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Review

A Comparison between the Production of Edible Macroalgae Worldwide and in the Mediterranean Sea

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Abstract: Macroalgae are beneficial for consumers and producers due to their high productivity, their chemical composition and their efficient cultivation without additional feed. Asia dominates global macroalgae production, while European production is still marginal and mainly based on wild harvesting in the North Atlantic. The European Commission has launched initiatives to promote the sustainable production, safe consumption and innovative use of macroalgae products in European regional seas, including the Mediterranean Sea. A variety of coastal and seabed types and a wide range of environmental conditions make the Mediterranean a hotspot of marine biodiversity while providing good conditions for the cultivation of macroalgae. The aim of this paper is to compare the global macroalgae production and macroalgae production in the Mediterranean Sea, focussing on the cultivation of edible macroalgae. The paper also discusses the limitations and possibilities of macroalgae production in the region. Macroalgae production is one of the most promising sectors of the blue economy in the Mediterranean. The production of edible macroalgae suitable for human consumption has great potential, considering future population growth and related food security and health issues, as well as the additional ecosystem benefits of macroalgae production.

Keywords: environmental impact; farming; food; harvesting; macroalgae; production; sustainability; the European Union; the Mediterranean Sea

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1. Introduction

Algae is a common name for a polyphyletic group of taxonomically unrelated organisms. In the broadest sense, algae are a functional group of oxygen-evolving photosynthetic autotrophs that use light to synthesise complex organic compounds from carbon dioxide and water [1–3]. Marine macroalgae or seaweeds are macroscopic marine algae that can grow to several metres in length and belong to the domain Eukarya and the kingdoms Plantae (phylum Chlorophyta—green algae and phylum Rhodophyta—red algae) and Chromista (phylum Ochrophyta, class Phaeophyceae—brown algae) [2]. AlgaeBase (http://www.algaebase.org (accessed on 31 December 2023)) currently contains 175,050 species and infraspecific names of algae, and there are about 1800 different species of brown algae, 6200 species of red algae and 1800 species of green algae [2]. As macroalgae require both sufficient light and a fixation point, they mostly inhabit the rocky substrate of coastal areas, with some exceptions that float freely [4].

In addition to their great ecological importance, they are also of great commercial importance as food, food additives, animal feed, fertilisers, nutraceuticals and pharmaceuticals, cosmetics, biofuels and biopackaging [3,5–7]. New algae-based products and new uses have yet to be discovered [8]. In recent decades, macroalgae have become interesting for consumers and producers due to their high productivity, their chemical composition and the fact that they can be grown efficiently without additional feed, antibiotics and pesticides [9]. The bioactive substances of macroalgae have a high nutritional, nutraceutical, industrial, agricultural, pharmacological and biomedical value, and are used daily in household and industrial products (in foods such as ice cream, yoghurt, cream, sauces, dressings, jam and cheese, and in hair, skin and oral care products such as shampoo, cream, toothpaste or deodorants, as well as in plastic bags and packaging) [2,6,10–17].

Coastal communities around the world have a long tradition of harvesting and cultivating macroalgae for food, medicine, rituals and coastal defence [18,19]. According to some authors, macroalgae have been used as food and medicine for at least 14,000 years [19] and have been part of the human diet in Japan and China for 2500 years [8]. Macroalgae are of great importance for the development of the human brain, as they contain essential elements for brain development [20,21]. Therefore, they have directly influenced the development of culture and society [22]. In Japan and China, edible macroalgae have been of great importance since ancient times due to the long coastlines and abundance of macroalgae [23], while in the rest of the world the custom of eating macroalgae has only survived in Ireland, Iceland, France (Brittany), Peru and Chile [11]. In Europe, macroalgae have long been used as animal feed and to improve the soil to combat plant diseases and insects [8,24,25]. The custom of eating macroalgae was brought to Europe and other Western countries from the Far East, but in some parts of Europe the consumption of algae was traditionally associated with poverty [10].

Nowadays, the consumption of macroalgae is associated with a healthy diet, as they are a natural food with a high nutritional value and a high content of minerals, vitamins, polysaccharides and a low fat content, which benefits human health [2,14]. As macroalgae are widespread and can be found in all climatic regions of the world, macroalgae gastronomy is experiencing a boom, together with the locavore movement [11].

The cultivation of macroalgae began in East Asia in 1640 [26], or perhaps much earlier [27], while commercial macroalgae cultivation began in the mid-twentieth century [9]. Although macroalgae cultivation has increased significantly in the last two decades, production is very low compared to the global agricultural production of 1.6 trillion tonnes [28]. Nevertheless, it is estimated that 5 million km^2 of macroalgae cultivation area could produce the same amount of biomass annually as the entire global agricultural sector [29]. Given the increasing global consumption of seafood and the sustainability of algae cultivation, the sector has great potential to feed the world's growing population and provide a livelihood for millions of people [7].

Of the approximately 220 commercially used macroalgae species [9], more than 150 species (85%) are used directly for human consumption and indirectly for food products as stabilisers, thickeners, emulsifiers and colourants [6,27]. Between 2000 and 2020, global macroalgae production increased from 10.6 million tonnes to 35 million tonnes, with 97% coming from cultivation mainly for human consumption and for food additives [7]. In 2020, the global production of marine macroalgae accounted for 99.8% of aquatic algae production and 51.4% of global mariculture production [7].

Macroalgae can not only be harvested in nature, but can also be cultivated in onshore, nearshore or offshore macroalgae farms, as well as in integrated multitrophic aquaculture systems (IMTA) or together with wind farms [30]. There are many reasons for integrating macroalgae farms with wind farms, including economic (savings in infrastructure costs by installing macroalgae farm moorings at the same time as wind farm moorings, and the potential for much larger macroalgae farms), social (a reduced occurrence of spatial conflicts through offshore relocation and the integration of human activities) and environmental (an increase in marine biodiversity and associated restorative ecosystem services) benefits [31,32]. Macroalgae farms are usually located on the coasts, while offshore farms are currently too expensive, but will probably be more economically viable in the future [9].

Cultivation techniques are selected according to species and site characteristics, and include line cultivation (with lines close to the seabed, submerged or floating), net cultivation (with floating or slightly submerged nets) and floating (submerged) raft cultivation (lines or nets on a floating or sometimes submerged fixed frame). Tank or pond cultivation consists of cultivation under controlled conditions for sensitive species (*Caulerpa* spp. or *Ulva* spp.) that are tied or free-floating), while rock cultivation involves growing macroalgae directly on the seabed or on artificial substrate [33,34]. In IMTA systems, macroalgae are cultivated in proximity to multiple species at different trophic levels, mitigating environmental impacts and producing biomass that can be economically utilised. As dissolved nutrients are an important limiting factor for macroalgae production, the nutrients excreted by fish and molluscs can accelerate macroalgae growth and production [35]. In IMTA systems, waste nutrients are recycled, less nutrients are released into the environment, and the overall productivity of the system is increased [35,36]. Therefore, energy and nutrient losses are minimised, while the efficiency of resource use is maximised by closing the nutrient cycle [37].

Macroalgae farms are a climate-friendly model of aquaculture where the species do not require freshwater, feed or fertiliser, and provide benefits to coastal ecosystems and communities by increasing food security, creating jobs and supporting ocean justice [38,39]. The choice of location for macroalgae harvesting and cultivation in coastal waters is a very important factor, influencing the quantity and quality of macroalgae composition [25] as well as the sustainability of macroalgae production [40]. The response to abiotic stress (temperature, salinity, nutrients, irradiance, desiccation, storms and currents) has implications for algal physiology and biochemical functioning [41]. At low sea temperatures, for example, membrane proteins and lipids can be damaged by the formation of crystals in the cells, which impairs growth [42], while at high temperatures the loss of chlorophyll and other photosynthetic pigments can lead to a partial or complete bleaching of the thalli and the inhibition of growth [43,44]. Abiotic stressors can also promote the transition from growth to the sexual and asexual reproductive phase [45].

