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Review

Bio-Based Products from Mediterranean Seaweeds: Italian Opportunities and Challenges for a Sustainable Blue Economy

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Abstract: Seaweeds are attracting increasing attention as an alternative healthy food and renewable drugs source and as agents of climate change mitigation that provide essential ecosystem services. In this context, seaweeds represent marine resources capable of supporting and pursuing the objectives of the Sustainable Blue Economy and the Bio-Based Circular Economy. In this review, we analyze the state of seaweed bio-based products and research on the Mediterranean Sea from the last 20 years. Results of this analysis show a large number of investigations focusing on antimicrobial, antioxidant and anti-inflammatory activities compared to on biofuels and bioplastics. Attempts at seaweed farming, although generally very limited, are present in Israel and some North African countries. Lastly, we focus on the Italian situation—including research, companies and legislation on seaweed production—and we discuss gaps, perspectives and challenges for the potential development of a sustainable seaweed industry according to the Sustainable Blue Economy.

Keywords: seaweed applications and production; Mediterranean Sea; bio-based products; Sustainable Blue Economy; Italian bioeconomy

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1. Introduction

Ocean-based natural capital, defined as the world's stocks of ocean assets that include biotic and abiotic components, provides to humans a wide range of ecosystem services (ESs). These include natural goods, such as food, raw materials and genetic resources, but also carry out functions, such as purification of air and water, climate regulation, pollination, protection against extreme events and many others ecosystem functions which benefit human well-being [1]. The ESs framework was, indeed, designed with the aim of including those benefits into decision-making processes in order to facilitate the transition of the global economy towards a sustainable state [2–4].

Among biotic resources, seaweeds (or macroalgae) are attracting increasing attention as alternative healthy food sources to feed the growing human population and as a renewable source of food supplements and drugs and as providers of essential ecosystem services such as the reduction of greenhouse gasses. Although analysis of seaweed production and its industrial use exists on a global scale, there are no surveys focusing on the entire Mediterranean area. In this review, keeping in mind ecosystem services delivery and the Sustainable Blue Economy, we analyze the current state of research and production of seaweeds in the Mediterranean Sea, one of the world's biodiversity hotspots. We conclude with a focus on the Italian context and discuss gaps, prospects and challenges for the potential development of a sustainable seaweed bioeconomy.

2. The Global Sustainable Bioeconomic Framework

The Blue Growth concept globally recognizes the marine space as an environmental and socio-economic system in which, through the principles of nature conservation, sustainable development and holistic management of human activities, 'the potential of our seas and oceans for jobs and growth' can be realized [5,6]. Blue Growth also assumes that additional value can be gained from managing diverse marine uses (e.g., fisheries, shipping and tourism) and marine ecosystem services (e.g., food provisioning, coastal protection and carbon storage) jointly rather than managing them separately [7].

Recently, the EU proposed a new approach named the Sustainable Blue Economy which is essential for achieving the objectives of the European Green Deal and ensuring a green and inclusive recovery from the pandemic [8]. Economic activities at sea and in coastal areas will need to reduce their cumulative impacts on the marine environment, and value chains will need to transform themselves to contribute to climate neutrality, zero pollution, a circular economy and waste prevention, marine biodiversity, coastal resilience and responsible food systems. At the same time, the Bio-Based Circular Economy has gained increasing attention [9,10]. This approach is based on: (i) the use of renewable biological (bio-based) resources (e.g., crops, animals, seaweeds, etc.) and their conversion into other products such as feed, materials for manufacturing and energy; (ii) the application of a closed-loop resource management system (circular economy), using reducing, reusing and recycling activities throughout; (iii) the maintenance of products, materials and resources for as long as possible [11,12].

3. The Seaweed Effectiveness: From Ecological Functions to Bioeconomy Contribution

Seaweeds play a key ecological role in marine environments, from temperate to polar ecosystems, contributing to ecosystem production, biodiversity and functioning. By producing oxygen and being a primary food source for several marine herbivores, seaweeds sustain complex food webs, contributing to particulate and dissolved matter cycling (carbon, nitrogen, phosphorus and other elements) [13–15]. Many seaweeds are structuring species as they provide a diversity of micro-habitats and ecological niches and serve as shelters and feeding, reproductive and nursery areas for a very highly diverse range of associated plants and animals, including species of economic value. The seaweed canopy provides protection to marine organisms from excessive light and predators and modifies the environment by changing hydrodynamic and sedimentation rates [16]. Moreover, by attenuating the energy and the wave motions [17], the canopy can influence sediment stability and particle retention, thus, protecting tidal areas from erosion [18].

All these ecological functions contribute to important ESs, including climate change mitigation, carbon sequestration [19–21], regulation of extreme eutrophication and absorption of toxic substances and heavy metals [22,23]. Moreover, apart from serving as a primary food source for marine herbivores, seaweeds can be directly consumed by humans and farmed animals in a wide variety of formats, directly contributing to market benefits and to human well-being (Figure 1).

Figure 1. Functions and benefits of seaweeds and its derived products; data source from Vincent et al. [24] and references therein.

To date, around 221 species of seaweeds have commercial value, and the global seaweed industry is worth more than USD 6 billion/year (~12 million tons/year in volume), of which more than 150 species (85%) are food products for human consumption [25]. Edible seaweeds can be used for food consumption and as a dietary supplement, providing a variety of nutrients essential to human health, including high levels of essential fatty acids and amino acids and low-calorie content [26–28]. Increasing attention is also focusing on the nutritional value of seaweed species, due to their high content of natural vitamins, minerals and proteins [29].

Seaweeds produce a variety of natural compounds called biometabolites, with a broad spectrum of biological activities (i.e., cytostatic, antiviral, anthelmintic, antifungal and antibacterial activity) extensively documented in the literature [30–35], which find application as the active ingredients of drugs or supplements. Biometabolites production may be different within the same species and dependent on environmental factors. This plasticity makes seaweeds ideal candidates for the screening of both new and known compounds with bioactive potential for the development of new sustainable, economic and environmentally friendly drugs [36].

