as controlling growth and quality) can also be used to promote the expression of desirable characteristics of the seaweeds, such characteristics may be morphological or biochemical. Further advantages of land-based seaweed production are the possibilities to quarantine foreign species, if grown on land with approved effluent water treatment systems. This feature is definitely not possible in open water cultivation systems, and can allow a land-based facility to work with more species than just those locally available. However, the environmental stewardship responsibilities for the introduction of nonnative species cannot be minimized nor lightly undertaken.

One promising avenue of future research associated with on-land cultivation of seaweeds would be to find the most appropriate culture conditions that maximize the production of particular, valuable biochemical constituents. This would be important for the promotion of a variety of seaweeds as functional foods or food-ingredients. More research is required into the genetics and responses of new target species which, in turn, could provide insight to achieve the high level of control. Unlike terrestrial plants and even microalgae, genetic transformation in seaweeds remains at a very low level. The first fully sequenced genome of a seaweed species are that of *P. umbilicalis*, *P. purpurea*, and *Ectocarpus siliculosus* and were concluded only recently ([40, 102]; the genome of *C. crispus* to follow shortly thereafter). Not forgetting the huge potential that remains in specific, selection of seaweed strains, the genomic and molecular tools now available for seaweeds could provide further insights into algal physiology and metabolism. Even taking into account the caveat of lack of public acceptance of GMO food, just as occurred with their terrestrial counterparts, this knowledge might be used in seaweed research to improve productivity, biofiltration efficiency, disease resistance, and to direct metabolic pathways to produce higher concentrations of desirable metabolites and secondary compounds (these might even play a role in biofuel production from seaweed feed stocks). Overall, these activities and discoveries could contribute to an improved market value of the target seaweeds, including new insights into human nutrition.

In addition, future research should focus on the evaluation and selection of more seaweed species suitable for land-based aquaculture that may be used as the extractive inorganic nutrient component in IMTA systems. In fact, we believe that IMTA systems will play an important role in the overall development of land-based seaweed production in the future. Several factors may account for this:

(a) The availability of water and its quality
(b) The size and morphological characteristics of seaweeds making them suitable candidates for tank cultivation
(c) The diversity of products derived from various target species produced in the same system

The water requirements of intensive animal aquaculture ensure a plentiful supply of water available for seaweed cultivation. In terms of synergies and efficiencies, particularly in engineering, the use of the same water stream allows for sharing of the energetic costs associated with water pumping. On the other hand, since water quality is also important for animal production and health, the seaweed component should have access to high-quality water, free of toxins, heavy metals, and other pollutants. Finally, but equally very important, and the essence of the IMTA concept, the extractive, seaweed production system would have access to nutrient-enriched seawater derived from the animal (fed aquaculture) component of the system. As an example, Burri [103] tested the inclusion of the IMTA-produced red seaweed (*G. vermiculophylla*) in a new form of vegetarian sausages for children. This author verified that the chemical composition of the seaweed chemical was below the permitted values for children consumption in terms of mercury (Hg), lead (Pb), and cadmium (Cd). Even when the initial wild collected stocking biomass had metal values close to or above the limits, these values decreased after 4 weeks in the IMTA conditions. In conclusion, pollutant-free seawater, nutrient-rich and at a free or shared cost, would be available for the seaweed production system when associated with an IMTA system.

As mentioned previously, intensive, land-based seaweed production allows for exploitation of seaweeds which are not necessarily suited to open water techniques such as those applied to various kelps or *Porphyra*. For obvious reasons, open water seaweed production is not the most suited, for instance, for free-floating techniques and vegetative propagation for seaweed cultivation. The free-floating method of tank or pond production can, however, be highly suited to land-based systems, allowing for optimization of water volume in the tanks as well as stocking density, thereby ensuring access to light and nutrient supply. Furthermore, on-land production methods are also highly suited to seaweeds where vegetative, or clonal,

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propagation is possible, in as much as the seaweed production system guaranties the homogeneity of the biomass (provided that the environmental conditions do not overly influence it). This feature can also decrease the operational costs associated with the production of seaweeds with a complex life cycle.

In terms of the production diversity, land-based systems could be planned to include several independent production units. Even considering the increase in the operation costs, these production units, managed independently from one other but sharing common parts of the infrastructure, could have two main advantages:

1. Produce different species/varieties of seaweed
2. Allow for an easier control of the environmental parameters that can influence the quality of the biomass

Depending on the applications of the biomass, the production units could be scaled to produce either a few kilograms or a few tons per year instead of the thousands of tons required for seaweed such as those used as raw materials for polysaccharide extraction. Such relatively small volumes might be more appropriate for the biomass required for some direct human consumption products or for application as ingredients of functional foods and cosmetic products. In turn, this smaller scale would allow a better control of production parameters and the biomass can be tailored more closely to the needs of the final consumer.