The Mediterranean Sea is the largest and deepest enclosed sea, covering 0.8% of the surface and 0.32% of the volume of the world's oceans [46]. A variety of coastal and seabed types and a wide range of environmental conditions make the Mediterranean a hotspot of marine biodiversity, with more than 1124 macroalgae species (20% endemic) [47], offering good potential for the cultivation of edible macroalgae.

The Mediterranean region has a long and rich history and great cultural importance. It is a densely populated region along the coasts of 21 countries, and almost a third of the Mediterranean population lives in coastal areas [46]. The population of the Mediterranean coastal region will reach 690 million people by 2050 [48]. Population growth and the associated intensification of human activities will increase the risks for the coastal environment, but also for coastal communities. These risks include hazards such as flooding, storms, heat stress, coastal erosion and loss of agricultural land, as well as health problems related to air pollution, lack of water supply, sewage treatment and waste disposal. Nature-based solutions, including regenerative macroalgae cultivation, could help Mediterranean countries to improve their resilience and adaptability to environmental changes (restorative ecosystem services). As macroalgae absorb pollutants (nitrogen, phosphorus and heavy metals), remove carbon dioxide, and produce oxygen, macroalgae cultivation can help to reduce water pollution, oxygen depletion and acidification, and mitigate climate change [49]. In addition to carbon sequestration, there are two other mechanisms by which macroalgae can contribute to climate change mitigation: through carbon offsets (by using macroalgal products to reduce carbon dioxide emissions from the industry) and methane reduction in agriculture (by using algal feed to reduce methane emissions from livestock) [50].

Mediterranean countries are also facing a deficit in food production due to the limited availability of water and agricultural land. Together with population growth and climate change, this will increase dependence on food imports [48]. Another important issue is the increasing obesity in almost all Mediterranean countries since 2012, which is linked to the replacement of the traditional healthy Mediterranean diet with the "Western" diet [48]. The food deficit could be solved by expanding and promoting the cultivation of macroalgae, which can also help to combat unhealthy eating habits and promote the consumption of locally produced, better quality food.

Although macroalgae production has been well analysed at the global level [7,51,52] and in Europe [30,53–57], data on macroalgae production in the Mediterranean are fragmented, incomplete and of low quality [6,58].

Considering all these facts, the aim of this study is to compare the global macroalgae production and the production of macroalgae in the Mediterranean region, with a special focus on the cultivation of edible macroalgae. The paper also discusses the limitations and possibilities of macroalgae production in the Mediterranean region.

2. Macroalgae Fit for Human Consumption

2.1. Global Production

According to the Food and Agriculture Organisation (FAO) data, global algae production (including cultivation and wild harvesting) increased 60-fold from 0.56 million tonnes in 1950 to 35.8 million tonnes (35.7 million tonnes of macroalgae and 56,456 tonnes of microalgae) in 2019 [52].

In 2020, global macroalgae production amounted to 35 million tonnes, worth USD 9.7 billion [59], and 85% of the macroalgae produced were used for human consumption [7]. Some sources have corrected the macroalgae production reported by the FAO to 26.9 million tonnes, as they have calculated that the production of the main producers is six to seven times lower than reported [60].

In 1969, the production of macroalgae from cultivation was, for the first time, as high as the production from wild collection (1.1 million tonnes) [52]. Interestingly, the wild collection of macroalgae has remained at the same level since 1969, while macroalgae production from cultivation has increased rapidly. In 2020, 97% of macroalgae came from cultivation [7].

In the period between 1990 and 2019, the amount of cultivated macroalgae increased significantly, mainly due to the increase in the cultivation of brown macroalgae (from 3.1 million tonnes to 16.4 million tonnes) and red macroalgae (from 1 million tonnes to 18.3 million tonnes), while the cultivation of green macroalgae decreased (from 31,000 tonnes to 17,000 tonnes) [52]. Despite the rapid growth of macroalgae cultivation, it is far from reaching its full potential, which is estimated at up to 100,000 million tonnes [34]. While in Asia, 99.5% of macroalgae were cultivated [36], and outside Asia they were mainly harvested from the wild [34].

In the period between 1976 and 2018, trade in macroalgae increased from USD 65 million to USD 1.3 billion, with Indonesia, Chile and the Republic of Korea being the main exporters, while China, Japan and the United States of America were the main importers [51]. In 2021, world trade in macroalgae and other algae fit for human consumption, fresh, chilled, frozen or dried, totalled USD 895 million, and the main exporters were South Korea, China, Indonesia, Japan, and the USA [61]. The global market for macroalgae was worth USD 8.3 billion in 2023 and is estimated to reach USD 17.8 billion by 2032 [62].

The growth of macroalgae production has been mainly driven by the increasing demand for macroalgae-based food and food additives [30], and the market for macroalgae food will continue to grow with the increasing awareness of healthy and sustainable eating [63].

2.2. Important Taxa

Of the more than 650 known edible macroalgae species [10], around 150 are used as food [6,27]. The consumption of brown macroalgae predominates (66.5%), compared to the consumption of red (33%) and green (5%) macroalgae [64].

Table 1 shows the annual global production of the eight most important species in relation to the production volume in the years 2000, 2005, 2010, 2015 and 2020 [7].

Table 1. The annual global production (in thousand tons, live weight) of the eight most important macroalgae species in relation to the production volume in the years 2000, 2005, 2010, 2015 and 2020 [7,65,66].

Species	The Global Annual Production (in Thousand Tons, Live Weight) 2000	2005	2010	2015	2020	Total (%) in 2020
Saccharina japonica Royal Kombu, Sea tangle or Japanese kelp	5380.9	5699.1	6525.6	10,313.7	12,469.8	35.5
Eucheuma spp.	214.3	983.9	3472.6	10,182.1	8129.4	23.2
Gracilaria spp.	55.5	933.2	1657.1	3767.0	5180.4	14.8
Undaria pinnatifida Wakame, Sea mustard	311.1	2439.7	1505.1	2215.6	2810.6	8.0
Porphyra spp./*Pyropia* spp. Nori, Laver	424.9	703.1	1040.7	1109.9	2220.2	6.3
Kappaphycus alvarezii Elkhorn sea moss	649.5	1283.5	1884.2	1751.8	1604.1	4.6
Sargassum fusiforme Fusiform sargassum	12.1	115.6	97.0	209.3	292.9	0.8
Eucheuma denticulatum Spiny eucheuma	85.3	174.5	265.5	280.8	154.1	0.4
Subtotal of eight important species in total aquatic algae production (%)	67.3	83.2	81.5	96.0	93.7	93.7
Total aquatic algae production	10,595.6	14,831.3	20,174.3	31,073.5	35,077.6	100

Some taxa, such as *Laminaria* spp., *Saccharina* spp., *Undaria* spp., *Porphyra* spp., *Eucheuma* spp., *Gracilaria* spp., *Macrocystis* spp. and *Caulerpa* spp., are primarily used for human consumption, while their production residues are used for other purposes (feed for abalone culturing) [51]. *Gelidum* spp. is used for salad and jelly, but also in the production of agar. *Gracilaria* spp. is mainly used as feed for abalone and for the production of agar, and *Eucheuma* spp. for the production of carrangeenan [27]. *Undaria pinnatifida* and *Porphyra* spp. are among the most consumed macroalgae taxa [67].

