Seaweed Cultivation and Its Applications in Colombia

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Colombia has a diverse range of marine ecosystems in the coastal and insular areas of the Caribbean Sea and the Pacific Ocean. Seaweed research has focused mainly on the identification and taxonomic distribution of 628 species identified so far, mainly in the Caribbean Sea. Among the most widely cultivated genera of seaweeds in open-sea pilot systems in Colombia are Hydropuntia, Gracilaria, Hypnea, Kappaphycus, and Eucheuma. These genera have shown low yields as a consequence of high tissue fragility, epiphytism, sedimentation, and nitrogen deficiency. In addition, the evaluation of the biological activity of selected seaweed compounds has advanced considerably, focusing on their composition and their use for direct consumption by humans and animals. Despite the diversity of seaweeds, as well as certain technical and scientific advances, Colombia is still lagging behind other countries in seaweed exploitation, both in Latin America and worldwide.

agro-tech future trends | biodiversity | biological activity | Colombia | seaweed resources

1. Introduction

In recent years, the cultivation and marketing of seaweeds and their products worldwide have attracted growing attention, being valued at USD 5.9 billion in 2019, and expected to show an estimated compound annual growth rate (CAGR) of 9.1% until 2027 [1]. This growth is largely based on applications of various seaweeds in the food, chemical, pharmaceutical, cosmetic, and energy industries [2][3].

Marine macroalgae, commonly known as seaweeds, are macroscopic, multicellular, photosynthetic eukaryotic organisms that can be classified into three taxonomic groups, i.e., Phaeophyceae (brown), Rhodophyta (red), and Chlorophyta (green) based on their characteristic pigmentation. It is estimated that the global diversity of all algae (micro and macro) is around 164,000 species [4], about 9800 of these are seaweeds [5], of which only 0.17% have been domesticated for commercial exploitation [6].

The most traditional uses of seaweeds comprise the manufacture of fertilizers/biostimulants since Roman times [7], animal feed since 45 BC [8][9], human nutrition, and source of medicinal compounds since the fourth century in Japan [10] and South America [11], and fuel production since 1940 [12][13]. Seaweeds are mainly used in the food industry as a source of hydrocolloids. Agars, alginates, and carrageenans are the main hydrocolloids obtained from red and brown algae [14]. In recent years, some seaweeds have been considered a source of natural bioactive compounds with potential nutraceutical [15][16][17][18], cosmeceutical [19][20][21][22], and pharmaceutical value [23][24][25].

Colombia is located in the northwestern region of South America, it is bordered by the Caribbean Sea to the north, Venezuela to the east, Brazil to the southeast, Ecuador and Peru to the south, the Pacific Ocean to the west, and Panama to the northwest (**Figure 1**).

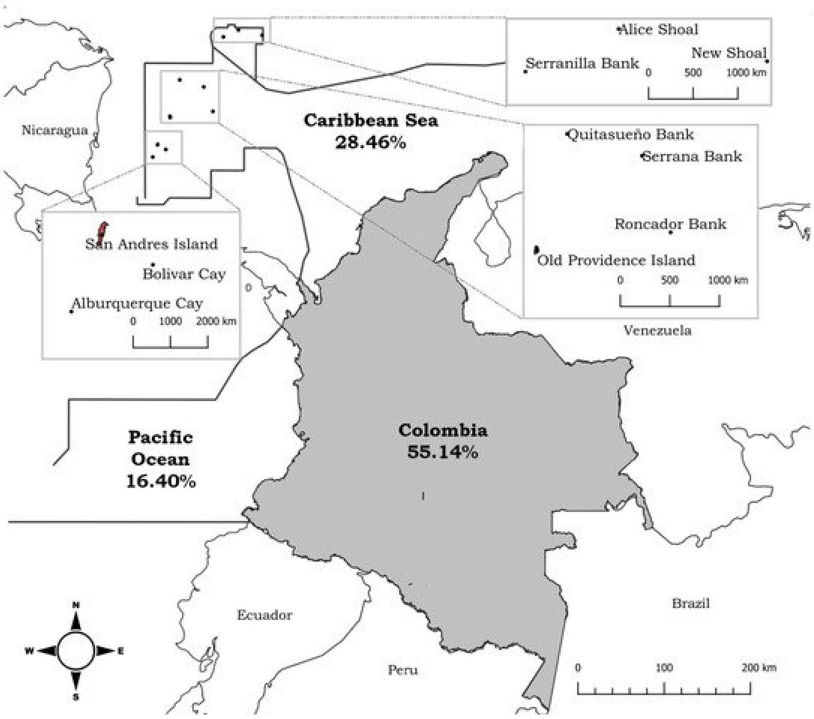

Figure 1. Continental and insular zone of the Caribbean and Colombian Pacific with the oceanic and terrestrial percentage of Colombian territory.

Colombia has a coastline with a length of 3531 km and approximately 892,102 km^2 of surface area and coasts in both the Caribbean Sea and the Pacific Ocean, corresponding to 44% of the national territory [26]. The continental Caribbean region is made up of the coastal regions, as well as the insular area that includes San Andres, Old Providence, and Santa Catalina islands, in addition to seven cays as shown in **Figure 1**. In 2000, this insular zone was declared an International Seaflower Biosphere Reserve by the United Nations for Education, Science, and Culture [27][28]. The Pacific region includes the continental coasts, as well as the insular coasts of the Gorgona and Malpelo islands (**Figure 1**).

Colombia can be considered one of the South American countries with high marine biodiversity due to its diverse eco-regions distributed in both the Caribbean and the Pacific regions, previously described by Díaz and Acero [29]. These regions show heterogeneous climatic, oceanographic, geological, and biochemical characteristics, and contain a variety of environments such as beaches and rocky coasts, coral reefs, seagrass meadows, and mangrove forests, which harbor high biological diversity [30]. Seaweeds are part of this biological resource, integrating several ecosystems and contributing to their balance and ecological function.

2. Seaweed Cultivation Experiences in Colombia

Although Colombia has a wide diversity in terms of macroalgal genetic resources [31], there is a low number of specimens in the areas where they are located. This could be associated with seasonality and environmental conditions that hinder the development of productive processes in the natural environment.