Different and new bio-based materials produced by seaweeds are continuously being investigated. The superior performance of their manure compared to the conventional organic one has been reported, as well as the effectiveness of seaweed as a source of stimulants in agriculture and horticulture [37,38]. This efficacy covers broad aspects, such as seed germination, better root development, enhanced frost resistance, increased nutrient uptake, resistance to phytopathogenic organisms and higher yields with the better restoration of plant health under high-salinity conditions [39–41]. The use of seaweed is proposed as an efficient and natural solution to overcome the threats caused by the extensive use of chemical fertilizers, considering that, in 2014, over 120 million tons of fertilizer was used, of which, about 15–30% was released into the ocean [41].

Seaweeds rich in polysaccharides show a wide range of industrial applications and are increasingly used as third-generation biomass. The production of biofuels—biomethane, bioethanol, biodiesel and bio-oils—can be achieved by different conversion methods of seaweed biomasses, especially the brown ones, including anaerobic digestion, fermentation, transesterification, liquefaction and pyrolysis processes [42–46]. According to Suutari et al. [43], however, biofuel production from dedicated seaweed farming is not yet economically sustainable. These authors suggest that sustainable chain production could be achieved by using industrial seaweed residues. Recently, research has focused on sulfated polysaccharides (agar, carrageenan and alginate) as a starting material and an additive for bioplastic production, helping to generate a sustainable product and, at the same time, reduce the environmental impact. Furthermore, as reported by Dang et al. [47], a desirable bioplastic quality can be obtained by the manipulation of specific functional groups, such as the carboxyl, hydroxyl and sulfate functional groups. In addition to the plastic for bags and packaging, seaweed polymers are used to replace synthetic polymers in textiles [48,49], biomedical instruments and drug delivery systems [50,51] and in 3D modelling [52,53].

The demand for seaweeds and their products is constantly growing globally, leading to improved materials, cultivation and processing technologies at the same time [54]. Several market studies indicate that seaweed product innovation in Europe is second to the Asian and the Pacific regions, which achieve more than 80% of seaweed product innovation [25]. Moreover, the activities related to the use of marine algae fall into those sectors (i.e., aquaculture, biotechnology, renewable energy) that have a high potential for sustainable jobs and growth, according to the above concepts of the Sustainable Blue Economy and the Bio-Based Circular Economy.

4. Seaweed Research, Production and Use in the Mediterranean Basin

The Mediterranean Sea is only 0.82% of the surface area and 0.32% of the volume of the world's ocean; nevertheless, it represents the largest and deepest enclosed sea and marine biodiversity hotspot [55,56]. About 1,124 seaweed species are reported in the Mediterranean Sea, of which at least 20% is endemic [57]. The current high biodiversity of the Mediterranean Sea is the result of geological events, such as the closure of the Strait of Gibraltar and the resulting drastic changes in salinity, climate and sea level, but also anthropogenic events, such as the opening of the Suez Canal. The Mediterranean Sea has multiple uses and pressures; fishing pressure, the introduction of non-indigenous species

(NISs) and climate change cause major changes in Mediterranean marine biodiversity, as does the presence of humans, such as vessel traffic and tourism, underwater noise and pollution [58]. Furthermore, since the Mediterranean basin is surrounded by 21 states belonging to three continents (Europe, Asia and Africa) and is characterized by a vast political heterogeneity, different coastal management policies and aquaculture activities are in place. An updated overview of the governance, research and innovation in the Mediterranean region is reported in the "Blue Economy in the Mediterranean Report" [59], which includes the marine and maritime economic and safety sectors of particular interest to the Sustainable Blue Economy. Within this document, "algae" are included in one of the goals for the diversification of mariculture products to be pursued over the next ten years [59].

We extrapolated data through a literature search covering the past 20 years of research on the properties and potential applications of Mediterranean seaweeds, which are shown in Table S1. Among the various phyla of seaweed, Rhodophyta is the most investigated (Figure 2a). A large amount of published data refers to the antimicrobial activity, followed, in a smaller percentage, by the antioxidant and anti-inflammatory activities of seaweed extracts [60–126], whereas only a few studies reported on seaweed bio-products [127–139], such as biofuels and bioplastics (Figure 2b). Among Mediterranean countries, Tunisia, Italy and Egypt were the ones with the largest number of published papers focusing on the potential applications of Mediterranean seaweeds (Figure S1), including NISs.

To date, few Mediterranean countries, such as Spain, Morocco and Tunisia, harvest seaweed from the wild or farm it and also do so only in low quantities [140,141]. The harvesting of seaweeds is not an industrial activity practiced in this area since natural seaweed production is low and not appropriate for meeting industry demand when compared to oceanic resources. Furthermore, the absence of very significant tidal excursions in most of the Mediterranean basin limits the abundance of accessible raw material and, hence, the development of harvesting techniques. Mediterranean aquaculture to date has been primarily focused on the production of fish [142], whereas seaweeds have received increasing attention only lately and in a few North African countries [140].

By integrating data obtained from a web search with those obtained from the EMODnet 2022 (www.emodnet-humanactivities.eu/view-data.php (accessed on 25 February 2022)) and the Phyconomy Seaweed (https://phyconomy.net/ (accessed on 16 February 2022)) databases, we compiled a list (which is not meant to be exhaustive) of the main companies and start-ups working on the production and/or processing of seaweed products in the Mediterranean region (Table 1).