Saccharina japonica (kombu) is the most commonly eaten species. It is a brown alga that is restricted to Japan, China, the Pacific coast of Russia, North America and the Mediterranean [68]. *Saccharina japonica* has been consumed by the Chinese for at least 1500 years, but it was first successfully cultivated on floating rafts in the early 1950s [67]. The species can be easily cultivated by attaching young samples to ropes hanging from the floats. Sites suitable for the cultivation of *S. japonica* should have a total nitrogen content of over 5 mg/m^3, while the optimum temperature is between 5 °C and 10 °C, but growth is still good enough at 20 °C [67]. However, under aquaculture conditions, kelp is grown for one winter [69].

Undaria pinnatifida (wakame) is a brown alga native to Northeast Asia [65]. It occurs in the lower intertidal zone and in shallow, partially sheltered intertidal zones (up to 18 m, but mainly at a depth of 1 to 3 m) [69]. In its natural range, the species prefers average monthly sea surface temperatures of −0.6 °C to 16.8 °C in winter and 23 °C to 29.5 °C in summer [70]. It is an opportunistic species that forms dense kelp forests and can compete with native species for space and light [65]. Wakame has considerable economic importance as a food in Japan, Korea and China [68]. It has been cultivated in Japan since the Nara Period (710–794) [11], but large-scale longline cultivation began in 1957 [11].

Porphyra spp./*Pyropia* spp. are commonly known as nori, which are used for the preparation of sushi. The biology of *Porphyra* spp. has been extensively studied for its economic value, but many species have been reclassified as *Pyropia*. There are currently 53 accepted species names of the genus *Porphyra* in AlgaeBase, [67], and 79 accepted species names of the genus *Pyropia*. *Porphyra* spp. is found on rocky shores worldwide, including some species in the tropics or at the poles, and optimal growth conditions vary. In Wales, traditional laverbread is made by cooking *Porphyra umbilicalis* in salt, and the Irish counterpart is sleabhac or sloke. The cultivation of *Porphyra* spp./*Pyropia* spp. began in the 17th century in Japan, Korea and China, but scientifically based cultivation began in the 1960s [67]. It is a thriving sector of aquaculture, but no dramatic change in overall volume is expected [71]. Several different *Porphyra* and *Pyropia* species are cultivated and used for nori preparation (mainly *Pyropia yezoensis* and *Pyropia tenera*).

3. Macroalgae Fit for Human Consumption in Europe

3.1. Production

Only a small proportion of the 1700 macroalgae species in European waters [72] are commercially exploited in limited coastal areas [73]. In Europe, interest in macroalgae has increased in recent decades due to the global increase in macroalgae production, the many sustainable uses of macroalgae, and the wide range of macroalgae species [74]. While macroalgae production in Asia has increased significantly over the years, European production has hardly grown at all, as the harvest from the wild has remained at the same level due to overharvesting and weather changes [30,53,54]. In 2015, 296,194 tonnes of macroalgae were produced in Europe and only 0.5% were cultivated [27], while in 2019 only 287,033 tonnes of macroalgae were produced (0.8% of global macroalgae production) and only 3.9% were cultivated (0.03% of global macroalgae cultivation) [52].

European macroalgae production is concentrated in the Atlantic region and is dominated by Spain, France and Ireland in terms of the number of companies, while Norway, France and Ireland dominate in terms of biomass production [56,57,75]. Taking into account the number of companies that produce macroalgae in Europe, wild collection dominates, with 68% compared to cultivation (32% of seaweed production, 76% of which is produced in sea-based facilities and 24% in land-based facilities) [56].

In 2018, the European algae sector had an economic value of EUR 1.7 billion and provided employment for 14,000 people, while macroalgae accounted for EUR 700 million (8% of the global market), with large multinational companies dominating the sector at 80% [8]. The annual growth rate is between 7 and 10%, with a wholesale value of around EUR 24 million and a focus on *Alaria esculenta* (dabberlocks), *Saccharina latissimi* (sugar kelp), *Porphyra* sp., *Palmaria palmata* (dulse) and *Ulva* sp. [54,76,77]. The production of edible macroalgae for food is still relatively small, but the market is growing with a variety of food products [54].

The opportunity for an expansion of macroalgae in Europe lies in the poor reputation of Asian producers in the environmentally conscious European market, which demands the best quality of sustainable products [77]. The European macroalgae market could be worth up to EUR 9.3 billion in 2030, with the edible macroalgae sector accounting for a large share (worth up to EUR 1.8 billion), and the remaining share split between animal feed, biostimulants, biopackaging, pharmaceuticals and nutraceuticals, additives, cosmetics and biofuels [30].

European countries were the world's leading importer of macroalgae products in 2016 with 180,000 tonnes (USD 613 million) [27], and demand for these valuable commodities will continue to rise with the popularity of vegan and plant-based diets and Japanese cuisine in Europe [63]. European exports of seaweed and other algae fit for human consumption, fresh, chilled, frozen or dried, totalled USD 75 million (8% of global exports) in 2021 [61]. Europe is also one of the most innovative regions in the field of food ingredients from macroalgae [6,78].

3.2. Important Taxa and Consumption

More than 650 edible algae species consumed worldwide have entered the EU market, although they are not listed in the EU Novel Food Catalogue (NFC) [10]. A detailed list of algae species consumed as food, food supplements and/or food additives in Europe before and/or after 1997 has been published, together with region/country and source [77]. More than 150 edible algae species have been identified in Europe, including 130 seaweed species, but only 30 species have been authorised by the EU as novel foods [77]. Interestingly, the list of Novel Food Priorities currently contains 104 macroalgae taxa [79].

It is interesting to note that 36% of European macroalgae companies produce macroalgae for direct human consumption and 15% for the production of food additives and supplements, while the remaining percentage is divided between cosmetics and well-being (17%), animal feed (10%), fertilisers and biostimulants (11%), and other applications (11%) including biofuels, bioremediation or biomaterials [56]. Edible macroalgae species are mainly sold fresh or dried for human consumption in France, Iceland, Ireland and Spain [7,11], while in the other European countries the consumption of macroalgae is negligible [56].

In Europe, 60% of the seaweed consumed are *Pyropia* spp., and are mainly imported from Asia (only 1% comes from Europe) [77]. *Palmaria palmata* is one of the most popular edible macroalgae species in Europe [11] and has a long tradition of harvesting in France, Iceland and especially in Ireland, where it is considered a delicacy [73]. A total of 90% of the consumed *P. palmata* is wild harvested in France [77]. The most commonly harvested taxa in Europe are Laminaria spp., *Ascophyllum nodosum*, *P. palmata*, *Chondrus crispus*, *Porphyra* spp., *Ulva* spp., *Himanthalia elongata*, *Undaria pinnatifida* and *Fucus spiralis* [56].

The price of edible macroalgae depends on the product (dry products usually have lower prices), on the type of production (harvested macroalgae usually have lower prices) and on the taxa [56]. The macroalgae with the highest average value are as follows: *Porphyra* spp. (251 EUR/kg dry weight), *Codium* spp. (155 EUR/kg dry weight), *Gracilariopsis longissima* (155 EUR/kg dry weight), *P. palmata* (114 EUR/kg dry weight), *U. pinnatifida* (108 EUR/kg dry weight), *Saccharina latissima* (88 EUR/kg dry weight), *H. elongata* (86 EUR/kg dry weight), *C. crispus* (72 EUR/kg dry weight), and *Fucus* spp. (25 EUR/kg dry weight, on the online seaweed market in Spain) [56].

The French Centre d'Etudes et de Valorisation des Algues (CEVA) has revised a seaweed standard for food and cosmetics that includes farmed and wild harvested seaweed and takes into account that the classification of seawater should follow the shellfish regulation. It has also proposed a positive list of (safe) seaweeds (in France): seaweeds (including all major edible seaweed taxa as well as *Phymatolithon calcareum* and *Ulva* spp.), [80].