To date, some research has been conducted in the establishment of pilot seaweed cultivation in Colombia, both in the open sea and land-based as presented in **Table 1**. Some publications that provide a chronological account of experiences carried out in mariculture in Colombia stand out, e.g., Álvarez et al. [32], Molina and Álvarez [33] and Peña and Álvarez [34]. Much of the reported research was conducted by Foundations, Environmental Corporations, and other institutions, where the results obtained (undergraduate thesis, progress, and final reports) can be classified as grey literature [35][36][37] since they are not included in indexed databases and therefore access is difficult.

Table 1. Seaweed species cultivated in Colombia.

Specie	Region	Type of Culture 1	DGR 2	Reference
Rhodophyta				
Order Gracilariales				
Grateloupia sp.	Guajira	B, R	-	[38]
Gracilariopsis tenuifrons	Guajira	B, R	0.59	[39]
Gracilaria cervicornis	Guajira	B, R	0.44	[38]
Gracilaropsis longissima (as *Gracilaria verrucosa*)	Magdalena	B	-	[33]
Crassiphycus corneus (as *Hydropuntia cornea*) *Kappaphycus alvarezii* *	Guajira Guajira	B, R R	0.97, 0.51 5.1	[38][39] [40]
Order Gigartinales				
Hypnea musciformis	Guajira-Santa Marta	B, R	2.66, -	[38][41]
Eucheumatopsis isiformis (as *Eucheuma isiforme*)	Guajira	B, R	1.58	[39]
Order Halymeniales				
Grateloupia filicina	Magdalena	-	-	[32]
Chlorophyta				
Order Bryopsidales				
Caulerpa sertularioides	Nariño	P	4.82	[42]

Having access to this information is highly valuable because it covers what is being done beyond the academic sphere and reports both advances and difficulties at the national level. Therefore, it is necessary to look for strategies within these institutions to allow access to information more simply and effectively, granting the extrapolation of their experiences to future work and productive processes.

Among the most mentioned works are those of Delgadillo and Newmark [38] and Camacho and Montaña [41] who established cultures of *Hypnea musciformis* in the regions of La Guajira and Santa Marta, respectively. The environmental characteristics of both areas were similar in terms of temperature and salinity. The strong water movement at La Guajira together with the mechanical fragility of the species was responsible for the high loss percentages, which prevented the establishment of the cultures [38]. In Santa Marta, an average daily growth rate of 2.66% was reached; however, the authors do not mention the swell conditions in the area. This lack of specific information prevents any conclusion regarding the influence of environmental conditions on the viability of *H. musciformis* culture viability. The growth rate reported by Camacho, although lower, may be comparable to open-sea cultures developed in Bangladesh (3.2%) [43] and, to a lesser extent in Brazil (5.7%) [44] and India (7.6%) [45] showing the potential of Santa Marta for the establishment of *H. musciformis* cultures. In the same way, Molina and Álvarez [33] and Rincones and Moreno [39] cultivated *Gracilariopsis* sp. in Atlántico and La Guajira, respectively. Of these works, only Rincones and Moreno reported average daily growth values of 0.6%, a value that was considered low for the establishment of a productive culture in the study area. Considering that growth rates of 2.8% have been reported for net bag cultures of *G. tenuifrons* in Venezuela [46], 4.7% and 8% for rope [47] and net [48] cultures of *G. longissimi* in Spain, and 5% in rope cultures of *G. lemaneiformis* in China [49], the results of Rincones and Moreno [39] indicate that, for the moment, suitable conditions for the cultivation of this species are not guaranteed.

The daily growth rate of the different species cultivated in Colombia was between 0.44 and 4.82% day^{-1} (**Table 1**). These data show that there is great variability in the daily growth rates, which depends on the species and the cultivation conditions, including seasonal variation. Therefore, it is necessary to continue to determine the optimal conditions that allow the scaling up of seaweed cultivation in the coastal areas of Colombia.

In general terms, reports related to seaweed cultivation in Colombia provide limited information (e.g., description of the study areas and algal growth results), while specific and relevant factors associated with the cultivation conditions are missing. Therefore, a complete and integrated analysis of the seaweed cultivation field is challenging, and the decision-making process aimed at designing commercially successful seaweeds cultures is considerably impaired.

In the early 1990s, the Food and Agriculture Organization of the United Nations (FAO), in partnership with the von Humboldt Institute were looking for alternative productive activities for local Wayuu communities in the La Guajira Peninsula [40][50][51]. To that end, the FAO and the von Humboldt Institute introduced and established cultures of *Kappaphycus alvarezii*, through vegetative propagation. This species is widely cultivated in tropical regions of the world to produce carrageenan [52] and shows high growth rates compared to other cultivated species (**Table 1**). Cuban thalli as seedstock, which themselves originated from Venezuela, were used and an average growth rate between 5.1 and 6.5% day^{-1} in floating rope systems was achieved. These cultures were characterized by a significant loss of plant material in the cultivation areas. The main causes of these losses were climatic (wind, temperature, rainfall), hydrological (current patterns) and biological (epiphytes) conditions [40].

The cultivation of *K. alvarezii* in Colombia was quite controversial as its introduction was considered troublesome by some Colombian seaweed researchers and phycologists interviewed in this study. The environmental impact studies necessary to assess the possible risks of the introduction of *K. alvarezii* as an invasive species of reef and seagrasses ecosystems, as previously reported in other coastal areas of the world [53][54][55][56] were lacking. In 2008, *K. alvarezii* was included in the list of invasive alien species in Colombia, (Resolution 848-2008 of the Ministry of Environment, Housing and Territorial Development).

Pilot seaweed cultivations have been conducted in coastal areas with environmental conditions similar to those of Colombia. *Eucheuma* spp., *Gracilaria* spp., and *K. alvarezii* are some of the species successfully cultivated in Belize [57][58] and Panama [59]. Nevertheless, there is no clear information about what was the successful approach used in these pilots. This makes it difficult to identify the lessons learned in these areas and the failures that are being committed at the national level, which should be explored in depth.