In the eastern Mediterranean basin, Israel is undoubtedly a pioneer country in land-based seaweed cultivation [143,144], and its advanced technologies have been adopted by emerging local companies and exported abroad [145]. In Israel, the preferential use of tanks and ponds for seaweed culture is due to the conformation of its coastline [144]. Detailed culture techniques and approaches for producing seaweeds were published as early as 1982 [145], whereas cultivation surveys of *Ulva* sp. and *Gracilaria* sp. in nets or single-layer lines were only recently tested [129,146]. These two species are among the most cultivated by local companies for human consumption (Seakura Ltd., Mikmoret, Israel, www.seakura.co.il (accessed on 21 February 2022)) or for cosmetics and veterinarian products [145] (Sealaria Ltd., Haifa, Israel, www.sealaria.co.il (accessed on 21 February 2022)). Along the Adriatic and Ionian Sea coasts, algal production is restricted to microalgae [67] (e.g., *Spirulina/Arthrospira*) in Greece, whereas seaweeds have received less attention concerning their biological activities and nutritional composition (Table S1).

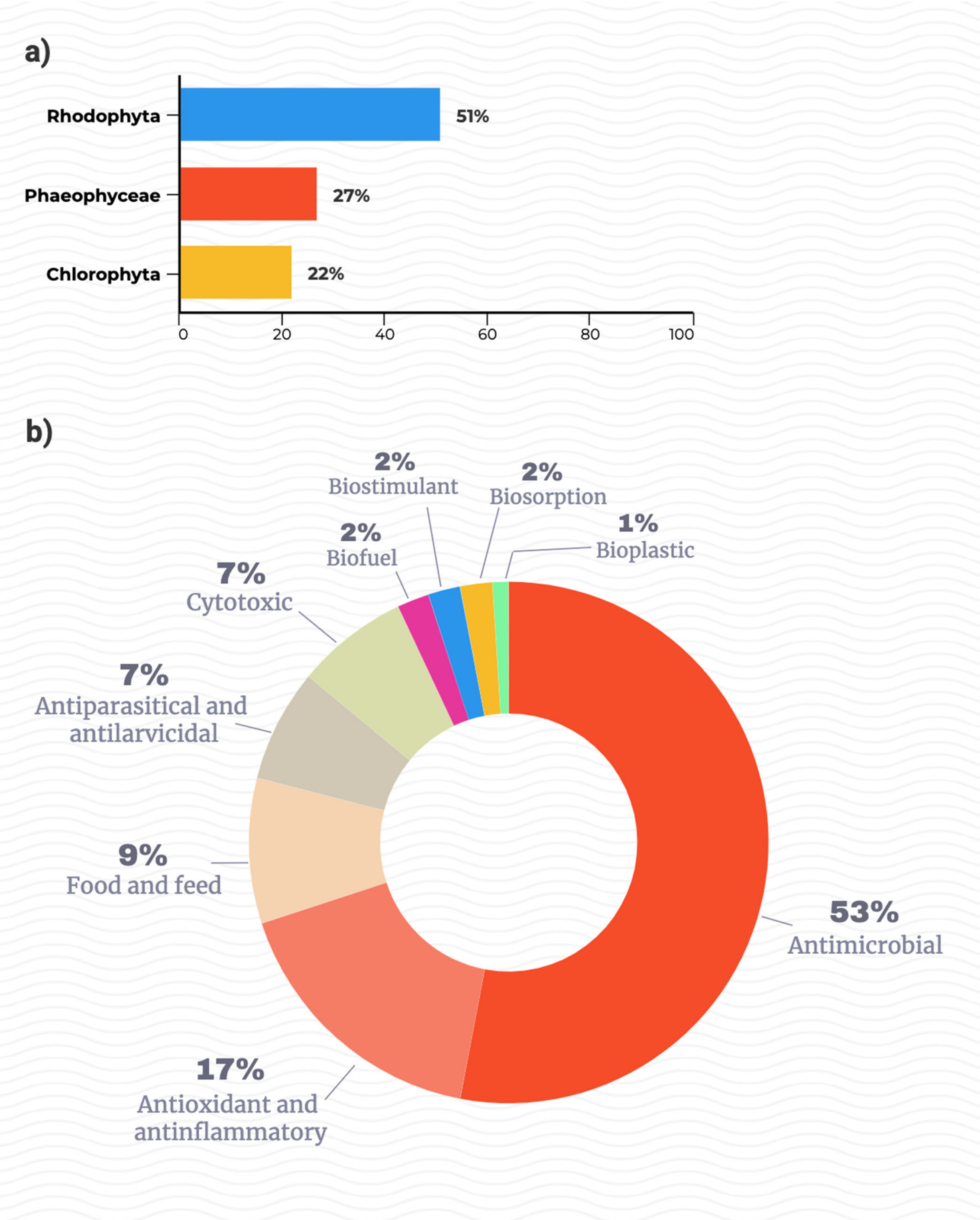

Figure 2. State of research on Mediterranean seaweed uses in the last 20 years: (**a**) Percentage of seaweed phyla investigated for their properties and potential applications; (**b**) Percentage of the main seaweed applications and products investigated for the Mediterranean Sea. Data from Table S1 and references therein.

Table 1. Main companies and start-ups working on the production or processing of seaweed products in the Mediterranean area. Data from web search with those obtained from the EMODnet 2022 (https://www.emodnet-humanactivities.eu/view-data.php (accessed on 25 February 2022)) and the Phyconomy Seaweed database (https://phyconomy.net/ (accessed on 16 February 2022)).