3.3. The Development of Cultivation

The vast majority of macroalgae are wild harvested in Europe (e.g., *Palmaria palmata*), including all dominant producers: Scotland, Ireland, Iceland, Portugal, Spain, France, the Netherlands, Denmark, Sweden and Norway [58,81]. In Europe, the cultivation of macroalgae began in the mid-1980s [53,54], but has been hampered by a lack of technology, poor infrastructure, complicated management, limited investment and the lack of integration into the value chain [30]. Macroalgae are cultivated in 13 European countries, mainly in near-shore systems [56], while some species (*Ulva* spp.) are mainly cultivated in land-based systems due to their high growth capacity [74]. In limited European coastal areas, only a few taxa, such as *Saccharina latissima*, *Alaria esculenta* and *Ulva* spp., are cultivated on a larger scale [82].

Europe is the leading region in the number of seaweed start-ups (more than 50% in 2022), but investment in start-ups fell from USD 67 million in 2021 to USD 34 million in 2022 and flowed mainly into downstream companies that process seaweed into products, while cultivation start-ups are the least popular [60]. In the period between 2020 and 2022, USD 70 million was invested in the algae food sector. However, the biggest challenge for seaweed cultivation in Europe is the high cost of cultivated seaweed and the imbalance between the demand for taxa for human consumption, such as *Ulva* spp., *Palmaria* spp. and *Porphyra* spp., and the mainly cultivated taxa, such as *Saccharina* spp. [60].

As European macroalgae production depends on the harvesting of wild stocks, the demand for certain taxa could jeopardise wild ecosystems [55]. The future expansion of macroalgae cultivation in Europe is expected not only due to the ban on wild collection for some species or the low wild biomass, but also due to the high demand for edible macroalgae and their high commercial value. It is estimated that 30% of demand in the European macroalgae market and around 20% of demand for edible macroalgae could be met by European producers, and that this sector could create 85,000 jobs. However, to reach this target, between 7700 and 26,300 hectares of marine farms, and 300 to 1000 hectares of onshore farms are needed [30].

There are several factors that could promote the increase macroalgae cultivation in Europe, including favourable environmental conditions (nutrient-rich, cold waters suitable for cultivation) in European coastal regions and socio-economic conditions [30,83,84], but also a growing global and European macroalgae market [63]. The socio-economic conditions include the quality of regulation, the efficiency of administration, and the quality of the trading infrastructure, but also a high standard and associated high-calibre customers who are willing to buy high-quality products). According to some authors, the production of species with high market demand, such as *P. palmata*, *Porphyra* spp. and *Ulva* spp., should be expanded [54]. The main macroalgae species cultivated in Europe in 2030 will be *Ulva lactuca* (sea lettuce) for food, *S. latissima* for food and feed, and *A. esculenta* and *P. palmata* for food and cosmetics [30].

4. Macroalgae Fit for Human Consumption in the Mediterranean Region

4.1. Production

Only a few of the 21 Mediterranean countries, including Spain, France, Morocco and Tunisia, harvest or cultivate macroalgae, albeit in very small quantities [28,56], which is mainly due to low natural macroalgae production, the lack of significant tidal fluctuations and inefficient harvesting techniques [6]. Unfortunately, there is a lack of a serious analysis of the algal sector in the Mediterranean, including the edible macroalgae sector, and it is difficult to obtain complete and reliable data on macroalgae production [6,58]. In the European part of the Mediterranean, France and Spain are the largest macroalgae producers [8]. The majority of European macroalgae production is concentrated on the Atlantic coasts due to the larger intertidal zone, wider geographical distribution and greater abundance and size of macroalgae species [56].

Italy reported the production of *Gracilaria* sp. in the period from 1990 to 2000 with a production between 3000 and 5000 tonnes for the marine waters of the Mediterranean and Black Sea [85]. Since 2016, Morocco has reported the production of *Gracilaria gracilis*. Production was 8.1 tonnes in 2016, reached a maximum of 272.8 tonnes in 2019, and totalled 174 tonnes in 2022 in the Mediterranean and Black Sea marine waters [85]. Tunisia reported the production of *Gracilariopsis longissima* in quantities of 50 tonnes in 2019, 20 tonnes in 2020, 30 tonnes in 2021 and 79 tonnes in 2022 for the Mediterranean and Black Sea marine waters [85].

The list of start-ups and scale-ups worldwide involved in macroalgae breeding and propagation, cultivation and harvesting, processing infrastructure and equipment, and monitoring and laboratory analyses is available online [86]. It also contains data on species, production methods, and applications. Of all the listed companies involved in the cultivation and harvesting of macroalgae, only four are located on the Mediterranean coast (one in Spain, one in France and two in Israel) (Table 2).

There is one land-based farm for *Ulva* spp. and one harvesting site for *Ascophyllum nodosum* on the Spanish Mediterranean coast, and one land-based farm for *Ulva rigida* on the French Mediterranean coast [87].

In Italy, most of the macroalgae biomass is imported, and only one out of a total of fifteen companies harvests local macroalgae today [6], although there were several companies in the past that utilised *Ulva* spp. and *Gracilaria* spp. from the Venice Lagoon [88]. The lack of macroalgae farms in Italy is explained by the high initial investment and the lack of a supply chain [6]. The coasts of the Adriatic and Ionian Seas offer many suitable sites for the production of macroalgae, but only the production of microalgae has been developed there [89].

Table 2. Production process, annual production (in tonnes, wet weight) and application of macroalgae species in Mediterranean countries (Spain, France, Morocco and Israel) [86].

Country	Species	Production Process	Annual Production (Wet Weight/Tonnes)	Application
Spain (Mediterranean)	*Ulva* sp.	Onshore aquaculture	0–10	Food, personal care, plant and soil nutrition
Spain	*Saccharina* sp.,	Wild harvesting	0–10	Food
Spain	*Himanthalia elongata*, *Undaria* sp.	Wild harvesting	0–10	Food
Spain	*Laminaria ochroleuca*, *Palmaria palmata*, *Saccharina latissima*	Wild harvesting	0–10	Food
Spain	*Gracilaria* sp., *Ulva* sp.	Aquaculture	10–100	Food
Spain	*Codium* sp., *Gracilaria* sp., *Ulva* sp.	Wild harvesting	10–100	Food
Spain	*Codium* sp., *Himanthalia elongata*, *Porphyra* sp., *Ulva* sp., *Undaria* sp.	Wild harvesting	10–100	Food
Spain	*Chondrus crispus*, *Codium* sp., *Gigartina pistillata*, *Himanthalia elongata*, *Laminaria ochroleuca*, *Mastocarpus stellatus*, *Porphyra* sp., *Saccharina latissima*, *Ulva* sp., *Undaria* sp.	Wild harvesting	100–1000	-
Spain	*Codium* sp., *Ulva* sp., *Undaria* sp.	Wild harvesting and aquaculture	100–1000	Food
Spain	-	Wild harvesting	10,000–100,000	Hydrocolloids
France	*Alaria esculenta*, *Saccharina latissima*, *Undaria* sp.	Offshore aquaculture	10–100	Food, personal care
France	-	Wild harvesting and aquaculture	10–100	Feed
France	*Alaria* sp., *Chondrus crispus*, *Fucus* sp., *Himanthalia elongata*, *Palmaria palmata*, *Phymatolithon calcareum*, *Porphyra* sp., *Saccharina latissima*, *Ulva* sp., *Undaria* sp. *Porphyra* sp., *Undaria pinnatifida*	Wild harvesting	10–100	-
France	-	Wild harvesting	10–100	Food
France	*Alaria* sp., *Himanthalia elongata*, *Palmaria palmata*	Wild harvesting	10–100	Food
France	*Laminaria digitata*, *Palmaria palmata*	Wild harvesting	10–100	Plant and soil nutrition
France (Mediterranean)	*Ulva rigida*	Aquaculture and wild harvesting	100–1000	Bioplastics
France	*Saccharina latissima*, *Palmaria palmata*	Aquaculture, IMTA	100–10,000	-
France	*Himanthalia elongata*, *Palmaria palmata*, *Porphyra* sp., *Ulva* sp., *Undaria* sp.	Wild harvesting	100–10,000	Food
France	*Himanthalia elongata*, *Palmaria palmata*, *Porphyra* sp., *Saccharina latissima*, *Ulva* sp., *Undaria* sp.	Wild harvesting	100–10,000	-
France	*Himanthalia elongata*, *Palmaria palmata*, *Porphyra umbilicalis*, *Saccharina latissima*, *Ulva* sp., *Undaria* sp.	Wild harvesting	100–10,000	Food
France	*Himanthalia elongata*, *Palmara palmata*, *Porphyra* sp., *Saccharina latissima*, *Ulva* sp., *Undaria pinnatifida*	Wild harvesting	100–10,000	Food

