Review

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The seaweed resources of Peru

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Abstract: The coast of Peru (3.5-18°S) is one of the most productive marine areas in the world. The updated seaweed checklist reports a total of 260 specific/intraspecific taxa, of which the Rhodophyta show the highest number (185 species), followed by Chlorophyta (41 species) and Phaeophyceae (34 species). Since 2012, an increase in molecular studies has been reported mostly in Rhodophyta, while Chlorophyta and Phaeophyceae have lagged far behind. Utilization of seaweed resources has been based on artisanal collection from natural beds. These are mainly consumed fresh or salt-dried (Chondracanthus chamissoi and Porphyra/Pyropia species), or exported for polysaccharide extraction (Lessonia nigrescens, Lessonia trabeculata, Macrocystis pyrifera). Although some regulations for brown seaweed extraction exist, overexploitation is a constant threat that must be addressed. Biomass from seaweed farms accounts, at most, for only 4% of the total annual landings, and there is a decreasing trend on seaweed aquaculture production since 2012. However, some cultivation projects for C. chamissoi and Porphyra/ Pyropia species are currently being undertaken. In addition, recent studies have started to explore new uses of commercial and non-commercial seaweeds. Uncovering the Peruvian seaweed diversity and establishing well sustained culture and management projects are essential for utilizing and preserving the seaweed resources of Peru.

Keywords: aquaculture; checklist; molecular studies; Peru; seaweed resources.

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1 Introduction

Peru borders the Pacific Ocean to the east. Its coastline stretches from 3°23'S to 18°21'S on the western side of South America. It has a length of 3080 km, with a continental shelf with a variable width: from 150 km off northern and central Peru to less than 10 km off parts of southern Peru (Bruland et al. 2005; Hooker et al. 2013). Around 77 islands (94.36 km²) can be found in the Peruvian Sea, 22 of them belonging to the "Reserva Nacional Sistema de Islas, Islotes y Puntas Guaneras" (RNSIIPG), a marine protected network (Hooker et al. 2013; MINAM 2019). Diverse ecosystems are presented on the coast, such as bays, cliffs, kelp and macroalgal beds, rocky shores and sandy beaches. Coastal wetlands, which include the southernmost limit to the tropical Pacific mangrove ecosystem, are also important components of the Peruvian coast (Fernandez-Baca et al. 2007; Tarazona et al. 2003).

The ocean circulation on the coast of Peru is dominated by two systems: the northward flowing cold Peruvian Current (PC), coming from the southern tip of Chile; and the southward flowing warm South Equatorial Current (SEC) (Kämpf and Chapman 2016; Spalding et al. 2007). The coastal upwelling ecosystem supported by the PC makes the marine ecosystem of Peru one of the most productive in the world, earning the title of the "heavyweight champion" in terms of producing fish biomass (Bakun and Weeks 2008). This ecosystem is largely affected by inter-annual variations during El Niño Southern Oscillation (ENSO) events, where warm equatorial and oceanic waters are brought to the coast by the intrusion of Kelvin waves (Arntz et al. 2006; Fahrbach et al. 1991).

In this review, three biogeographical units are considered for the Peruvian coast (Figure 1): the Panamic Province (PP; 3.5–4.5°S), a Transitional Zone (TZ; between 5 and 5.5°S), and the Humboldt (Peruvian) Province (HP; 6–13.5°S). Ibanez-Erquiaga et al. (2018) proposed this zonation based on rocky intertidal communities along the coast of Peru, increasing the precision of the previous biogeographical zonations. In a regional perspective, three out of 27 marine Eco regions described for South America are within (totally or partially) the Exclusive Economic Zone (EEZ) of Peru (Chatwin 2007). The Guayaquil region includes PP, TZ and the northern part of HP, while the Central

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Peru and Humboldt regions encompass the rest of HP. The diversity of marine environments (shaped by the PC and SEC, continental shelf, islands and the Peru trench) allows a diversity of the marine macroalgae in these zones (Figure 2) that, in turn, supports diverse ecosystems (e.g., kelp forests in central and southern Peru; IMARPE 2012) and provides important resources that need to be regulated (Alemañ et al. 2019).