Country	Industry Name	Value Chain	Species	Products
France	Eranova	Farming and harvesting; applications	*Ulva* sp.	Bioplastics
Israel	Seakura Ltd.	Farming and harvesting; applications	*Ulva* sp.; *Gracilaria* sp.	Nutraceuticals
Israel	Sealaria Ltd.	Farming and harvesting; applications	*Gracilaria* sp.	Nutraceuticals and cosmetics
Israel	Y.A. Maof	Farming and harvesting	*Sargassum* sp. *	Biogas
Israel	Biotic	Applications		Bioplastics
Israel	Algaeing	Applications	seaweeds	Textile
Italy	FAVINI	Applications	*Ulva* sp. *; *Gracilaria* sp. *	Paper
Italy	South Agro	Farming and harvesting; applications	*Ascophyllum nodosum* *; *Macrocystis* sp. *; *Laminaria digitata* *; green and red seaweeds	Biostimulants and Biofertilizers
Italy	Guam	Applications	*Laminaria digitata* *; *Fucus* sp. *; *Undaria pinnatifida* *	Cosmetics
Italy	Consonni Bioalghe	Applications	*Ulva* sp. *; *Fucus* sp. *; *Undaria pinnatifida* *; *Palmaria palmata* *; *Chondrus crispus* *; *Laminaria* sp. *; *Lithothamnum calcareum* *; *Saccharina latissima* *; *Porphyra* sp. *; *Himanthalia elongata* *	Nutraceuticals and cosmetics
Italy	Aboca	Applications	*Fucus vesiculosus* *	Nutraceuticals
Italy	B&V Italy	Applications	*Gracilaria* sp. *; *Gelidium* sp. *; *Pterocladia* sp. *	Hydrocolloids
Italy	Prodotti Arca	Applications	*Ascophyllum nodosum* *	Nutrition and zootechnical products
Italy	Java Biocolloid Europe	Farming and harvesting; applications	*Gracilaria* sp. *; *Gelidium* sp. *	Hydrocolloids
Italy	Specialagri	Applications	brown seaweeds *	Biostimulants and biofertilizers
Italy	Forfoods	Applications	*Ulva* spp.	Food
Slovenia	EKOGEA	Applications	*Ascophyllum nodosum* *	Biostimulants
Spain	Mediterranean Algae	Farming and harvesting	*Ulva lactuca*	Cosmetic products; alimentation; biofertilizers
Tunisia	SELT Marine Group	Farming and harvesting; applications	*Gracilaria* sp.; *Gelidium sesquipedale*; *Kappaphycus alvarezii* *; *Eucheuma spinosum* *; *Ulva lactuca*	Hydrocolloids

* imported raw materials.

Among the North African countries (southern Mediterranean coastlines), seaweed has not attracted as much aquaculture interest as bivalves and fish [56]. For example, in Egypt, massive use of seaweeds is still an emerging field and is limited to pilot studies on the chemical characterization of some potentially usable species [68,147,148] (Table S1), including NISs such as *Grateloupia gibbesii* [147]. In Tunisia, several studies were performed on the properties of seaweeds (Table S1), and many of these were mainly focused on the culture of the most promising species, the red agarophytic alga *Gracilaria gracilis* in the Bizerte Lagoon. The SELT Marine Group (http://www.seltmg.com/ (accessed on 21 February 2022)) is the only farm industry in Tunisia for the manufacture of agar and carrageenan, produced from the cultivation of local algae, as well as from algae originating from non-Mediterranean countries such as Mozambique and Zanzibar. As reported by Ktari et al. [56], the export of seaweed phycocolloids from Tunisia amounted to 109.7 tons in 2015, 95% of this being agar. The harvesting and cultivation industries present in Morocco operate mainly with seaweed species from the Atlantic coasts.

Regarding the northern Mediterranean countries, France supports the largest number of macro- and microalgae companies in Europe; however, 90% of its production originates from the Atlantic coast [141]. Along the Mediterranean coast, Eranova (/eranovabioplastics.com/ (accessed on 25 February 2022)), a French, pilot, land-based system, uses green macroalgae stranded on beaches as a resource for the production of bio-based, recyclable and compostable resins. Several pieces of research on seaweed properties, including the antifouling activity of *Dictyota* sp. and the properties of agars from *Gracilaria dura* and *Gracilariopsis longissima*, were conducted in the Brusc and Thau Lagoons (Table S1). In Spain, the utilization of seaweed resources was mainly developed on the northwestern coast, where monospecific stands of red and brown macroalgae occur. The Spanish start-up Mediterranean Algae (https://www.mediterraneanalgae.com/ (accessed on 20 February 2022)) is dedicated to the land-based cultivation of Mediterranean *Ulva* spp. To obtain biomass and bioactive compounds with high added value for different applications such as human food, biofertilizers and cosmetics.

5. Current Status of Seaweeds Production and Research in Italy

5.1. Biodiversity and Traditional Use of Seaweeds

The Italian floristic list of seaweeds includes over 800 taxa [149]. According to biogeographical origin, seaweed biodiversity is characterized by a high incidence of Atlantic taxa (41.87%), followed by Mediterranean (25.74%) and cosmopolitan ones (21.51%), whereas a lower percentage has Indo-Pacific (5.06%), Circumtropical (4.03%) and Circumboreal (1.79%) origins [149]. Italian seaweed biodiversity is characterized by peculiar paleoendemisms, such as the brown algae *Saccorhiza polyschides*, *Laminaria rodriguezii* and *Fucus virsoides.* Around 65 macrophytes were reported as NISs, the expansion and introduction of which were facilitated by the presence of human activities [150]. However, according to taxonomic and molecular revisions, seaweed biodiversity data are constantly being updated and revised.

Although, in Italy, the use of seaweed does not have a solid and constant tradition compared to the countries of central and northern Europe, the first texts on seaweed uses date back to the period of the Roman Empire. In the *De re rustica* agriculture treaty by L. Giunio Moderato Columella (4–70 d.C.), it is reported as "the cabbage, when it has six leaves, must be transplanted, first spreading the liquid manure root and inserting it in the earth wrapped in three seaweed bands. For this use is made, so quickly and keeps the cooking and green colors without the use of soda".

In the Sicilian Egadi Islands, an aqueous extract made with a mixture of red algae was widely used to treat worm infections in children, and it was marketed out of the islands [151]. To date, the use of local seaweeds is limited to food and concerns localized folk customs, such as the Ulvaceae used in the "Italian fried" in Campania or the salads of red algae *Gracilaria*, called *mauru*, in eastern Sicily.