Table 2. *Cont.*

Country	Species	Production Process	Annual Production (Wet Weight/Tonnes)	Application
France	*Laminaria* sp., *Palmaria* sp., *Himanthalia elongata*, *Ascophyllum nodosum*	Aquaculture and wild harvesting	1000–10,000	-
France	*Gracilaria* sp., *Gelidium corneum*, *Kappaphycus alvarezii*, *Eucheuma denticulatum*	Wild harvesting and aquaculture	1000–10,000	Hydrocolloids
France	*Ulva* sp.	Wild harvesting	1000–10,000	-
France	*Sargassum* sp., *Solieria* sp., *Ulva* sp.	Wild harvesting	1000–10,000	-
France	*Sargassum* sp.	Wild harvesting	10,000–100,000	-
France	*Solieria* sp., *Ulva* sp.	Wild harvesting and aquaculture	100,000–1,000,000	Plant and soil nutrition, feed
Morocco	*Ulva lactuca*, *Gelidium corneum*, *Gracilaria* sp., *Gigartina* sp., *Laminaria* sp.	-	0–10	-
Morocco	*Gelidium corneum*	Wild harvesting	1000–10,000	Hydrocolloids
Israel	*Gracilaria* sp.	Onshore aquaculture	0–10	Personal care, pharmaceuticals
Israel	*Ulva* sp., *Gracilaria* sp.	Onshore aquaculture	10–100	Nutraceuticals, food, personal care

It is important to remember that Israel is a pioneer in land-based seaweed cultivation, especially in innovative technologies, since 1982 [90–92]. In addition to Israel and Morocco, macroalgae production is still in the pilot phase in Egypt [93] and Tunisia (*Gracilaria* sp.) [94].

In 2022, the export value of seaweed and other algae fit for human consumption amounted to USD 12.6 million, while imports totalled USD 20.7 million for 15 countries in the Mediterranean region (Figure 1). France, Spain, Israel and Morocco dominated the export value with USD 4.7 million, USD 3.4 million, USD 3.5 million and USD 0.7 million, respectively [61].

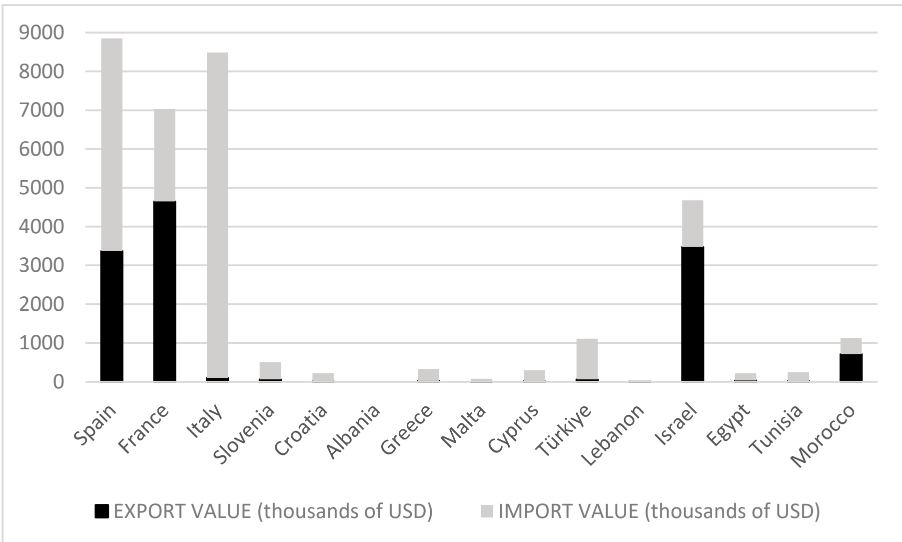

Figure 1. Export and import values (in thousands of USD) of seaweed and other algae fit for human consumption, fresh, chilled, frozen or dried, whether ground or not, for 15 Mediterranean countries in 2022 [61].

4.2. Important Taxa and Their Commercial Potential

Native algal species from the Mediterranean represent only a minority of the total European production [56,74] and are mainly used as food, especially *Ulva* spp. and *Gracilaria* sp. [6,77]. *Ulva lactuca* and *Chondracanthus teedei* were traditionally consumed fresh by fishermen in the Italian coastal regions, especially in Sicily [77,95].

Table 3 shows the list of edible macroalgae in the Mediterranean Sea [96].

Table 3. Edible macroalgae in the Mediterranean Sea [96].

Species	Common Name	Habitat	Used as Food
Green algae			
Caulerpa racemosa alien	sea grape, green caviar, grape caulerpa	tide pools, reef flats	peppery flavour, common in Polynesian, Asian and Island cuisines in salad
Ulva clathrata	Aonori	rocks and stones, from mid-littoral to sublittoral	commonly eaten fresh as a sea vegetable or dried, particularly with eggs
Ulva compressa	Green nori, plat darmwier	marine and estuarine, rock pools and sandy rocks, varying salinities	very popular due to fine texture and lovely fresh taste (Hawaii)
Ulva intestinalis	Gut weed	sheltered and exposed locations, natural and artificial structure, also epiphytically, from the upper littoral pools into the sublittoral	yes
Ulva lactuca	Sea lettuce, green laver	intertidal to shallow infra-littoral, often in tide pools, quick colonizer, blooms in the presence of nutrient run-off and fresh water input	delicate with mild flavour fresh and dried, in flakes, powders, used as a seasoning in soups and salads
Ulva linza	Breed darmwier, bright grass kelp, welded green nori	rocks or rock pools, usually in marine water sometimes in brackish	in many cultures, due to high nutrient content and silky texture
Ulva prolifera	Green ribbon plant	on rocks or other algae, on open coasts, estuaries and harbours, mixed with other species of the same genus	yes
Ulva rigida	Green laver	epilithic, in the entire littoral zone to the sublittoral	used as a fresh sea vegetable by many island cultures due to high nutrient content and fresh taste
Red algae			
Amphiroa cryptarthrodia		on rocks in sheltered waters, tide pools, forms large lawns	used on functional foods
Amphiroa fragilissima		up to 10 m depth, in seagrass meadows and rock hollows	used on functional foods
Chondracanthusteedei		habitats in the intertidal and subtidal zone, semi-exposed or sheltered areas	used for salads (máru) in parts of Italy
Gracilaria bursa-pastoris		epilithic, calm water of the upper sublittoral	yes
Grateloupia filicina		on rocks in pools, mid-littoral to shallow sublittoral, sporadic	yes
Grateloupia turuturu alien		epilithic, shallow tide pools, sand covered rocks near coast	commonly used in Japan as a sea vegetable, rich in dietary fibre