In this context, the present work aims: 1) to compile all the information regarding Peruvian seaweed diversity into a comprehensive list accessible to the world scientific community; 2) to assess its current biodiversity status; 3) to report uses and potential applications of seaweeds in Peru; and 4) to summarize the past and present of seaweed cultivation in the country. We discuss our perspectives for seaweed research in Peru, with emphasis on taxonomy and culture.

2 Seaweed flora of Peru

2.1 A brief history of seaweed biodiversity studies

The history of seaweed exploration in Peru dates back to 1802, when Humboldt and Bonpland collected the first specimens from the Peruvian coast, in places such as Huanchaco, in the north coast, and Callao, in the central coast (Humboldt and Bonpland 1814). These collections

were later studied by Humboldt (1815–1825) and C. A. Agardh (1822), thus giving the starting point of seaweed biodiversity studies in the country. During the 19th century, several researchers such as Bory de Saint Vincent (1826–1828); Montagne (1839, 1846); Suhr (1840); Kützing (1843, 1849, 1851–1869); J. G. Agardh (1841, 1851–1863) and Piccone (1886), increased the list of Peruvian macroalgal species. De Toni's Sylloge Algarum (1900-1924) closed the century, listing about 65 species attributable to Peru.

The 20th century began with a landmark document for Peruvian phycology: The Marine Algae of Peru, by M. A. Howe (1914), the first comprehensive account of marine algal biodiversity in the country. This work was based on the materials collected by R. Coker (1906–1908), the specimens from various European herbaria, and a few collections of the U.S. Exploring Expedition (Wilkes Expedition) of 1839. Howe reported 115 species (excluding Cyanobacteria), 26 of which were new species and 29 were new records for Peru. A few years later, Collins (1915) added five more species to the Peruvian algal list based on a small collection made at Chincha Islands, while Kylin and Skottesberg (1919) reported for the first time the red alga Callophyllis variegata. Subsequent studies did not mention Peruvian algae until 1941, when Dawson revised several species of *Rhodymenia* (Dawson 1941). During the 1940s and 1950s, Taylor (1947) contributed to the description of several new Peruvian species, whereas Juhl-Noodt (1958) provided a brief annotated list of seaweeds collected

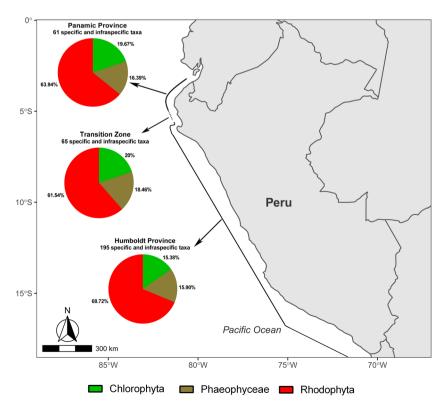


Figure 1: Map of Peru showing the proportions of specific and intraspecific. taxa, belonging to Chlorophyta, Phaeophyceae and Rhodophyta.

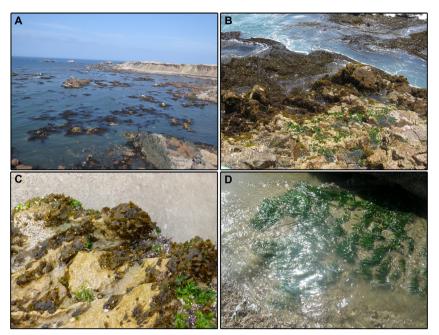


Figure 2: Some characteristic seaweed communities from the Peruvian coast. (A) Kelp forests seen from the cliffs of Marcona (Humboldt Province). (B) Algal diversity on the intertidal shores of Marcona (Humboldt Province). (C) Intertidal Petalonia fascia and Ulva spp. from Paracas (Humboldt Province). (D) A patch of Caulerpa filiformis in Cabo Blanco (Panamic Province).

during a survey for the Compañía Administradora del Guano in 1956. Later, Dawson et al. (1964) published The Seaweeds of Peru, a taxonomic review that reported 156 species, seven of which were new species and 29 were new records. This review constitutes an important landmark for seaweed taxonomy and diversity in the country during the second half of the 20th century.