Up to this point, the present review shows that the results in extensive open sea cultures carried out in Colombia were characterized by low productivity and in the cases where good biomass growth was achieved, it was not possible to maintain it throughout the year, due to seasonality. The results indicated that the limited success of seaweed cultivation in the open sea seems to be related to the difficulty of taking in situ measurements and controlling the physical, chemical, and biological variables that affect culture yield and productivity.

Several other factors are involved in the establishment and productivity of seaweed cultures. Human activities, such as the increasing contamination of water bodies by domestic, industrial, and agro-industrial discharges, mining activities, as well as the emission of CO_2 into the atmosphere, cannot be ignored. These are some of the major factors responsible for the environmental changes (e.g., alterations in the carbon cycle, stratification, eutrophication, increases in UVB radiation, surface temperatures, and decreases in pH, among others) recorded in marine ecosystems [60][61][62]. Additionally, in Colombia, according to several interviews with highly regarded seaweed researchers, it was possible to identify that some of the main difficulties to establishing commercial seaweed cultures are the idiosyncrasy and socio-economic conditions of the communities.

Colombia has little or no experience in land-based cultivation, except for the laboratory work carried out by Mosquera and Peña [42] with *Caulerpa sertularioides*. This work was focused on the effect of salinity on algal growth while maintaining constant illumination, temperature, and nutrients, and optimal growth was achieved at a salinity of 25 with artificial seawater. Nevertheless, the study did not provide any extra information regarding *C. sertularioides* cultivation, indicating the importance of studying the effect of other variables on the in vitro growth of this seaweed.

So far, this review indicates that despite some experiences of pilot-scale seaweed cultivation in Colombia, there is an opportunity to adopt technologies for land-based seaweed cultivation that are successful elsewhere, such as those of Seakura in Israel [63] and Acadian Seaplants in Canada [64], to trigger the potential application of this technology in the country.

3. Applications of Seaweeds in Colombia

The worldwide application of seaweeds in the food, pharmaceutical, cosmetic, and energy industries is based on the nutritional and biological value of their content of minerals, vitamins, carbohydrates, proteins, and fatty acids [65]. In Colombia, the applications of seaweeds are mainly focused on: (i) the study of their composition [32], both for direct consumption or fertilizer production, (ii) evaluation of the biological activity of extracts, and (iii) the extraction of polysaccharides and pigments.

3.1. Fertilizers

The most feasible applications of seaweed comprise the field of fertilizers; due to their contribution of minerals, nutrients [66] and their activation in the production of growth regulators. Bula-Meyer [67] reviewed several applications of seaweed in Colombian agriculture showing their potential to be used as fertilizers. His work focused on *Sargassum*, highlighting the nutritional composition as well as the effect of derived products on important plant crops variables such as fruit aging, frost resistance, and nutrient absorption.

3.2. Biological Activity

The increasing demand for products with the biological activity of importance to medicine (e.g., antimicrobial, antiviral, antitumor) has promoted the discovery and production of new compounds by chemical synthesis or extraction and purification from natural sources. The biological activity of various seaweeds in Colombia has been focused on the evaluation of antimicrobial, cytotoxic, and antioxidant activity. The main findings of biological activities from seaweed extracts collected in Colombia are reported in **Table 2**.

Table 2. Biological activities of seaweed identified in Colombia.

Species	Biological Activity	Reference
Rhodophyta		
Order Gelidiales		
Gelidiella acerosa	Cytotoxic	[68]
Order Corallinales		
Amphiroa fragilissima	Cytotoxic	[68]
Order Gracilariales		
Gracilaria mammillaris	Antioxidant	[69]
Order Gigartinales		
Hypnea musciformis	Antibacterial—Phenolic and steroidal compounds	[70][71]
Order Ceramiales		
Digenea simplex	Cytotoxic	[68]
Laurencia sp.	Antioxidant	[72]
Laurencia microcladia	Antibacterial	[73][74]
Chlorophyta		
Order Ulvales		
Ulva sp. (as *Enteromorpha* sp.)	Antibacterial	[70]
Order Bryopsidales		
Caulerpa mexicana	Antibacterial—Antioxidant	[70][72]
C. sertularioides	Cytotoxic	[68]
Ochrophyta		

Species	Biological Activity	Reference
Order Dictyotales		
Dictyota bartayresiana	Antibacterial—Feeding inhibitor	[73][74]
Dictyota pulchella	Antibacterial-Cytotoxic—Feeding inhibitor	[73][74]
Dictyota sp.	Antioxidant	[72]
Padina boergesenii	Antibacterial	[73][74]
Order Fucales		
Sargassum cymosum	Antibacterial-Cytotoxic – Feeding inhibitor	[68][72][73]
Sargassum sp.	Antioxidant	[72]
Sargassum schnetteri (as *Cladophyllum schnetteri*)	Feeding inhibitor	[73]

Antimicrobial activity assays focus on susceptibility testing of pathogenic microorganisms (e.g., bacteria and fungi) in the presence of potential compounds of interest. Studies of antimicrobial activity in Colombia date back to the 1970s, when Nuñez et al. [75] evaluated the antibacterial activity of extracts obtained from the algae *Halimeda opuntia*, *Ulva lactuca*, *Gracilaria mammillaris,* and *Agardhiella subulata* (as *Agardhiella tenera*) collected on the Atlantic coast. The results of this work are incomplete, only mentioning that *H. opuntia* and *U. lactuta* did not exhibit antimicrobial activity, which makes it difficult to make decisions and extrapolate the results. Arteaga and De Silvestri [70] complemented Nuñez's work with new extraction techniques, including the study of the effects of seasonal variability and pH. The authors reported a higher antimicrobial activity of *Ulva* sp. (as *Enteromorpha* sp.), *Hypnea musciformis*, and *Caulerpa mexicana* extracts, prepared in phosphate buffer (10%) and pH of 6.8, as well as the variability of the compounds obtained as a function of seasonality.

Similarly, Martínez et al. [72] evaluated the antimicrobial activity of methanolic extracts of eight seaweeds on Gram-positive (*Staphylococcus aureus* and *Bacillus cereus*) and Gram-negative (*Escherichia coli*) bacteria. The results indicated that extracts from two species of *Dictyota* showed activity against *S. aureus* and *B. cereus*. *Padina boergesenii* showed activity against *B. cereus*, and finally *Laurencia microcladia* against *S. aureus*. The extracts of all these algae only showed activity on Gram-positive bacteria. The lack of activity on Gram-negative bacteria may be related to masking by other compounds [76] or to the non-production of compounds that act on these bacteria.