Table 3. *Cont.*

Species	Common Name	Habitat	Used as Food
Hypnea spinella alien		lower intertidal to 7 m, attached to small shells or rubble, in seagrass beds	commonly eaten (boiled in coconut milk) in the Pacific and Asia
Nemalion elminthoides		exposed rocky shores, generally on barnacles and limpets	yes
Osmundea pinnatifida	Pepper dulse	perennial, intertidal and sublittoral, on exposed rocks, generally distributed, abundant	aromatic seaweed, a pepper- or curry-flavoured spice in Scotland, Ireland, and Portugal
Plocamium cartilagineum	Cock's comb, kammtang, kamwier, red comb weed	depths from 2 to 26 m, strong to moderate wave action, on other algae	yes
Porphyra umbilicalis	Purple laver, pink laver, laver, nori	on rocks, mussels, in the littoral to splash zone, especially on exposed coasts	in flaked and whole leaf form, as a nori substitute, as laver, as an ingredient in snack mixes
Brown algae			
Colpomenia sinuosa		Epiphytic, hard surfaces lower intertidal up to 15 m deep	yes
Dictyopteris plagiogramma	Limu lipoa	on hard substrates, often attached to coral fragments or scattered rocks on deep sand plains from 9 to 55 m deep	yes
Hydroclathrus clathratus	Perforated brown seaweed	mid-littoral, wave-exposed rocks	in traditional Asian cuisine for centuries
Petalonia fascia		on rock in the mid intertidal to shallow sublittoral, protected or semi-exposed	yes
Scytosiphon lomentaria	Sausage weed	Littoral, wave-exposed shores and rock pools	yes
Treptacantha abies-marina		wave-exposed sublittoral zone	yes
Undaria pinnatifida alien	Wakame	shallow sublittoral zone	sweet flavour and slippery texture, dried and fresh, a delicacy in East Asian countries, miso soup and salads

Some of the species listed in Table 3 are non-native species in the Mediterranean Sea, which has the largest number of alien macroalgae of any sea in the world, with more than 60 alien macroalgae [97]. In the coastal areas of the Mediterranean, non-native macroalgae with a high reproduction rate have a high probability of becoming invasive, although their invasion need not be a global phenomenon [97].

For example, *Undaria pinnatifida* was introduced to the Mediterranean Sea (Thau Lagoon) in 1971 via oyster farming [98]. As an introduced species in many coastal areas worldwide, it has attracted much attention [90–101]. *Undaria pinnatifida* is one of the 100 worst invasive alien species in the world [99,102], and is listed as a species with a negative impact on biodiversity and ecosystem services in European seas and the Mediterranean [100,101]. In Venice, it is considered a pest related to the problem of marine structure fouling [101]. Some authors suggest [70], that *U. pinnatifida* can be managed as a potentially valuable species that creates new habitats and fisheries. Similar to *U. pinnatifida*, *S. japonica* was accidentally introduced via oyster farming in the Thau Lagoon (France, the Mediterranean Sea) in 1984 [103], while according to other sources it was introduced much earlier, in 1976 [66].

Sometimes commercial harvesting is a good option for dealing with alien species (e.g., *U. pinnatifida* in New Zealand), but under no circumstances should species be introduced into new areas [104–106]. Commercial harvesting measures for alien species should be accompanied by commercialisation plans and a risk assessment of commercial use [106].

Of the species listed in Table 3., *Ulva* spp., *C. teedei*, *Osmundea pinnatifida* and *Porphyra umbilicalis* have a long culinary tradition in Europe.

Chondracanthus teedei is a small red algae that can grow up to 15 cm in size. It is widely distributed in the Atlantic, Mediterranean and Black Seas and has also been introduced in Japan, Brazil and the Indian Ocean [68]. It occurs in intertidal and subtidal zone habitats, in semi-exposed or sheltered areas [107]. *Chondracanthus* sp. has potential for utilisation due to its importance to the carrageenan and food industries [107]. In Andalusia (Spain), *Ulva* sp., *Gracilaria* sp., *Gracilariopsis longissima* and *C. teedei* are cultivated in earth ponds [107,108]. The species is used as máru in the traditional cuisine of some Italian regions (Veneto region and the southern regions of Puglia, Sardinia, Sicily and Campania), but this tradition is not widespread [95]. In summer, it is harvested by hand and sold on the street dressed with lemon juice and salt [107].

Osmundea pinnatifida (pepper dulse) is a perennial, abundant, medium-sized red alga (up to 15 cm long). *Osmundea pinnatifida* is found in the North-East Atlantic, the Atlantic Islands, the Mediterranean and Black Sea, Southwest and East Asia, and South Africa and Australia [109]. It occurs at a sea surface temperature of 5 to 25 °C, a salinity of 30–35 PSU and at a depth of 0 to 30 m on exposed to moderately sheltered rocky shores [109]. It is exposed to fluctuations in low tide, temperature and light, and varies in size and colour depending on its location on the coast [110]. The peak of the vegetation is in summer, and reproduction takes place in spring and summer [109]. *Osmundea pinnatifida* has a taste and odour similar to a mixture of garlic, pepper and truffle (the truffle of the sea). Information on the cultivation of *O. pinnatifida* is very scarce [110]. In Spain, 100 kg were produced and marketed fresh/pickled/chopped for flavouring in 2013 [109]. Further studies are needed to develop cultivation methods and potential commercialisation [109].

Porphyra umbilicalis (purple laver, pink laver, laver, nori) is a red alga that occurs under a wide range of conditions in the littoral to splash zone, especially on exposed rocky shores. It is well adapted to desiccation, strong light, extreme and rapid temperature and salinity changes, and can tolerate stronger water movements than most other red algae [111]. The confirmed distribution is currently the North Atlantic, while the global distribution needs to be verified [68]. Of the 133 species of *Porphyra* sp. (*Porphyra* sensu lato includes species that are closely related to *Porphyra* or until recently belonged to the genus *Porphyra*, such as *Pyropia*), only six species are usually cultivated, and cultivation requires sophisticated technology and large investments [112]. *Porphyra umbilicalis* is harvested by hand in France and Spain and cultivated in France, Ireland and Norway (trials) [113]. It is used in the form of leaves and flakes, as a nori substitute, as a laver and as an ingredient in snack mixes. The consumption of *P. umbilicalis* is associated with many health benefits due to its high protein and low fat content, as well as its high content of mineral salts, trace elements, vitamins, amino acids and polyunsaturated fatty acids, etc. [114].

One of the most promising taxa in the field of macroalgae production in the Mediterranean region is the genus *Ulva*. There are several pilot projects for the cultivation of *Ulva* spp. in the Mediterranean region [6]. In the Eastern Mediterranean, the experimental system for the cultivation of *Ulva* spp. was tested in a shallow coastal area in central Israel, as it is abundant on the Israeli coasts and has high biomass productivity, as shown by its extensive offshore cultivation for biofuel [115]. In this study, the authors used 2 m^3 cages with air outlets to test the influence of tumbling, air mixing and external water exchange on the intensification of *Ulva* sp. growth. The advantage of *Ulva* spp. is their high abundance and availability in coastal waters around the world [116], their rapid growth under a wide range of environmental conditions, their valuable chemical composition, their high nutrient uptake (bioremediation efficiency) and their diverse applications [115,117]. The genus

Ulva often dominates in macroalgae blooms, known as green tide, and can affect coastal ecosystems and associated ecosystem services [118,119].