During the 1970s and 1980s, Acleto (1972, 1973, 1980, 1981, 1984, 1988), and Acleto and Endo (1977) contributed greatly to the knowledge of the macroalgal flora along the coast of Peru. Acosta (1977a) provided the first detailed algal list of Pisco, one of the most productive marine areas in the country. By the beginning of the 1990s, Ramírez and Santelices (1991) published a catalogue of the benthic marine algae from the southeastern Pacific Ocean, which compiled all the reported taxa, including their bibliography and distribution, from Peru and Chile. This work registered 226 species on the Peruvian coast (39 Chlorophyta, 31 Phaeophyceae and 156 Rhodophyta), and it represents the last checklist of the marine macroalgae of Peru to date.

The 21st century brought the first molecular studies that included Peruvian samples, such as the model organism Ectocarpus siliculosus (Peters et al. 2004) and specimens of the genus Lessonia (Cho et al. 2006). However, it was not until 2012 that the molecular taxonomy of seaweeds started to increase, with works in Rhodomelaceae (Bustamante et al. 2012a,b, 2016, 2019b), Halymeniaceae (Calderon et al. 2014a,b), Gracilariaceae (Arakaki et al. 2015), Phyllophoraceae (Calderon and Boo 2016a,b,

2017) and Bangiaceae (Márquez-Corigliano et al. 2019). Additional regional lists have contributed to a better understanding of seaweed distribution in the country (Gil-Kodaka et al. 2002; Ramírez et al. 2015; Rodríguez-Rodríguez et al. 2018; Roque-Sánchez et al. 2017). Also, three catalogues of seaweeds from the central coast of Peru (Arakaki et al. 2018a,b: Carbaial et al. 2018, 2019) have been released as a result of a DNA barcoding project for marine macroalgae. Finally, the first transcriptomic and genomic analyses of Peruvian seaweeds have been recently published (Bustamante et al. 2019a; Salavarría et al. 2018).

2.2 Diversity of marine macroalgae in Peru

As a result of compiling all earlier species records in both international and Peruvian publications, the updated checklist of seaweeds from Peru consists of a total of 260 specific/intraspecific taxa (41 Chlorophyta, 34 Phaeophyceae and 185 Rhodophyta; Supplementary Tables S1-S3). A summary of the seaweed flora of Peru can be found in Table 1. This work represents the most inclusive list of Peruvian flora to date, including 34 species more than in the list of Ramírez and Santelices (1991). We expect this number to increase as there are several generic records that might represent new species or new reports for the country (Table S4). Although the number of species reported for Peru in AlgaeBase (Guiry and Guiry 2019) is slightly higher (277), 39.35% of the records are synonyms. Also, 14 species have been incorrectly attributed to Peru in AlgaeBase

(Table S5). One red algal species, *Archeolithothamniun chilense*, did not have matching records, either in Algae-Base or in the INA Database (Silva 2019), and possibly represents an invalid name (Table S6). The best represented genera in Peru are *Ulva* with 10 species, *Desmarestia* with four species and two subspecies, *Gelidium* with nine species, *Gracilaria* with six species and one subspecies, and *Cryptonemia* and *Rhodymenia* with seven species each. Key references for seaweed diversity in Peru are presented in Table 2. The entire literature used for the checklist can be found in the reference list for the Supplementary Tables.

The bulk of new species and new records of seaweeds from Peru were published in the following publications: Howe (1914), Taylor (1947), Dawson et al. (1964), and Acleto (1973, 1980). From 1984 to 2009, the discovery rate of new species/records diminished (less than one per year). However, from 2011 onward, there has been an increase in this number (more than two species/records per year) together with an increase in the number of algal publications (Figure 3). When divided into algal groups, most of the new species/records relate to red algae (Figure 4). In fact, molecular phylogeny has helped to describe nine new species and to establish five new genera based on Peruvian samples in recent years (Bustamante et al. 2012a,b, 2019b, Calderon and Boo 2016a,b, 2017, Calderon et al. 2014a,b). On the other hand, no new records have been reported for green and brown algae since 1980 and 2006, respectively. Also, no new species in these two groups have been described from Peru for over 50 years (Dawson et al. 1964; Taylor 1947). From this, it is clear that taxonomic and biodiversity studies on Peruvian seaweeds have begun to increase significantly with the help of molecular techniques. However, less attention has been paid to the taxonomy of green and brown seaweeds compared to red ones.