Regarding cytotoxic activity tests, these tests evaluate damage at the cellular level either sublethal (e.g., decreased cell proliferation) or lethal (e.g., apoptosis or autophagy). Seaweed cytotoxic activities have been evaluated in different cellular systems such as fertilized sea urchin (*Lytechinus variegatus*) eggs [73], colon cancer cells (HT29) [68], and human myeloid leukemia cells (Jurkat) [77].

The methanolic seaweed extracts obtained by Martínez et al. [74] showed a low cytotoxic activity as no retarding effects were observed in the mitotic processes in fertilized sea urchin eggs [73]. These results, although preliminary, indicated that the evaluated extracts could be used without the risk of generating cell damage mainly at the level of cell division and proliferation, which is a desirable property for algal-derived materials used in cosmetic products.

Methanolic extracts of six seaweeds (Amphiroa fragilissima, Gelidiella acerosa, Dichotomaria obtusata, Dictyota fasciola, Sargassum cymosum, and Caulerpa sertularioides) [68], as well as different fractions of the ethanolic extract of Digenia simplex [77][78], showed a potent cytotoxic effect on colon cancer cells and human myeloid leukemia cell line (Jurkat), respectively. The cytotoxic activity occurred as a consequence of a blockage of the mitotic phase (antimitotic activity) which could activate the process of programmed cell death [68]. This antimitotic activity could be a more effective strategy than those compounds that try to interrupt the progression of cell proliferation (e.g., Colcemid®) making these extracts potential antitumor agents.

Concerning the antioxidant capacity and the content of phenolic compounds, ethanolic extracts from *Caulerpa mexicana*, *Laurencia* sp., *Sargassum* sp., *Dictyota* sp. and *Sargassum cymosum* [72], *Hypnea musciformis* [71], and *Gracilaria mammillaris* [69], among other species, have been studied. The results indicated that the antioxidant capacity observed was mainly related to the production of phenolic compounds. Amongst the species studied, the following were highlighted: *S. cymosum* for its concentration of phenolic compounds (0.822 mg acid gallic equivalent/g extract), *H. musciformis* for its antioxidant activity (550 µmol Trolox equivalent/L), and *G. mammillaris* which showed a high level of antioxidant activity in edible oils, inhibiting 42.1% of thiobarbituric acid reactive substance (TBARS) formation in accelerated oxidation assays. These results are preliminary as they could be improved by the implementation of more effective extraction techniques [79], as well as the fractionation of the extracts [80], which would increase the antioxidant activity of the extracts and project the extracts obtained from seaweeds as a new natural source of antioxidant compounds in the food and cosmeceutical industry.

3.3. Polysaccharides and Pigments

Another important topic of the research in seaweed application is the production of polysaccharides and pigments, among which: agars, alginates, carrageenans, and fucoxanthins, stand out.

Studies related to polysaccharides and pigments focus mainly on the evaluation of the extraction processes and how they affect variables such as gelation times, viscosity, gel strength, and absorption capacity. **Table 3** shows some of the polysaccharides and pigments extracted from seaweeds in Colombia.

Table 3. Polysaccharides and pigments extracted from seaweeds in Colombia.

Species	Extract/Compound	Reference
Rhodophyta		
Order Gracilariales		
Gracilariopsis longissima (as *Gracilaria verrucosa*)	Agar-agar	[81]
Gracilariopsis tenuifrons	Agar and carrageenan	[82]
Ochrophyta		
Order Fucales		
Sargassum sp.	Alginate	[83]
S. cymosum	Alginate	[83]
S. filipendula	Fucoxanthin	[84]
Turbinaria spp.	Fucoxanthin	[84]
S. polyceratium	Fucoxanthin	[84]
Order Dictyotales		
Dictyota caribaea	Fucoxanthin	[84]
D. pinnatifida	Fucoxanthin	[84]

Among the works with polysaccharides, the production of agar from *Gracilariopsis longissima (as Gracilaria verrucosa)* was favored by the extraction under acidic conditions, obtaining better gelation times, color, and texture [81]. The production of alginate from *Sargassum* sp. and *Sargassum cymosum* showed low viscosity (16.95 mPa.s) but high gel strength (787.5 g cm^{-2}) [83]. These results are attractive, for the application of these types of alginates in raw materials requiring high gel strength whilst maintaining good porosity. The extraction of kappa and beta carrageenan polysaccharides from *Gracilariopsis tenuifrons* showed good absorption in the UVB and UVA range, giving them a broad spectrum of photoprotection [82][85].

Concerning pigment production, Restrepo [84] studied the fucoxanthin content in brown seaweeds, e.g., *Dictyota*, *Sargassum*, *Spatoglossum*, and *Turbinaria*. The highest fucoxanthin content (10.03 mg g^{-1}) was reported for the extract of *Sargassum filipendula*, followed by *Dictyota caribaea* (8.36 mg g^{-1}) and *Dictyota pinnatifida* (6.77 mg g^{-1}). According to the authors, the high values of fucoxanthin may be related to the environmental conditions of the areas where the collections were made, being higher in those where exposure to light was greatest since this compound fulfills functions of light capture, as well as protection against oxidative stress generated by UV radiation.

Finally, Vargas [86] is one of the few works found that elaborated products using seaweed extracts and also evaluates their biological activity. Vargas developed cosmetic products such as moisturizing cream, sunscreen, and gel mask, with the addition of *Hypnea musciformis* ethanolic extracts. Results showed an improvement in physicochemical and microbiological properties, as well as UV absorption, as compared to the respective controls.

As previously indicated, the application of seaweed in Colombia has focused on chemical composition, biological activity, and extraction of polysaccharides and pigments. While among the most unexplored fields are biofuels and direct human consumption. This situation could be related to the fact that their application in these sectors requires high quantities of biomass, which has not been possible to obtain despite the resources that have been used in the few pilot cultures developed in the country.