It has already been mentioned that *Ulva lactuca* is likely to be the main macroalgae species cultivated for food in Europe in 2030. *Ulva* spp. are listed in the NFC and the European Union list of Novel Food (ULNF) [120]. The genus *Ulva* contains a high content of proteins, carbohydrates, polysaccharides, minerals and lipids that make it suitable as food, but the economic viability of large-scale cultivation is still questionable [117]. The major challenge in the cultivation of *Ulva* spp. is that the genus is not well supported taxonomically, and that species identification based on morphology has led to different species being proposed [116], although genetic analysis does not support the existence of different species [121]. Furthermore, the polymorphism of *U. lactuca* is largely dependent on environmental conditions (especially salinity) and geographical location [122,123]. The cultivation of *Ulva* spp. in open systems requires further research, as different environmental conditions influence the quantity and quality of the cultivated organisms [124]. Nitrogen-rich wastewater from fish farms provides optimal conditions for *Ulva* spp. production [125]. Integrating *Ulva* spp. into IMTA with species that feed on *Ulva* spp., and thus reducing not only the nutrient output of the farms but also the need for additional feed for these species, seems to be a promising solution [117].

In contrast to the low commercial harvesting and cultivation of macroalgae in the Mediterranean region, there has been relatively good research and development activity over the last 20 years. In the period between 2002 and 2022, of the 263 publications on the properties and potential applications of 121 macroalgae taxa, 51% concerned red algae (62 taxa), 27% brown algae (34 taxa) and 22% green algae (25 taxa), with Tunisia, Italy and Egypt in the lead [6]. Only 13 publications focused on the potential utilisation of Mediterranean macroalgae species for food purposes, mainly in Egypt and Tunisia. The following 12 species took centre stage: *Codium tomentosum*, *Ulva* sp., *Ulva intestinalis*, *U. lactuca*, *U. rigida*, *Colpomenia sinuosa*, *Cystoseira* sp., *Gracilaria bursa-pastoris*, *Gracilaria longissimi*, *Hypnea musciformis*, *Jania rubens* and *Pterocladiella capillacea* [6].

There is a great opportunity for the use of macroalgae as food, but it is necessary to study which of the species are suitable as food, emphasising their organoleptic properties, and also to develop cultivation techniques and use in gastronomy [107].

4.3. Feasibility of Cultivation

The most important questions related to the expansion of macroalgae cultivation are which species can be produced in which quantities and in which locations [30]. The selection of the most suitable species not only influences the profitability of production, but can also have an impact on biodiversity conservation. To achieve the best results in terms of quantity and quality of production, these species should be native, high-yielding, adapted to low-nutrient conditions, disease-resistant, and resilient to different climate change scenarios [126].

As the cultivation of macroalgae in the Mediterranean is still in its infancy, the physiological screening approach [127] could be applied to the species native to the Mediterranean (with characteristics such as a large size and simple morphology, rapid growth leading to a large biomass, a high photosynthesis/respiration ratio, thermal tolerance to high temperatures, and capacity to store a large nitrogen reserve) to provide a solid scientific base for the development of macroalgae culturing under the expected future environmental conditions in the region. The criteria for the selection of macroalgae in a warmer, more variable climate should include traits that demonstrate the robustness/resilience and adaptability of individuals and populations to the expected future conditions [127]. In addition to climate-related environmental changes, it is also important to identify other causes of possible fluctuations in macroalgae productivity. Strong support for the pilot cultivation projects of the most promising macroalgae species for possible commercial production is also welcome.

The Mediterranean Sea has high water temperatures in summer and generally low productivity (Class III ecosystem—less than 150 g C/m^2 year) [46]. Therefore, the most suitable sites for macroalgae production are along the coasts near urban areas and estuaries, where production is high, and in some parts of the Adriatic Sea, where eddies and upwelling increase productivity [46].

The decision whether to cultivate macroalgae on land, in nearshore or in offshore facilities depends on the species, the chosen location and the cultivation facilities. However, the nearshore macroalgae farms have great advantages over the other two options as they help bioremediate nutrient-polluted coastal waters [128] and require less cost and labour [34]. Locations that are sufficiently exposed to waves and currents (semi-exposed sites) are desirable for the cultivation of macroalgae, as they ensure an even supply of nutrients to the cultivated species, but can also reduce the quality of the product due to mechanical damage [118]. The depth range for cultivating macroalgae is between 2 and 50 metres [129], usually up to 27 metres on hard substrate, mostly gravel, but also on sand [118].

The global estimation of ecologically suitable areas for macroalgae cultivation, suitable for 21 commercially farmed macroalgae species based on environmental data on 12 abiotic variables related to macroalgae distribution (depth, distance from land, salinity, sea surface temperature, pH, wave height, dissolved oxygen, nitrate, etc.), revealed some interesting facts [130]. The study concluded that for Tunisia, Slovenia, Croatia, Montenegro and Albania, more than 75% of the area in their Exclusive Economic Zones (EEZs) is ecologically suitable for macroalgae cultivation, while for Greece, Türkiye and Italy, between 50% and 75% of their EEZs is suitable for macroalgae cultivation [130].

As the development of mariculture depends on the availability of sites, the establishment of Allocated Zones for Aquaculture (AZAs) is an important tool for the development of macroalgae farming in combination with IMTA practises. The inclusion of macroalgae cultivation in the IMTA does not require too much space, as macroalgae can grow in a vertical garden near the fish cages [131]. Offshore IMTA can simultaneously solve the problem of competition for coastal sites and the high nutrient content required for macroalgae cultivation, but is logistically more complex and therefore more expensive [6].

Some of the common challenges for macroalgae farms related to environmental factors are as follows: decreasing water quality, nutrient deficiencies, extreme weather events, rising water temperatures, lack of high quality seedlings, natural predators, and low productivity [59]. Climate change is not only associated with extreme weather events and rising water temperatures, but also promotes increased grazing and more frequent and severe disease outbreaks [132].

The suitability of certain areas for macroalgae production depends not only on environmental factors, but also on socio-economic factors (quality of legislation and logistical performance, including administrative efficiency and quality of trade infrastructure) [30]. The socio-economic challenges for macroalgae farms are related to strict policies on cultivation areas, poor access to capital, lack of labour, high labour costs, poor market access and price fluctuations [59].

Additional challenges to the expansion of macroalgae cultivation include competition with other commercial/recreational activities, the negative public perception of extensive farming systems visible from the coast, slow and complicated administration, difficulties in commercialising products, local markets, investment in research and innovation, and low cooperation between countries [133].

4.4. The Limitations and Possibilities of Production

Despite the strong historical connection between the Mediterranean countries, there is a large gap between the northern and southern Mediterranean countries in terms of natural resources, political context and, above all, the development gap [48]. It is interesting to note that despite the long coastline and strong maritime identity, the Mediterranean region is facing a growing seafood deficit and only six countries (Morocco, Tunisia, Türkiye, Albania, Croatia and Greece) are exporters, while the others rely on imports [133]. Macroalgae production is one of the most promising sectors of the blue economy in the Mediterranean, not only for its environmental and economic benefits, but also for the social benefits of providing a reliable food source and creating new jobs [58]. It represents a valuable nature-based solution to mitigate climate change and restore coastal ecosystems, including protecting the coast from natural and man-made hazards [134].

Macroalgae production fits perfectly with SDG 12: Responsible production and consumption, as macroalgae are abundant, and the fast-growing organisms and the cultivation methods are environmentally friendly, without the need for fertilisers and with low resource requirements (fresh water and space). One of the main advantages of macroalgae cultivation and harvesting is the relatively simple technology and the short time span from start to harvest [27]. As the cultivation of macroalgae is a more sustainable option for wild macroalgae populations than wild harvesting, efforts to promote and commercialise macroalgae production in the Mediterranean should be prioritised over simple harvesting methods. In addition, the large-scale production of macroalgae offers higher quality, product traceability and predictable biomass, providing a solid foundation for any long-term development strategy. As the large-scale expansion of macroalgae cultivation can threaten biodiversity and marine habitats [55], the selection of suitable cultivation areas and species, together with regular monitoring, is crucial to minimise environmental risks.