In conclusion, land-based seaweed aquaculture can provide for the production of biomass required for human food and other advanced applications. Rather than focusing on biomass production in the order of thousands of tons, this form of seaweed production can specialize in niche markets, which requires highly specific and tailored biomass. By doing this, land-based seaweed production can contribute to the development of more seaweed or seaweed-based products for human food and health. Finally, when used as part of an IMTA system approach, land-based seaweed production can contribute to the sustainable development of intensive fed aquaculture in an economical and ecological perspective.

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Seaweed Aquaculture for Human Foods, Land-Based. Table 1 Some examples of seaweeds with their functional ingredients and possible effects on human health (Adapted from Plaza et al. [20]; Kumar et al. [21], Bocanegra et al. [22])

Seaweed	Functional ingredient	Possible health benefits
Sargassum vulgare (B)	Alginic acid, xylofucans	Antiviral activity
Himanthalia elongata (B)	PUFAs	Reduce risk of certain heart diseases
	α-Tocoferol	Antioxidant activity
	Sterols	Reduce total and LDL cholesterol
	Soluble fiber	Reduce total and LDL cholesterol
U. pinnatifida (B)	PUFAs	Reduce risk of certain heart diseases
	Sterols	Reduce total and LDL cholesterol
	Soluble fiber	Reduce total and LDL cholesterol
	Folates	Reduce risk of certain types of cancer
	Sulfated polysaccharides	Antiviral activity
	Fucoxanthin	Preventive effect on cerebrovascular diseases; Increase the metabolism
Porphyra spp. (R)	PUFAs	Reduce risk of certain heart diseases
	Sterols	Reduce total and LDL cholesterol
	Soluble fiber	Reduce total and LDL cholesterol
C. crispus (B)	PUFAs (n-3) fatty acids	Reduce risk of certain heart diseases
	Sterols	Reduce total and LDL cholesterol
	Soluble fiber	Reduce total and LDL cholesterol
Cystoseira spp. (B)	Terpenes	Valuable curative properties
	Sterols	Reduce total and LDL cholesterol
	Sulfated polysaccharides	Regulate the bioactivity of growth factors and cytokines
Ulva spp. (G)	Sterols	Reduce total and LDL cholesterol
Grateloupia filicina (R)	"methanolic extract"	Antioxidant activity
Brown algae (non specified)	Phlorotannins	Detoxification of heavy metals; antibacterial effects
	Fucoidan	Anti-inflammatory, anticoagulant
Colpomenia sinuosa (B)	Fatty acid profile (ω-3)	Increase HDL cholesterol
Hypnea charoides (R)	Fatty acid profile (ω-3)	Decreased LDL cholesterol
A. nodosum (B)	Sodium-binding fiber	Antihypertensive effects

R red, *B* brown, *G* green seaweed

Seaweed Aquaculture for Human Foods, Land-Based. Table 2 Main seaweed aquaculture production and value in 2008, according to FAO 2010 [45]

Genera	Production (metric tons)	Value	
		(*1,000 USD)	USD/ton
Laminaria (=*Saccharina*)	4,765,076	2,835,558	595
Eucheuma/Kappaphycus	3,551,273	563,146	159
Undaria	1,755,913	749,213	427
Porphyra	1,389,360	1,345,414	968
Gracilaria	1,418,986	600,223	423
Others	2,661,054	1,262,018	474

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Seaweed Aquaculture for Human Foods, Land-Based. Figure 1
Aspect of the seaweed tank system as part of a pilot scale IMTA in a land-based intensive fish aquaculture. A. Coelho e Castro Lda, Póvoa de Varzim, Portugal

Seaweed Aquaculture for Human Foods, Land-Based. Figure 2
Detail of a seaweed production tank (1,200 L) as part of a pilot scale IMTA system in a land-based intensive fish aquaculture. A. Coelho e Castro Lda, Póvoa de Varzim, Portugal

Seaweed Aquaculture for Human Foods, Land-Based. Figure 3
Aerial view of Acadian Seaplants Limited seaweed production facilities, south-western Nova Scotia (2010) (Photo courtesy of ASL)

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Seaweed Aquaculture for Human Foods, Land-Based. Figure 4
Hana Tsunomata™ (*C. crispus*) commercial product from Acadian Seaplants Limited. Hana = “flower”; Tsunomata = *Chondrus* (Photo courtesy of ASL)

Seaweed Aquaculture for Human Foods, Land-Based. Figure 5
S. latissima seeded by Sylter Algenfarm on 8-mm diameter rope, grown out to harvesting size by Danish cooperator Rasmus Bjerregaard, holding up the harvested kelp (Photo, courtesy of Dr. Klaus Lüning)