Regarding seaweeds for human consumption, there is less interest, since these have not been part of the Colombian diet. Consequently, this situation could conduct to greater difficulties for its implementation in the short and medium-term. However, considering the transformation of the agri-food industry that focuses on achieving healthier and more environmentally sustainable foods, new global food trends have positioned selected seaweeds as candidates to lead this transformation [87][88][89]. These trends could generate new food proposals that seek to revive and reinvent cuisine with seaweed as it has been developed in other areas of the world [90][91].

The integration of suitable seaweeds in the Colombian economy would contribute to the implementation of a transition towards a blue economy as one of the highest priority goals included in Colombia Potencia Bioceánica Sostenible 2030 [92] as well as with the objectives of the United Nations Development Programme for Colombia [93].

References

1. Grand View Research. Global Commercial Seaweeds Market Size Report, 2020–2027. Report Overview. 2020. Available online: https://www.grandviewresearch.com/industry-analysis/commercial-seaweed-market (accessed on 20 November 2020).
2. Cioš, A.M.; Jerković, I.; Molnar, M.; Šubarić, D.; Jokić, S. New trends for macroalgal natural products applications. Nat. Prod. Res. 2019, 35, 1180–1191.
3. Wei, N.; Quarterman, J.; Jin, Y.-S. Marine macroalgae: An untapped resource for producing fuels and chemicals. Trends Biotechnol. 2013, 31, 70–77.
4. Algaebase: Listing the World's Algae. Available online: http://www.algaebase.org/ (accessed on 12 November 2021).
5. Pereira, L. Macroalgae. Encyclopedia 2021, 1, 17.
6. Duarte, C.M.; Marbá, N.; Holmer, M. Rapid domestication of marine species. Science 2007, 316, 382–383.
7. Pereira, L.; Cotas, J. Historical use of seaweed as an agricultural fertilizer in the european atlantic area. In Seaweeds as Plant Fertilizer, Agricultural Biostimulants and Animal Fodder; Pereira, L., Bahcevandziev, K., Joshi, N., Eds.; CRC Press: Boca Raton, FL, USA, 2019; pp. 1–23.
8. Chapman, V.J.; Chapman, D.J. Seaweeds and Their Uses, 3rd ed.; Springer: Dordrecht, The Netherlands, 1980.
9. Newton, L. Animal and human nutrition from seaweed resources in Europe: Uses and potential. In Seaweed Utilization; Sampson Low: London, UK, 1951; pp. 31–57.
10. Kılınç, B.; Cirik, S.; Turan, G.; Tekogul, H.; Koru, E. Seaweeds for food and industrial applications. In Food Industry, 1st ed.; Muzzalupo, I., Ed.; IntechOpen: London, UK, 2013.
11. Dillehay, T.M.; Ramírez, C.; Pino, M.; Collins, M.B.; Rossen, J.; Pino-Navarro, J.D. Monte verde: Seaweed, food, medicine, and the peopling of South America. Science 2008, 9, 784–786.
12. Gao, G.; Burgess, J.G.; Wu, M.; Wang, S.; Gao, K. Using macroalgae as biofuel: Current opportunities and challenges. Bot. Mar. 2020, 63, 355–370.

13. Kelly, M.S.; Dworjanyn, S. The Potential of Marine Biomass for Anaerobic Biogas Production. The Crown Estate: London, UK, 2008. Available online: https://arpa-e.energy.gov/sites/default/files/The%20Potential%20of%20Marine%20Biomass%20for%20Anaerobic%20Biogas%20Production (accessed on 20 August 2020).

14. Qin, Y. Production of seaweed-derived food hydrocolloids. In Bioactive Seaweeds for Food Applications: Natural Ingredients for Healthy Diets; Qin, Y., Ed.; Elsevier: Amsterdam, The Netherlands, 2018; pp. 53–69.

15. Coas, J.; Leandro, A.; Pacheco, D.; Gonçalves, A.M.M.; Pereira, L. A comprehensive review of the nutraceutical and therapeutic applications of red seaweeds (Rhodophyta). Life 2020, 10, 19.

16. Ganesan, A.R.; Tiwari, U.; Rajauria, G. Seaweed nutraceuticals and their therapeutic role in disease prevention. Food Sci. Hum. Wellness 2019, 8, 252–263.

17. Shannon, E.; Abu-Ghannam, N. Seaweeds as nutraceuticals for health and nutrition. Phycologia 2019, 58, 563–577.

18. Tanna, B.; Mishra, A. Nutraceutical potential of seaweed polysaccharides: Structure, bioactivity, safety, and toxicity. Compr. Rev. Food Sci. Food Saf. 2019, 18, 817–831.

19. Couteau, C.; Coiffard, L. Seaweed application in cosmetics. In Seaweed in Health and Disease Prevention; Fleurence, J., Levine, I., Eds.; Elsevier: Amsterdam, The Netherlands, 2016; pp. 423–441.

20. Mrais, T.; Cotas, J.; Pacheco, D.; Pereira, L. Seaweeds compounds: An ecosustainable source of cosmetic ingredients? Cosmetics 2021, 8, 8.

21. Pereira, L. Seaweeds as source of bioactive substances and skin care therapy-cosmeceuticals, algotheraphy, and thalassotherapy. Cosmetics 2018, 5, 68.

22. Thomas, N.V.; Kim, S.-K. Beneficial effects of marine algal compounds in cosmeceuticals. Mar. Drugs 2013, 11, 146–164.

23. Rengasamy, K.R.R.; Mahomoodally, M.F.; Aumeeruddy, M.Z.; Zengin, G.; Xiao, J.; Kim, D.H. Bioactive compounds in seaweeds: An overview of their biological properties and safety. Food Chem. Toxicol. 2020, 135, 111013.

24. Siahaan, E.A.; Pangestuti, R.; Kim, S.-K. Seaweeds: Valuable ingredients for the pharmaceutical industries. In Grand Challenges in Marine Biotechnology; Rampelotto, P.H., Trincone, A., Eds.; Springer: Cham, Switzerland, 2018; pp. 49–95.

25. Smit, A.J. Medicinal and pharmaceutical uses of seaweed natural products: A review. J. Appl. Phycol. 2004, 16, 245–262.