5.2. Research, Harvesting and Industrial Activity of Seaweeds

The first research activities on seaweed use in Italy were carried on during the Second World War (1940–1945) as part of a research project funded by the Central Laboratory of Hydrobiology of Rome for the production of agar-agar used in laboratories. At that time, the agar-agar was extracted exclusively from Gracilariaceae originating from Japan and the Indo-Pacific area, and the start of such studies in Italy followed the drastic reduction of products imported from the East. The red algae *Gracilaria* and *Gelidium* harvested from the Venice Lagoon turned out to be the most promising; consequently, several collection activities were started by local fishermen, and extraction was carried out by a local company [152]. With the end of the war, seaweed harvesting ended, although, in the 1980s, collection activities were still carried out for the production of agar but only for food gelatin. Since the 1960s, several pieces of research have been conducted to identify and to extract agar and alginic acid from seaweeds to be used in food and for pharmaceutical or cosmetic uses and as fertilizers. *Caulerpa prolifera*, abundant in the Marsala Lagoon (Sicily), showed good qualities as a technical zoo feedstuff, suggesting an industrial exploitation potential [153].

In the last ten years (Table S1), research has focused on the potential of seaweed extracts in the pharmaceutical field as antimicrobics [154–160], anticoagulants [161,162] and antidiabetics [64]. In the technological field, biomaterial as bio-oils [163] was obtained from *Gracilaria gracilis*, whereas chlorophylls from *Undaria pinnatifida* were tested as dye in photovoltaic cells [164]. Moreover, a cascade biorefinery approach for *Gracilaria gracilis* was developed by Francavilla et al. [163], as well as various extraction protocols [165,166].

Although Italy is among the top three countries in Europe for *Spirulina* production [141] according to FAO [25], it is only in 16th place for production of wild-stock seaweeds, producing 1200 tons in total, and it is not present among farming countries. In the early 2000s, the Italian food and pharmaceutical industries imported annually ~2000 tons of products derived from algal processing, as national production was insufficient [167]. The main reason for the absence of seaweed farmers was probably the high cost of initial investment and personnel; moreover, the absence of a supply chain made the final product uncompetitive compared to in other countries.

Industrial use of seaweed biomasses was successfully attempted in some Italian coastal lagoons. These ecosystems, often rich in nutritive salts, produce high quantities of seaweeds compared to other coastal environments. As reported by Petrocelli and Cecere [168], *Gracilaria gracilis* (as *Gracilaria confervoides*) was harvested in the Lesina Lagoon (southern Adriatic Sea) by local fishermen in the years 1970–1990 for agar extraction, yielding up to ~100 tons dry weight year^{-1}. Moreover, following its drastic overexploitation, *Gracilaria* field cultivation trials were carried out, increasing biomass to ~1200 tons dry weight year^{-1} [168].

According to our web search, the majority of Italian companies import raw material for their products (Table 1 and Figure 3).

In the Venice Lagoon (northern Adriatic Sea), Shiro Alga Carta is a type of paper designed and manufactured by the Favini Srl company (Rossano Veneto, Italy) (www.favini.com (accessed on 10 January 2022)). In the early 1990s, production started using the excess biomass of *Ulva* species in the lagoon, while, in recent years, the company has been using algae imported from Brittany to make up for the little biomass produced in the lagoon. Similar to the Favini company, the multinational B&V Italy (https://www.agar.com (accessed on 10 January 2022)), since the 1980s, has been using the biomass of *Gracilaria* spp. From the Venice Lagoon for the production of a full range of different agar types for food, bacteriological and technical applications [168]. To date, however, most of the seaweed biomass is imported from a farm located in Vietnam.