2.3 Distribution of seaweeds along the Peruvian coast

Locality data enabled us to analyse, to some extent, biogeographic and richness patterns. Among the three

biogeographical units considered in this review, the highest number of seaweed species is found in the HP (195), followed by the TZ (65) and the PP (61), from which 71.28, 24.62 and 44.26%, respectively, are exclusive to each region. More than 60% of the reports for each region correspond to Rhodophyta (Figure 1). Most of the species have been found in intertidal habitats. Some species or genera are representative of these areas, such as Bryopsis plumosa, Lessonia and Rhodymenia species for the HP; Ulva compressa, Gracilaria textorii and Laurencia paitensis for the TZ; and Caulerpa racemosa, Bachelotia antillarum and Caloglossa species for the PP. The differences in species diversity among the provinces are most likely influenced by differences in research effort and their geographical extent. For example, HP presents the highest seaweed diversity among the three regions, probably because that it covers most of the Peruvian coast and more research has been conducted there. It is worth noticing that some species might not be present any longer, in areas where they had been reported decades ago. For example, Macrocystis pyrifera is currently reported to have its northernmost limit in the central coast (Lima; Carbajal and Gamarra 2018); however, Juhl-Noodt (1958) found this species on the northern coast (Mancora) more than 60 years ago.

In relation to endemism, five green algae, three brown algae and 27 red algae have been described as endemic so far. These numbers are likely to change in the next years as molecular analyses can help to clarify their endemic status (e.g., Bustamante et al. 2019a). Regarding potential invasive species, there are studies only on the rapid expansion of the green alga *Caulerpa filiformis* along the Peruvian coast (MINAM 2014; Ramsar 2015); and on the possibly fortuitous introduction and spread of the green alga, *Codium fragile* in Cherrepe Bay, northern Peru (Castilla and Neill 2009).

2.4 Diversity of marine macroalgae in Peru compared to neighbouring countries

The diversity of the Peruvian seaweeds was compared with that of a number of neighbouring areas (Chile, Galapagos

Table 1: Summary of the seaweed flora of Peru.

Phylum/Class							Numbers
	Classes	Orders	Families	Genera	Species	Sub-species	Varieties
Chlorophyta	1	4	11	14	39		2
Phaeophyceae	1	7	12	22	32	2	
Rhodophyta	4	21	35	90	182		3
Total	6	32	58	126	253	2	5

Table 2: Main studies on Peruvian seaweed diversity.

Reference	Title	Publication
Howe (1914)	The marine algae of Peru ^a	Memoirs of the Torrey Botanical Club 15:1–185
Dawson et al. (1964)	The seaweeds of Peru	Beihefte zur Nova Hedwigia 13:1–111
Acleto (1973)	The marine algae of Peru (in Spanish)	Boletín de la Sociedad Peruana de Botánica 6:1-164
Acosta (1977)	The marine algae of Pisco, Ica, Peru (in Spanish) ^b	Publicaciones del Museo de Historia Natural Javier Prado Serie B 28:1–34
Acleto (1980)	Notes on marine algae from Peru I. New records (in Spanish) ^b	Publicaciones del Museo de Historia Natural Javier Prado Serie B 30:1–33
Ramirez and Santelices (1991)	Catalogue of the benthic marine algae from the temperate coast of Pacific South America (in Spanish) ^a	Monografías Biológicas 5:1-437
Alvítez and Rodríguez (2005)	Diversity, taxonomy and ecology of Phaeophyceae from the Peruvian coast (in Spanish) ^c	Rebiol 25:15–30
Arakaki et al. (2018b)	Macroalgae from central coast of Peru I-Rhodophyta (in Spanish) ^d	Universidad Nacional Agraria La Molina, Perú
Carbajal et al. (2018)	Macroalgae from central coast of Peru II-Chlorophyta & Phaeophyceae (in Spanish) ^d	Universidad Nacional Agraria La Molina, Perú

^aAvailable online in Algaebase (http://www.algaebase.org).

fbclid=IwAR09D0ggI5PvvcNOv9GecDEFTiFNnOhB9RgNoOC8xdAwv6VSO-WDvpFSSrw.