In the Mediterranean region, the production of macroalgae is marginal compared to global or even European production. There are only a few locations where macroalgae are harvested or cultivated on the Mediterranean coasts, even in countries with a long tradition of macroalgae harvesting on their Atlantic coasts, such as France or Spain, or in Israel, the pioneer of macroalgae cultivation in the Mediterranean. According to some authors [58], the low number of macroalgae producers in the region and the slow transition from pilot projects to the full commercialisation of macroalgae production, especially in the macroalgae farming sector, is held back by the lack of national strategies and incentives to support private small and medium enterprises, and the link between incubators/accelerators and maritime clusters.

The lack of co-operation and support is not the only problem in this sector. On the one hand, there are the higher costs of macroalgae production outside East Asia and, on the other, there is a lack of harvesting and consumption traditions in the Mediterranean region, with a few exceptions. The low production of macroalgae goes hand in hand with the low consumption, which is related to the lack of local supply of macroalgae, the health and safety risks associated with human consumption hazards (microbiological and chemical (excessive iodine, heavy metals, allergens)), legality, and the lack of knowledge of the nutritional properties of macroalgae [21,77]. The consumer's ambiguous perception of macroalgae is sometimes related to the lack of attractiveness of the sensory properties (appearance, odour, flavour, taste, and texture of foods detectable by human senses) [135,136].

In order to make macroalgae more appealing as a food, the adaptation of products to regional tastes is essential for the development of the macroalgae food market in the Mediterranean [27]. According to the paper on the Italian edible macroalgae market [95], it is a promising sector because Italian consumers want to eat macroalgae, as they are familiar with macroalgae in Asian dishes and in national dishes. Besides a new food design, new marketing strategies are also important to promote the consumption of macroalgae in the Mediterranean region, including publicity campaigns about health and the sustainability effects of macroalgae consumption. An example of good practice to popularise the consumption of seaweed is the Chilean project Here we eat seaweed, which aims to diversify restaurant menus by including new seaweed-based recipes [21].

One of the advantages of macroalgae as a commodity is that it can be certified and promoted as a sustainable, organic, healthy, vegan, macrobiotic and halal food, making it more recognisable on the market. The Marine Stewardship Council and the Aquaculture Stewardship Council published the Seaweed Standard (ASC-MSC Seaweed Standard) in 2017. The joint Seaweed Standard ensures the sustainability of wild harvesting and farming, taking into account the sustainability of wild populations, environmental impact, effective management, social responsibility and community relations [137]. As macroalgae fit well with the green consumption trend and the environmentally friendly lifestyle in Western societies [77,138], the Mediterranean countries could also benefit from the expansion of the European macroalgae market.

Considering all the benefits associated with the production and consumption of macroalgae (SDG 3: Good health and well-being, SDG 12: Responsible production and consumption), macroalgae are an underexploited seafood resource in the Mediterranean. The report of the General Fisheries Commission for the Mediterranean (GFCM) on the status and future of seaweed farming in the Mediterranean and Black Seas points out that an improvement in data quality and close cooperation between all stakeholders, as well as improvements in legislation and funding, are needed to unlock the full potential of seaweed [139]. A multi-stakeholder platform for knowledge exchange and capacity building on the technical, market and regulatory aspects of macroalgae cultivation has been established, working with producers and research institutions to develop best practices and create a regulatory framework for responsible macroalgae cultivation [139].

The important initiative is the COST (European Cooperation in Science and Technology) Action Tomorrow's Wheat of the Sea: Ulva, a Model for an Innovative Mariculture (SEAWHEAT) CA20106 (https://seawheatcost.haifa.ac.il/ (accessed on 11 June 2024)). It was approved by the European Committee in 2021 with the aim of developing an Ulva-based blue biotech industry in European algaculture and beyond. One of the objectives of this action is to create an efficient network of stakeholders (scientists, producers, end-users, policy makers, NGOs, and the public), dealing with all aspects of *Ulva* spp.

Mediterranean countries have recognised the importance of the seaweed sector and, in the document Towards a Sustainable Blue Economy in the Mediterranean Region (2021), which deals with governance, research and innovation in the region, the seaweed sector is one of the priorities related to the diversification of mariculture products. The African Mediterranean countries are part of the Blue Belt Initiative, which is an important African instrument to support blue strategies and was launched by Morocco in 2016. One of the strategic objectives for the period 2023–2027 is the development of large-scale seaweed culture, which involves developing and expanding the techniques and diversity of macroalgaculture on open waters, developing the controlled reproduction (sporulation) techniques of seaweed, and supporting the development of land-based marine microalgae farming. One of the most important projects funded by the European Union is the Building the blue biotechnology community in the Mediterranean (B-Blue, 2020–2022) project, funded under the Interreg Mediterranean programme, which aims to create a cluster in the Mediterranean region as well as creating four value chains, including algae production for high-value compounds and sustainable IMTA [140].

In order to develop the edible macroalgae sector in the Mediterranean, it is necessary to invest in research and innovation in the field of cultivation, especially in native species, to avoid wild harvesting due to the risk of overexploitation [141]. Additional efforts should be made to close the identified research gaps in the biology of the Mediterranean macroalgae species (especially *Ulva* spp.). It is also necessary to enable a continuous flow of funding through structural investments, dedicated tax schemes, grants and loans [58]. Most importantly, strong cooperation and the continuous innovation of production and processing technologies, and capacity building, will make the Mediterranean macroalgae sector viable.

5. Conclusions

This paper gives an overview of the production of edible macroalgae on a global scale, but also in Europe and the Mediterranean, emphasising that data on macroalgae production in the Mediterranean are scarce and fragmented. The most abundant and popular edible macroalgae worldwide are listed, as well as the most promising edible macroalgae suitable for human consumption in the Mediterranean region. The taxon identified as the most promising for future cultivation in the region is *Ulva* spp. The paper also highlights some of the limitations of macroalgae production in the region, as well as the possible benefits of commercial macroalgae cultivation.

The Mediterranean is the largest and deepest enclosed sea, densely populated along its coasts, with a long and rich history and great cultural significance. The population of the Mediterranean coastal region will grow to 690 million people by 2050. As the population grows, so will human activity and the associated risks to the coastal environment and coastal communities. Mediterranean countries are already struggling with a deficit in food production due to the limited availability of water and agricultural land. In the future, population growth and climate change will further exacerbate the food deficit and dependence on food imports. The expansion of macroalgae cultivation and the popularisation of macroalgae eating habits can also help to combat unhealthy eating habits and promote the consumption of locally produced, better quality food in the Mediterranean region. The expansion of macroalgae production in the region can also contribute to the restoration of coastal ecosystems and associated ecosystem services, while promoting the socio-economic prosperity of vulnerable coastal communities.

Unfortunately, the sector is currently hampered by the lack of a tradition regarding macroalgae production and consumption in the Mediterranean, high production costs and the absence of local supply chains. Other challenges include the lack of national strategies and incentives to support companies, the lack of knowledge about the nutritional properties of macroalgae and sometimes the negative perception of macroalgae products by consumers. The European countries with experience in macroalgae cultivation on their Atlantic coasts (France and Spain), and the North African countries that are investing heavily in scientific research on macroalgae (Israel, Egypt, Tunisia and Morocco), should work together to commercialise the current pilot projects on edible macroalgae cultivation and lead the way for the rest of the region. In addition to the COST Action SEAWHEAT, further joint efforts are needed to address identified research gaps in the biology of Mediterranean macroalgae species (especially *Ulva* spp.), share information and knowledge from other regions, support capacity building, continuously innovate production and processing technologies, and responsibly manage natural and cultivated macroalgae resources. These efforts should also include customised campaigns to increase the acceptance and attractiveness of macroalgae consumption in the Mediterranean region and open up new potential research avenues in the ever-changing world.

It is obvious that the development of the edible macroalgae sector in the Mediterranean is a complex task with many economic, social and environmental challenges, but at the same time it is a promising sector with an exciting research landscape.

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