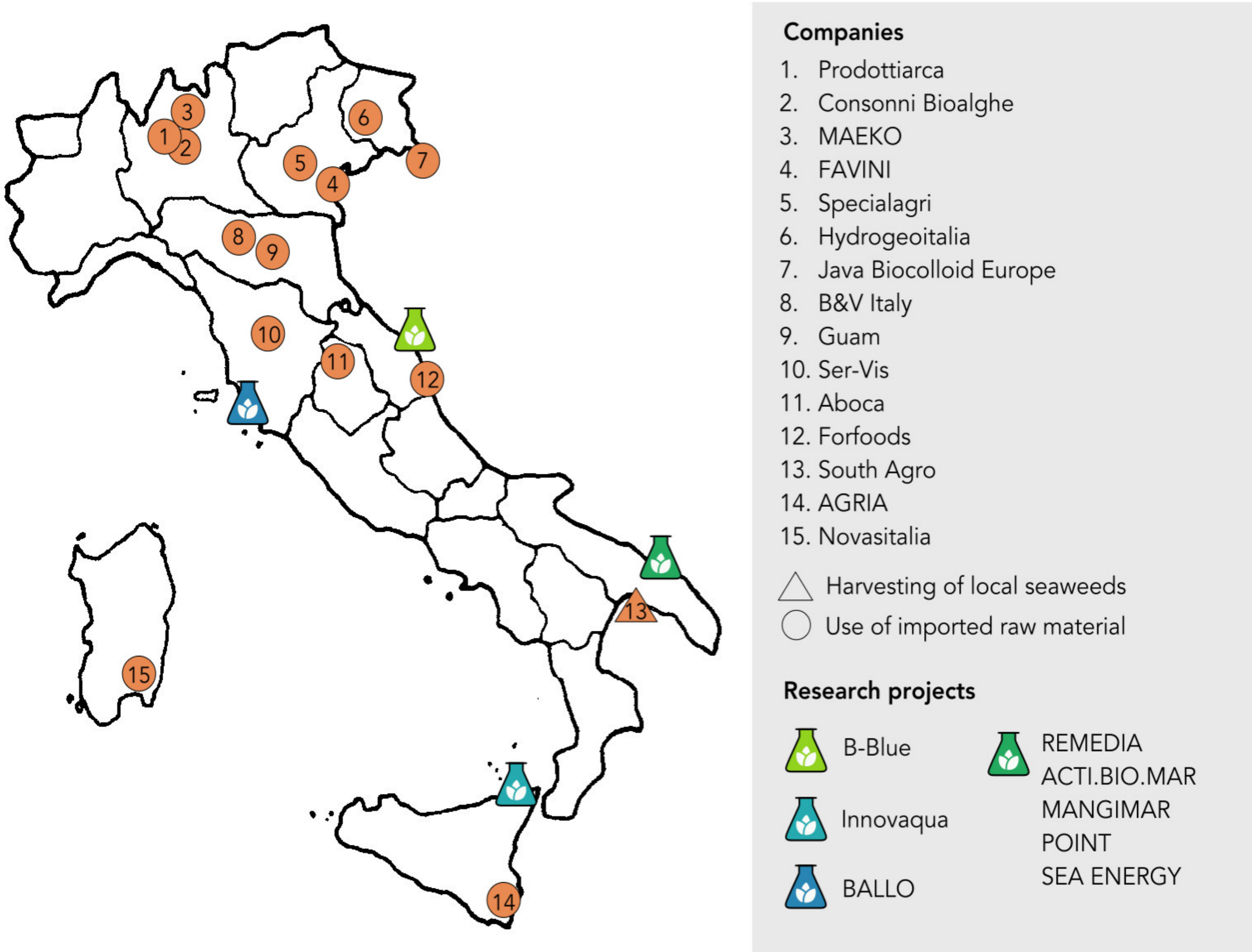

Figure 3. Companies and research projects related to seaweed uses in Italy.

Several companies sell mostly liquid and powder biostimulants based on the imported brown alga *Ascophyllum nodosum* from Atlantic coasts (Table 1). Among these, SouthAgro (Taranto, Italy) (https://southagro.com/ (accessed on 10 January 2022)) is the only start-up that, despite importing a quota of allochthonous biomass, cultivates and uses Mediterranean red and green seaweeds for the production of biostimulants and biofertilizer compounds.

In the field of wellness products, the Italian Guam brand (https://www.guam.it/ (accessed on 15 January 2022)) was created with the intention of developing an innovative anti-cellulite preparation based on dried seaweed from Brittany mixed with clay and natural extracts. To date, the range of products is particularly diverse, and the company continues to produce them thanks to the algae harvested in northern France.

Finally, a peculiar experience is that of the Java Biocolloids (https://www.java-biocolloid.com/ (accessed on 15 Juanuary 2022)), a leader company specializing in the production of agar and carrageenan, both for use in the food industry and the pharmaceutical sector. This Indonesian company created a branch in Trieste (northern Italy) to facilitate product distribution across Europe and to invest in research and innovation.

5.3. Italy's Commitment to Seaweed Research Projects in the Blue Economy

While companies linked to algal products are mostly distributed in northern Italy, in recent years, several research projects (Figure 3)—funded at a regional or European level—have been launched in southern Italy. The Apulia region has been particularly active in the context of the Sustainable Blue Economy and the Bio-Based Circular Economy.

The REMEDIA Life project—"Remediation of marine environment and development of innovative aquaculture: exploitation of edible/not edible biomass" (2017–2021)—tested an integrated, multi-trophic aquaculture (IMTA) system in the Adriatic Sea, including the cultivation of green algae *Chaetomorpha linum*, *Cladophora rupestris* and *Ulva prolifera* and the red algae *Gracilaria dura*, *Gracilaria gracilis*, *Gracilariopsis longissima* and *Hypnea cornuta* [64,168] (https://remedialife.eu/ (accessed on 16 February 2022)). The B-BLUE Project (2020–2022), financed under the Interreg MED Programme, aims to create a cluster in the Mediterranean in the field of marine biotechnology, including activities in the Adriatic Sea related to algae production for high-value compounds and sustainable, integrated, multi-trophic aquaculture (https://b-blue.interreg-med.eu/ (accessed on 15 February 2022)).

Different research projects focused on the extraction of secondary biometabolites for different uses. The MANGIMAR Project—"Innovative fodders from seaweeds and marine invertebrates" (2012–2014)—was funded by the Apulian Regional Administration for the formulation of fish feeds based on the green alga *Chaetomorpha linum* from the Mar Piccolo of Taranto. In this coastal lagoon, the ACTI.BIO.MAR Project—"Bioactive molecules from marine biomasses and their potential employment in pharmaceutics and dietetic" (2007–2010)—was funded with the aim of obtaining bioactive secondary metabolites from marine biomass, including polyunsaturated fatty acids (PUFA) of red algae *Gracilaria gracilis* and *Gracilaria dura* as improvers in the formulation of PUFA-rich food [109,168].

Some projects concerned the production of biometabolites or secondary products obtained from algae, which were used for bioremediation processes. This is the case with the INNOVAQUA Research Project—"Technological innovation for the improvement of the productivity and competitiveness of Sicilian aquaculture" (2012–2015)—funded by the National Operational Programme on Research and Innovation. The project focus was the use of active biomolecules extracted from Gracilariceae for the prevention and treatment of diseases of fishes. Actions were concentrated on the discovery of new substances with antibiotic properties and on the formulation of feed partially using biomass from *Gracilaria* spp. cultivated in fish farm wastewater. *Gracilaria gracilis* and *Gracilaria dura* from the Mar Piccolo were tested, as well in the POINT Project, in bioremediation to reduce nitrogen in seawater derived from mussel farming [168].

In the field of sustainable energy, the BALLO Project—"Biofuels from Algae in the Lagoon of Lesina and Orbetello" (2010–2011)—was funded by the Italian Ministry for Agricultural, Food and Forestry Policies with the aim of developing a sustainability assessment and feasibility analysis to produce biodiesel from seaweeds harvested in lagoons. The research consisted of the analysis of lagoon systems with the calculation of systemic indicators of environmental sustainability (https://www.ecodynamics.unisi.it/, (accessed on 15 February 2022)). The SEA ENERGY Project—"Sustainable Energy in Adriatic Regions: knowledge to invest"—financed under the Adriatic IPA Cross-Border Co-Operation Programme (2007–2013) focused on using Italian seaweed biomass harvested in the Adriatic Sea (Goro Inlet) for energy production. In this context, *Ulva* spp., *Gracilaria* spp. and *Chaetomorpha* spp. were tested for biogas production through anaerobic digestion [168].