26. Informe del Estado de los Ambientes Marinos y Costeros en Colombia. 2017. Available online: http://www.invemar.org.co/documents/10182/14479/IER_2017_baja_Final.pdf/76690566-f6e1-4610-906f-1c49c610b2c8 (accessed on 20 October 2020).

27. Comisión Colombiana del Océano. Reserva de Biósfera Seaflower. Available online: http://www.cco.gov.co/la-reserva.html (accessed on 3 October 2020).

28. Seaflower Biosphere Reserve. Available online: https://en.unesco.org/biosphere/lac/seaflower (accessed on 20 March 2020).

29. Díaz, J.M.; Acero, A. Marine biodiversity in Colombia: Achievements, status of knowledge, and challenges. Gayana 2003, 67, 261–274.

30. Márquez, G. Biodiversidad marina: Aproximación con referencia al Caribe. In Ecosistemas Estratégicos y Otros Estudios de Ecología Ambiental; Fondo FEN: Bogotá, Colombia, 1996; pp. 67–102.

31. Rincón-Díaz, M.N.; Gavio, B. Diversidad de Macroalgas Marinas del Caribe Colombiano, v2.8; Instituto de Investigaciones Marinas y Costeras—Invemar: Santa Marta, Colombia, 2020.

32. Álvarez, R.; Pardo, C.M.; Trespalacios, A.A. Evaluación y utilización potencial de las macroalgas marinas del caribe y el pacífico de Colombia: Estado actual de su conocimiento. Biosalud 2007, 6, 113–129.

33. Molina, J.N.; Álvarez, R. Resultados preliminares del cultivo experimental de Gracilaria Verrucosa (Hudson) Papenfuss (=G. caudata J. Agardh) (Rhodophyta: Gracilariaceae) en la costa caribe de Colombia. Rev. Acad. Colomb. Cienc. 2014, 38, 79–87.
34. Peña, E.J.; Álvarez, R. Experiencias en el cultivo experimental de algas rojas en el caribe y pacífico de Colombia. Rev. Luna Azul 2006, 23, 16–20.
35. Gallo, H.M.; Rincones, R.E. Factibilidad del Cultivo de Algas Marinas. Proyecto Corpoguajira/IIRBAvH/FAO. Fortalecimiento Para el Desarrollo de Empresas Rurales a Partir de Productos de la Biodiversidad en el Cabo de la Vela, Departamento de La Guajira; Consultoría Fase II: Bogotá, Colombia, 2003.
36. Montaña, J.C. Ensayos de Cultivo en Medio Natural de la Macroalga Hypnea Musciformis (Wulfen) Lamoroux en las Areas de Taganga y Puerto Luz (Santa Marta). Bachelor's Thesis, Universidad Jorge Tadeo Lozano, Cundinamarca, Colombia, 2006.
37. Rincones, R.E.; Gallo, H. Proyecto Jimoula: El Cultivo de Algas Marinas Como Alternativa Sustentable Para las Comunidades Costeras de la Península de la Guajira; BIOTACOL Ltda.: Rioacha, Colombia, 2004.
38. Delgadillo, O.; Newmark, F. Cultivo piloto de macroalgas rojas (Rhodophyta) en Bahía Portete, La Guajira, Colombia. Bol. Investig. Mar. Cost 2008, 37, 7–26.
39. Rincones, R.E.; Moreno, D.A. Aspectos técnicos y económicos para el establecimiento comercial del maricultivo de algas en Colombia: Experiencias en la península de la Guajira. Ambiente Desarro. 2011, 28, 1–52.
40. Peña, E.J.; Palacios, M.L. Introducción del alga roja Kappaphycus alvarezzi (Doty) en Colombia y experiencias de cultivo en la península de la guajira, caribe Colombiano. In Guiía de las Especies Introducidas Marinas y Costeras de Colombia; Gracia, A., Medelliín, J., Gil, D.L., Puentes, V., Eds.; INVEMAR. Ministerio de Ambiente y Desarrollo Sostenible: Santa Marta, Colombia, 2011; pp. 93–103.
41. Camacho, O.; Montaña, J. Cultivo experimental en el mar del alga roja Hypnea musciformis en el area de Santa Marta, Caribe Colombiano. Bol. Investig. Mar. Cost. 2012, 41, 29–46.
42. Mosquera, Z.; Peña, E.J. Effect of salinity on growth of the green alga Caulerpa sertularioides (Bryopsidales, Chlorophyta) under laboratory conditions. Hidrobiológica 2016, 26, 277–282.
43. Islam, M.; Khan, S.; Hasan, J.; Mallick, D.; Hoq, E. Seaweed Hypnea sp. culture in Cox's Bazart coast, Bangladesh. Bangladesh J. Zool. 2017, 45, 37–46.
44. Pereira, S.; Kimpara, J.; Valentin, W. A simple substrate to produce the tropical epiphytic algae Hypnea pseudomusciformis. Aquac. Eng. 2020, 89, 102066.
45. Ganesan, M.; Thiruppathi, S.; Jha, B. Mariculture of Hypnea musciformis (Wulfen) Lamouroux in South east coast of India. Aquaculture 2006, 256, 201–211.
46. Gómez, A.; Millán, J. Cultivo experimental de Gracilaria dentata Agardh y de Gracilariopsis tenuifrons (Bird et Oliveira) (Rhodophyta: Gigartinales) en la isla de Margarita, Venezuela. Rev. Biol. Mar. Oceanogr. 1997, 32, 137–144.
47. Bermejeo, R.; Cara, C.; Macías, M.; Sánchez-García, J.; Hernández, I. Growth rates of Gracilariopsis longissima, Gracilaria bursa-pastoris and Chondracanthus teedei (Rhodophyta) cultured in ropes: Implication for N biomitigation in Cadiz Bay (Southern Spain). J. Appl. Phycol. 2020, 32, 1879–1891.
48. Pérez-Lloréns, J.L.; Brun, F.G.; Andría, J.; Vergara, J.J. Seasonal and tidal variability of environmental carbon related physico-chemical variables and inorganic C acquisition in Gracilariopsis longissima and Enteromorpha intestinalis from Los Toruños salt marsh (Cádiz Bay, Spain). J. Exp. Mar. Biol. Ecol. 2004, 304, 183–201.
49. Jiang, H.; Zou, D.; Lou, W.; Chen, W.; Yang, Y. Growth and photosynthesis by Gracilariopsis lemaneiformis (Gracilariales, Rhodophyta) in response to di!erent stocking densities along Nan'ao Island coastal waters.