Archipelago and Continental Ecuador). Chile appears to be the most diverse country with a total of 633 species. Peru reports 260 species, which is comparable to the 321 species reported for the Galapagos Archipelago (Table 3). We used the Sørensen similarity index to compare seaweed diversity with neighbouring countries (Nguyen et al. 2013; Phang et al. 2019). The values obtained were all low ($C_s < 0.5$; Table 3), which is counterintuitive, especially in the case of Chile. This country, together with Peru, makes up the Humboldt Current Large region. One might expect that under similar climatic zones and without any major dispersal barriers, the similarity index would have been higher (Spalding et al. 2007). Although the subtropical influence in the HP could partially explain the low similarity with Chile, we are of the opinion that this value is primarily an artifact resulting from taxonomic inconsistencies and unequal research effort. The limited knowledge of seaweeds from Ecuadorian coastal waters can also explain the extremely low Sørensen similarity index for continental Ecuador (Miloslavich et al. 2011).

3 Economic seaweeds of Peru

3.1 Uses and potential applications

Peru is one of the few places outside of Asia with a long tradition of seaweed consumption (Mouritsen et al. 2018).

According to archeological evidence along the coast, seaweeds have been found in places that date back as far as 2500 B.C. (Patterson and Moseley 1968). Marine macroalgae have also been registered in mummies and represented in pottery from pre-Columbian Peruvian cultures (Kiple and Ornelas 2000; Yacovleff and Herrera 1934; Yacovleff and Muelle 1934). Apart from human consumption, seaweeds could have been used as means of exchange (Rostworowski 1981). Today, seaweeds are mostly used for human food or exported for the extraction of phycocolloids. Table 4 shows the uses and potential applications of Peruvian seaweeds. For a detailed review of the uses of marine macroalgae in Peru, we recommend the works of Acosta (1977b), Acleto (1986), and Noriega (2011).

Among red seaweeds, Porphyra/Pyropia species, locally known as "cochayuyo" (Márquez-Corigliano et al. 2019), and Chondracanthus chamissoi, locally known as "yuyo" or "mococho", are commonly consumed (Figure 5A and B). Acleto (1986) indicated that "cochayuyo" mostly include Py. columbina and Py. pseudolanceolata. These ones are eaten salt-dried in salads or stews after being washed and passed through hot water. Due to problems distinguishing species based on morphology and misapplied names, Porphyra/Pyropia species are currently being taxonomically re-assessed using molecular analysis (Guillemin et al. 2016; Márquez-Corigliano et al. 2019). C. chamissoi is consumed fresh in salads and in the traditional Peruvian ceviche, or added at the end of the

bavailable online in the website of the Natural History Museum "Javier Prado" (https://museohn.unmsm.edu.pe/pub_bot.html).

^{&#}x27;Available online in https://es.slideshare.net/egc1981/rebiol-vol-25?

Available online in the website of the National Agrarian University La Molina (http://www.lamolina.edu.pe/eventos/pesqueria/2019/ MACROALGAS_DE_LA_COSTA_CENTRAL_DEL_PERU_CATALOGO.pdf).

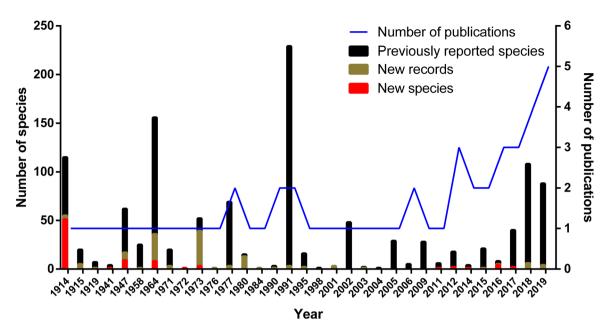


Figure 3: Number of publications on Peruvian seaweeds (blue line, right axis) and numbers of previously reported species (black bar chart, left axis), new species (red bar chart, left axis) and new algal records (brown bar chart, left axis) by year between 1914 and 2019.