Italy was involved as a partner in several EU projects investigating industrial processes and applications of microalgae and seaweeds, such as INTERCOME (INTERnational COmmercialization of innovative products based on MicroalgaE), SALTGAE (demonstration project to prove the techno-economic feasibility of using algae to treat saline wastewater from the food industry) and in the active COST Action (CA20106) on *Ulva* species as a model for an innovative mariculture.

6. European and Italian Strategies and Regulations on Seaweed Bioeconomy

Current EU political priorities (e.g., the EU Blue Growth Strategy, the European Green Deal and the EU Bioeconomy Strategy) favor a transition towards a sustainable economy, which favors the development of the algal-based, green industrial sector and the use of algae for sustaining the health of aquatic ecosystem.

In 2012, the European Bioeconomy Strategy 'paved the way for a more innovative, resource-efficient and competitive society that reconciles food security with the sustainable use of renewable resources for industrial purposes, while ensuring environmental protection' [169]. Italy has the third largest bioeconomy in Europe after Germany and France, with EUR 330 billion annual turnover and two million employees [170]. In 2019, the Italian Bioeconomy Strategy (BIT) was implemented (BIT II) [171] for greater interconnection of the key pillars: primary production, the food industry, bio-based industry and the blue bioeconomy. The main goal of BIT II is a 15% increase in turnover and employment in the Italian bioeconomy by 2030. Based on Italy's strategic geopolitical position in the Mediterranean basin, BIT II also includes actions to improve sustainable productivity, social cohesion and political stability through the implementation of bioeconomy strategies in this area. In addition to the BIT II, the National Program for Fisheries and Aquaculture supports the production and use of seaweeds at the national level (Figure 4).

Action plan	Opportunities and priorities		
National three-year program for Fisheries and Aquaculture (2022–2024)	Development of new integrated farming techniques (e.g., multitrophic aquaculture) for the production of new species (fish, shellfish and algae), to increase the competitiveness of companies, the range of products and innovations, optimizing farm management, reducing the environmental impact.		
	Food industry	Bio-based industry	Blue bioeconomy
Implementation Action Plan (2020–2025) for the Italian Bioeconomy Strategy BIT II	Research on alternative protein sources (including algae) utilizing existing industrial infrastructures anticipating climate change and novel food security needs.	New emerging technologies for capturing and converting CO_2 into fertilizers, chemicals and polymers; prominent national collections of organisms (including algae also from the sea); mapping the biomass supply - including novel and alternative feedstocks (marine biological resources) to develop strategies for different types of biomasses; developing a coherent policy framework and regulations promoting bio-based products, education, training, information and communication in the bio-based sector; exploiting trans-national synergies and complementarities in the Mediterranean area, also via initiatives like PRIMA and BLUEMED, aiming at the long-term coordination of European and non-EU countries of the whole Basin.	Environmentally safe practices for marine aquaculture (multi-trophic but and also offshore) and of robust aquaculture supply chains; promoting the production and processing of seaweed as possible sources of human edible proteins but also of biomass for the production of bio-based chemicals, pharmaceutical, materials, energy and methane.

Figure 4. Action plans to support the production of seaweed and derived products at the national level.

Several pieces of European legislation regulate seaweed end use and production, as well as its environmental monitoring and conservation. In addition, three Italian ministerial and legislative decrees regulate algal production (MD 03/04/2019) and algal use in medical products (LD 219/2006) and as fertilizers (LD 75/2010) (Figure 5).

Field	EU legislations	Italian legislations
Medicinal and cosmetic	Human Medicinal Products Directive (2001/82/EC) Veterinary Medicinal Products Directive (2001/83/EC) Cosmetics Regulation (1223/2009/EC) Regulation on Claims (655/2013)	Medicinal products for human use (LD 219/2006)
Food and Feed	Novel Food Regulation (2015/2283) Food Additive Regulation (1333/2008) Food Contaminants Regulation (1881/2006) Nutrition and Health Claim Regulation (1924/2006) Feed Materials Regulation (68/2013) Feed Additive Regulation (1831/2003) Feed Contaminants Directive (2002/32/EC) Food Contact Materials Regulation (1935/2004) Seaweed Contaminants Recommendation (COM 2018/464)	
Fertilizers and pesticides	Pesticide Residues Regulation (396/2005) Fertilizing Products Regulation (2019/1009)	Reorganization and revision of the regulations on the subject of fertilizers (LD 75/2010)
Energy	Renewable Energy Directive (2018/2001)	
Aquaculture	Fishery and Agriculture Products Labelling Regulation (1379/2013) Regulation on Access to Genetic Resources (511/2014) Regulation on use of alien and locally absent species in aquaculture (708/2007) Alien Species Regulation (1143/2014)	Production of animals and marine algae from biological aquaculture (MD 3/4/2019)
Environment	Habitat Directive (92/43/EEC) Environmental Impact Assessment Directive (97/11/EC) Marine Strategy Framework Directive (2008/56/EC) Water Framework Directive (2000/60/EC) Marine Spatial Planning Directive (2014/89/EU)	

Figure 5. European and Italian legislation for seaweeds end uses and aquaculture production.

7. Gaps and Perspectives of the Seaweed Based Bioeconomy in Italy

There are several limitations and gaps that need to be addressed in order to improve seaweed-based bioeconomy development in Italy. Here, we point out some of these limitations and provide potential perspectives, from basic research to that on the sustainable management of seaweed resources.