Aquaculture 2019, 501, 279–284.

50. Hayashi, L.; Reis, R.P.; Alves, A.; Castelar, B.; Robledo, D.; de Vega, G.B.; Msuya, F.E.; Eswaran, K.; Yasir, S. The cultivation of Kappaphycus and Eucheuma in tropical and sub-tropical waters. In Tropical Seaweed Farming Trends, Problems and Opportunities; Hurtado, A.Q., Critchley, A.T., Neish, I.C., Eds.; Springer: Cham, Switzerland, 2017; pp. 55–90.
51. Hurtado, A.Q.; Reis, R.P.; Loureiro, R.R.; Critchley, A.T. Kappaphycus (Rhodophyta) cultivation: Problems and the impacts of acadian marine plant extract powder. In Marine Algae; Pereira, L., Neto, J.M., Eds.; Taylor & Francis Group LLC: Oxfordshire, UK, 2014; pp. 251–299.
52. Hayashi, L.; Hurtado, A.Q.; Msuya, F.E.; Bleicher, G.; Critchley, A.T. A review of Kappaphycus farming: Prospects and constraints. In Seaweeds and Their Role in Globally Changing Enviorments; Israel, A., Einav, R., Seckbach, J., Eds.; Springer: Berlin/Heidelberg, Germany, 2010; pp. 251–283.
53. Chandrasekaran, S.; Nagendran, N.A.; Pandiaraja, D.; Krishnankutty, N.; Kamalakannan, B. Bioinvasion of Kappaphycus alvarezii on corals in the Gulf of Mannar, India. Curr. Sci. 2008, 94, 1167–1172. Available online: https://www.jstor.org/stable/24100697 (accessed on 2 December 2021).
54. Mulyani, S.; Tuwo, A.; Syamsuddin, R.; Jompa, J. Effect of seaweed Kappaphycus alvarezii aquaculture on growth and survival of coral Acropora Muricata. AACL Bioflux 2018, 11, 1792–1798.
55. Rajaram, R.; Rameshumar, S.; Ahmad, B.; Albeshr, M.F. Impacts of cultivation of red algae Kappaphycus alvarezii on planktonic and benthic faunal density in relation to environmental and hydrobiological parameters in tropical coastal ecosystem. Acta Ecol. Sin. 2021, 41, 39–49.
56. Reis, R.P.; Castelar, B.; Moura, A.L.; Kirk, R. Invasive potential of Kappaphycus alvarezii off the south coast of Rio de Janeiro state, Brazil: A contribution to environmentally secure cultivation in the tropics. Bot. Mar. 2009, 52, 283–289.
57. Chen, S.; Ganapin, D. Polycentric coastal and ocean management in the Caribbean sea large marine ecosystem: Harnessing community-based actions to implement regional frameworks. Environ. Dev. 2016, 17 (Suppl. 1), 264–276.
58. Chen, S.; Akhtar, T.; Currea, A.M. Sustainable seaweed production, Belize. In Scaling up Community Actions for International Water Management—Experiences from the GEF Small Grants Programme; The GEF Small Grants Programme: Port Louis, Mauritius, 2016; Available online: https://www.thegef.org/sites/default/files/publications/IW_PublicationCaseStudiesMay-Digital.pdf (accessed on 20 October 2020).
59. Gracilarias de Panamá. Available online: https://gracilarias.org (accessed on 10 May 2021).
60. Chung, I.K.; Sondak, C.F.A.; Beardall, J. The future of seaweed aquaculture in a rapidly changing world. Eur. J. Phycol. 2017, 52, 495–505.
61. INVEMAR. La calidad ambiental marina y costera en Colombia. In Technical Report: Informe de Estado de los Ecosistemas Marinos y Costeros; Invemar: Santa Mata, Colombia, 2004; pp. 39–74.
62. Rodríguez, L. Programa Nacional de Investigación, Evaluación, Prevención, Reducción y Control de Fuentes Terrestres y Marinas de Contaminación al Mar—Actualización del Plan de Acción 2014–2019; Comisión Colombiana Del Océano (CCO): Bogotá, Colombia, 2016; p. 70.
63. Seakura Sea of Life. Available online: https://www.seakura.co.il/en/ (accessed on 20 October 2020).
64. Craigie, J.S.; Cornish, M.L.; Deveau, L.E. Commercialization of Irish moss aquaculture: The Canadian experience. Bot. Mar. 2019, 62, 411–432.
65. Leandro, A.; Pereira, L.; Gonçalves, A.M.M. Diverse applications of marine macroalgae. Mar. Drugs 2020, 18, 17.
66. Sierra-Vélez, L.; Álvarez-León, R. Comparación bromatológica de las algas nativas (Gracilariopsis tenuifrons, Sargassum filipendula) y exóticas (Kappaphycus alvarezii) del caribe Colombiano. Bol. Cient. Mus. Hist. Nat. Univ. Caldas 2009, 13, 17–25.