preparation of fish stews. Some health food stores sell dried *C. chamissoi* as a food supplement or weight loss food (Noriega 2011). *C. chamissoi* is also an important source of carrageenan. Salas et al. (2009) showed that the highest yield of λ-carrageenan from this species was obtained from the tetrasporophytic phase (45.3%), while κ-carrageenan was predominant in the gametophytic phase (35.4–36.2%). They reported the use of λ-carrageenan as thickener in chocolate milk, and the inclusion of κ-carrageenan as a stabilizer in dairy products. *Gracilariopsis lemaneiformis* (Figure 5C), an important agarophyte worldwide, is used as

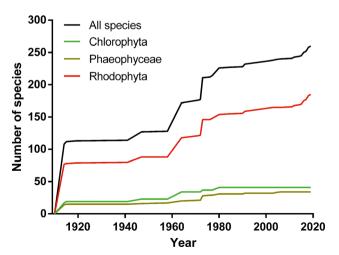


Figure 4: Cumulative curve of new seaweed species and new records (pooled) from Peru between 1914 and 2019.

forage in only small amounts (Noriega 2011). Recent studies have shown that *Porphyra/Pyropia* possess antioxidant and hypolipidemic properties (Aguilar-Velasquez 2015). Also, they can be used as flour in the preparation of cookies (Rosado-Alejos 2017).

Brown seaweeds are not usually part of Peruvian cuisine. Species like M. pyrifera, Lessonia nigrescens and Lessonia trabeculata (Figure 5D and F) are mainly exported for alginate production due to its gelling, thickening, emulsifying and stabilizing properties. Valiente and Mogollón (2013) showed that alginic acid was predominant in L. nigrescens (37.15%), followed by L. trabeculata (35.20%) and M. pyrifera (31.36%). Fishermen also harvest M. pyrifera for the extraction of flying fish ovas, although this represents a small percentage (less than 3.5%) of the harvested biomass in a year (PRODUCE 2015; Vásquez-Castro 2009). Recently, Castro et al. (2014) included an extract of M. pyrifera in a dermocosmetic formulation due to its antioxidant and antiaging properties. Currently, one company (PSW S.A. Peruvian Seaweeds) includes in its product portfolio agricultural growth promoters based on extracts from these three species (PSW 2020).

Green seaweeds are the less exploited algal group. They are not usually consumed in Peru, although *Ulva* species can be used instead of lettuce in some food applications (Noriega 2011). The nutritional properties of *Ulva lactuca* make it ideal for human consumption (Sumarriva-Bustinza et al. 2019) and animal feeds (Cruz 2019). In the last few years, *C. filiformis* has caught the attention of

Table 3: Comparison of Peruvian seaweed flora with neighbouring countries.

Neighbouring country Peru (Na = 2			
	N _b	N_{a+b}	Cs
Chile	633	129	0.289
Ecuador (Continental)	49	6	0.039
Ecuador (Galapagos)	321	51	0.176

The floristic data of the neighbouring countries were derived from Algaebase (Guiry and Guiry 2020). Nb, number of individuals in the neighbouring country; N_{a+b} , the number of taxa shared with Peru; Sørensen similarity index: $C_s = (2N_{a+b})/(N_a + N_b)$.

researchers due to its large unexploited biomass in places such as Paracas Bay (central coast of Peru). Biological and pharmacological properties of its extracts have been analysed with promising results (Egg et al. 2015; Hernández-Gómez et al. 2015; Mamani et al. 2020).

3.2 Traditional harvesting and aquaculture

Seaweed exploitation in Peru largely relies on harvesting from natural beds. In Latin America, Peru contributes 4% of the total seaweed harvest in the region. However, with

respect to seaweed cultivation, Peru only accounts for 0.01% of the biomass in Latin America (FAO 2018). According to annual landing data provided by the Ministry of Production (PRODUCE 2015, 2017), seaweed exploitation in Peru has increased since 2013 (Figure 6A), while the biomass from seaweed farms has been decreasing since 2012 (Figure 6B). A decrease in seaweed production from 2008 to 2012 can be attributed to legislation that is discussed later in Section 3.2. At its peak, only 4.1% of Peruvian seaweed production came from aquaculture. It is clear from this that cultivation of marine macroalgae in Peru is still in its infancy; however, some progress has been

Table 4: Commercial and non-commercial seaweeds from Peru with their common names and uses or potential uses in the country.