7.1. Research and Development

Although Italian aquaculture provides 150,000 tons of aquatic products farmed in 800 aquaculture sites based on land or in transitional and coastal waters, seaweeds are scarcely cultivated and are mainly imported from areas outside of the Mediterranean Sea. Very few industries use local raw materials, and only a small number of seaweed genera are currently being investigated in pilot-scale farming projects. Although, in the last 20 years, Italy has conducted numerous pieces of research on the application potential of seaweeds (Figure S1), the industrial level has not yet been developed. To achieve a robust research and development plan, it is necessary to invest in knowledge of seaweed biology (e.g., diseases and pests, reproduction, etc.), as well as in the optimization of farming technologies, including farm design and seeding techniques, by increasing collaboration and attracting skills from abroad. Other relevant issues are related to genetic conservation and the maintenance of biodiversity, including the evaluation of the seaweed natural capital. As reported by Barrento et al. [172], an essential tool for producing better strains for commercial seaweed species is the creation of national germplasm banks, which ensure the preservation of desirable local traits and genetic diversity at the same time.

7.2. Economy

Although there are important deficiencies in legislation and in new technology applications, the bioeconomy offers an interesting new approach, able to transform something unwanted or little valued into a resource. In this context, the major challenge is related to obtaining increased funding for the creation of a new supply chain that leads to socio-economic development, as well as to the sustainable management of seaweed production. In this sense, different international and national initiatives could contribute to a greater synergy among researchers and companies, i.e., the Blue Italian Growth Technology Cluster (BIG TC) (https://clustercollaboration.eu/content/blue-italian-growth-technology-cluster-big-tc (accessed on 7 March 2022)), the Safe Seaweed Coalition (https://www.safeseaweedcoalition.org/ (accessed on 16 February 2022)), Biovoices (https://www.biovoices.eu/ (accessed on 23 March 2022)) and others.

7.3. Resource Management and Conservation

New original ideas and visions of sustainable seaweed production in Italy and in the whole Mediterranean basin are needed and might even consider the coupling of integrated aquaculture and mariculture activities with environmental restoration and conservation practices.

As a response to multiple stressors, including eutrophication, increasing coastal sediment loads and the impacts of urbanization, wild stocks of Mediterranean seaweeds are being lost at alarming rates [173]. It is, therefore, widely recognized that a transition from wild harvesting to seaweed aquaculture is needed to meet the growing industrial demand, while avoiding the overexploitation of wild stocks. In order to maintain algal genetic diversity and wild stocks, resource conservation strategies should be put in place. There are several advantages to be gained from improving restoration measures (in addition to protection and conservation) of declining natural seaweeds stocks, as their health status is a prerequisite for maintaining ecosystem services and preserving genetic diversity. Restoration is possible only if basic information about seaweeds species, protocols and the areas to be restored are carefully addressed [174]. In this regard, a roadmap for Mediterranean macroalgal restoration has been recently proposed to assist researchers and stakeholders in decision making and considering the most effective methods (which also include the outplanting of farmed seaweeds) in terms of cost and cost effectiveness [173].

Seaweed cultivation for commercial use is only slowly attracting attention in the Mediterranean area, since several problems still persist, mainly in relation to the availability of suitable sites and nutrients and to their potential impacts on the surrounding environment. In particular, in this area, the high level of competition for coastal space utilization suggests that moving production offshore could be a solution (e.g., exclusive economic zones) [145]. Moreover, in these waters, the scarcity of nutrients could be overcome through the development of integrated, multi-trophic aquaculture systems. These could be designed by coupling, for example, offshore fishing production with the farming of filter-feeder invertebrates and macroalgae, which act as efficient reducers of fish cage wastes [175]. Although offshore algal biomass production holds promise for its sustainability, it remains an extremely challenging endeavor due to logistical and cost implications [145].

A further interesting perspective could consider the use of NISs [176] as an opportunity for combining environmental management and bioeconomy benefits, as seaweed NISs' commercial uses could encourage their harvesting and control [177]. For example, the species *Undaria pinnatifida* has caused concern all over the world because it has invaded coastal environments, significantly altering non-native habitats and disturbing navigation. In Italy, this species produces a large amount of biomass during its seasonal blooms, causing inconveniences for navigation activities. Lately, polysaccharides extracted from *U. pinnatifida* showed promising antithrombotic [160,161] and antimicrobial [158,160] activities, opening up new perspectives on NIS uses and waste conversion into valuable biomass. Despite monitoring and reports on NISs carried out in Italy in the last decade, there are no specific dedicated plans for their prevention, control and management. The time has come for new approaches that are able to integrate the correct environmental management of NISs with economic opportunities [36]. Moreover, real, sustainable seaweed resource management should be integrated within the Maritime Spatial Planning (MSP) framework, for example, by allocating the most suitable spaces for farming to reduce the competition with other human activities, i.e., ship traffic or tourist and recreational activities. This process should also include social and stakeholder acceptance and co-participation. At the same time, a new cultural approach is needed, both for producers—the cultivation and harvesting of algae would also allow greater diversification of fishing activities—and consumers, shifting the stereotype of seaweeds as organisms associated with polluted environments to those associated with the enhancement of properties and benefits.

8. Final Remarks

Sustainable Blue Economy development and efficient use of resources are the main methods for managing and coping with the uncertainty of our future.

In this article, we gave an overview of the knowledge of the potential uses of Mediterranean seaweeds with a focus on the Italian context. The open perspectives could be "food for thought" for the development of the seaweed bioeconomy in other Mediterranean countries. Although Italy has conducted numerous pieces of research on the potential application of seaweeds, there are important deficiencies in industrial-scale applications in conjunction with environmental management.

In this context, possible actions to promote a seaweed-based bioeconomy are:

- to invest in research on seaweed biology and farming technologies, also increasing synergy between research and industry;
- to support the production of autochthonous species, which are recognized for their uses, promoting a new seaweed-based supply chain;
- to combine correct environmental management of NISs with economic opportunities;
- to put in place conservation and restoration strategies for seaweeds within MSP with the aim of creating a real, sustainable supply chain; those strategies should include actions of co-participation to promote social and stakeholder acceptance.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14095634/s1, Table S1: Potential applications of seaweeds from the Mediterranean Sea; Figure S1: Number of reports on seaweed properties for each Mediterranean country.

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