67. Bula-Meyer, G. Marine macroalgae in the agronomy and potential use of floating Sargassum for manure production in the San Andres and Providencia Archipelago, Colombia. Rev. Intropica 2004, 1, 91–103.
68. Ospina, S.P.; López, J.B.; Márquez, M.E. Efecto antimitótico in vitro en el extracto metanólico de macroalgas marinas de la costa caribe Colombiana. Vitae 2007, 14, 84–89.
69. Ospina, M.; Castro-Vargas, H.I.; Parada-Alfonso, F. Antioxidant capacity of Colombian seaweeds: 1. extracts obtained from Gracilaria mammillaris by means of supercritical fluid extraction. J. Supercrit. Fluids 2017, 128, 314–322.
70. Arteaga, M.; De Silvestri, J. Estudio de las sustancias con propiedades antimicrobianas extraordinarias de algas marinas pertenecientes al litoral atlántico colombiano. Rev. Colomb. Cienc. Químico Farm. 1985, 4, 47–52.
71. Rozo, G.; Rozo, C.; Plazas, E.; Patiño, O. Fraccionamiento bioguiado del extracto etanólico de Hypnea musciformis en búsqueda de compuestos con actividad antioxidante. Vitae 2011, 18 (Suppl. 2), S162–S163.
72. Echavarría, B.; Franco, A.; Martínez, A. Evaluación de la actividad antioxidante y determinación del contenido de compuestos fenólicos en extractos de macroalgas del caribe Colombiano. Vitae 2009, 16, 126–131.
73. Díaz, M.C.; Bula-Meyer, G.; Zea, S.; Martínez, A. Ensayos de actividad biológica y ecología química de extractos orgánicos de macroalgas del caribe Colombiano. Bol. Investig. Mar. Cost 2006, 35, 241–247.
74. Martínez, A.; Arias, L.A.; Rueda, J.L.; Diaz, M.C.; Bula-Meyer, G. Antimicrobial activity study for alcohol extracts of some macroalgae from Colombian Caribbean Sea. Vitae 2002, 9, 49–55.
75. Nuñez, E.; Arteaga, M.; Castro, M. Investigación de actividad antibacteriana de extractos de algunas algas marinas colombianas. Rev. Colomb. Cienc. Químico Farm. 1972, 2, 123–130.
76. Sreenivasa, P.; Parekh, K. Antibacterial activity of Indian seaweed extracts. Bot. Mar. 1981, 24, 577–582.
77. Valle, H.; Ospina, S.; Galeano, E.; Martínez, A.; Márquez, M.E.; López, J.B. Obtención de una fracción antimitótica del extracto etanólico de la acroalga Digenia simplex. Bol. Investig. Mar. Cost 2009, 38, 109–117.
78. Valle, H.; Ospina, S.; Galeano, E.; Martínez, A.; Marquez, M.E.; López, J.B. Componentes de la fracción antimitótica del extracto etanólico de la macroalga Digenia simplex. Vitae 2008, 15, 141–149.
79. Cotas, J.; Leandro, A.; Monteiro, P.; Pacheco, D.; Figueirinha, A.; Goncąlves, A.M.M.; Jorge Da Silva, G.; Pereira, L. Seaweed phenolics: From extraction to applications. Mar. Drugs 2020, 18, 384.
80. Syad, A.N.; Rajamohamed, B.S.; Shunmugaiah, K.P.; Kasi, P.D. Neuroprotective effect of the marine macroalga Gelidiella acerosa: Identification of active compounds through bioactivity-guided fractionation. Pharm. Biol. 2016, 54, 2073–2081.
81. Molina, J.N.; de la Rosa, C.R.; Olivares, L.A.; Parra, X.J.; Serrano, A. Evaluación de las condiciones de extracción de agar-agar a partir de Gracilaria verrucosa en el balneario de Santa Verónica en el departamento del atlántico. Vitae 2011, 18 (Suppl. 2), S219.
82. Monsalve-Bustamante, Y.; Rincón-Valencia, S.; Puertas-Mejía, M.; Moreno-Tirado, D.; Mejía-Giraldo, J.; Restrepo-Moná, Y. Potencial material de encapsulación a partir del alga Gracilariopsis tenuifrons del mar caribe Colombiano. Vitae 2018, 25 (Suppl. 1), 153–155.
83. Camacho, O.; Hernández-Carmona, G. Phenology and alginates of two Sargassum species from the Caribbean coast of Colombia. Cienc. Mar. 2012, 38, 381–393.
84. Restrepo, N. Extracción, Purificación Y Análisis del Contenido de Fucoxantina en Algas Pardas del Caribe Colombiano. Bachelor’s Thesis, Universidad de Bogotá Jorge Tadeo Lozano, Cundinamarca, Colombia, 2015.

85. Monsalve-Bustamante, Y.; Rincón-Valencia, S.; Mejía-Giraldo, J.; Moreno-Tirado, D.; Puertas-Mejía, M. Screening of the UV absorption capacity, proximal and chemical characterization of extracts, and polysaccharide fractions of the Gracilariopsis tenuifrons cultivated in Colombia. J. Appl. Pharm. Sci. 2019, 9, 103–109.

86. Vargas, P.A. Efectos Fotoprotectores y Humectantes de Formulaciones Cosméticas que Contienen Extractos de Hypnea Musciformis Recolectadas en el Caribe Colombiano. Bachelor’s Thesis, Universidad de Bogotá Jorge Tadeo Lozano, Cundinamarca, Colombia, 2020.

87. Ferrara, L. Seaweeds: A food for our future. J. Food Chem. Nanotechnol. 2020, 6, 56–64.

88. Leandro, A.; Pacheco, D.; Cotas, J.; Marques, J.C.; Pereira, L.; Gonçalves, A.M.M. Seaweed’s bioactive candidate compounds to food industry and global food security. Life 2020, 10, 140.

89. Ullmann, J.; Grimm, D. Algae and their potential for a future bioeconomy, landless food production, and the socio-economic impact of an algae industry. Org. Agric. 2021, 11, 261–267.

90. Figueroa, V.; Farfán, M.; Aguilera, J.M. Seaweeds as novel foods and source of culinary flavors. Food Rev. Int. 2021, 37, 1–26.

91. Mouritsen, O.G.; Rhatigan, P.; Pérez, J.L. World cuisine of seaweeds: Science meets gastronomy. Int. J. Gastron. Food Sci. 2018, 14, 55–65.

92. Colombia Potencia Bioceánica Sostenible 2030—Documento CONPES 3990. Consejo Nacional de Politica Economica y Social—Republica de Colombia 91. 2020. Available online: https://www.co.undp.org/content/colombia/es/home/sustainable-development-goals.html (accessed on 30 May 2021).

93. Objetivos de Desarrollo Sostenible|El PNUD en Colombia. United Nations Development Programme. 2015. Available online: https://www.co.undp.org/content/colombia/es/home/sustainable-development-goals/background/ (accessed on 30 March 2021).