Phylum/Class	Species	Common name	Use/Potential use	Reference
Chlorophyta	Bryopsis plumosa	None	Antibacterial	Magallanes et al. (2003)
	Caulerpa filiformis	None	Photoprotective, antioxidant, spermicide	Egg et al. (2015), Hernández-Gómez et al. (2015), and Mamani et al. (2020)
	Ulva sp.	Lechuga de mar	Human food, animal feed, compost	Cruz (2019), Noriega (2011), Sumarriva- Bustinza et al. (2019), and Wosnitza and Barrantes (2005)
Phaeophyceae	Eisenia cokeri	None	Antioxidant	Rodríguez and Castro (2018)
	Lessonia nigrescens	Aracanto negro, aracanto	Agricultural growth promoter, alginates, heavy metal removal	Noriega (2011), Reyes et al. (2009), and PSW (2020)
	Lessonia trabeculata	Aracanto palo, calatillo	Agricultural growth promoter, algi- nates, heavy metal removal	Rivera et al. (2004), Noriega (2011), Valiente and Mogollón (2013), and PSW (2020)
	Macrocystis pyrifera	Aracanto huiro, huiro	Agricultural growth promoter, algi- nates, dermocosmetic, heavy metal removal	Reyes et al. (2009), Noriega (2011), Valiente and Mogollón (2013), Castro et al. (2014), and PSW (2020)
	Petalonia fascia	None	Antibacterial	Magallanes et al. (2003)
Rhodophyta	Chondracanthus cha- missoi, Gigartina paitensis	Yuyo, mococho	Carrageenans, human food	Salas et al. (2009) and Noriega (2011)
	Gracilariopsis lemaneiformis	Pelillo, pelo de mujer, pelo de indio	Forage	Noriega (2011)
	Neorubra decipiens	Piscuchaqui	Human food	Noriega (2011)
	Porphyra/Pyropia spp.	Cochayuyoª	Human food	Noriega (2011), Aguilar-Velasquez (2015), and Rosado-Alejos (2017)
	Rhodymenia howeana	None	Food supplement	Rojas-Vega et al. (2018)

Other species like Grateloupia doryphora, Mazzaella denticulata and Rhodymenia corallina are also commercialized under this name in Peru.

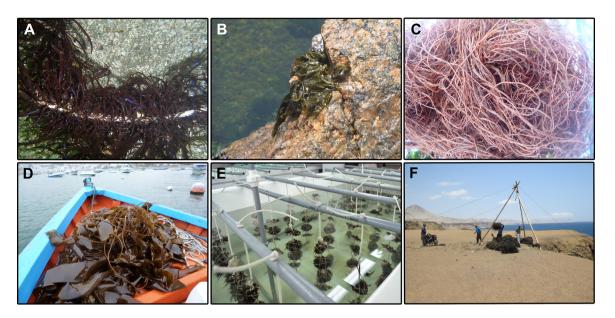


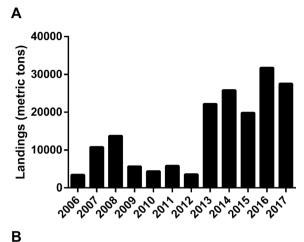
Figure 5: Economic seaweeds from Peru. (A) Chondracanthus chamissoi, locally known as "yuyo" or "mococho", growing on ropes from a farm in Pisco (photo credit: Paul Baltazar). (B) A Porphyra/Pyropia specimen, locally known as "cochayuyo", from the intertidal of Marcona. (C) A freshly collected Gracilariopsis lemaneiformis, locally known as "pelillo", from the bay of Ancon. (D) Macrocystis pyrifera, locally known as "aracanto", from the bay of Pucusana. (E) Vegetative propagation of C. chamissoi through secondary attachment discs in scallop shells at indoor cultures in Pisco (photo credit: Paul Baltazar). (F) Dried brown seaweeds (mostly Macrocystis pyrifera) being transported to the cliffs from a hard-to-access beach in Marcona. A pulley system is usually used by the fishermen, who later stack the seaweeds for air-drying and selling.

achieved with species such as *C. chamissoi*. In this regard, previous reviews have dealt with the situation of seaweed aquaculture of Peru in a regional perspective (Alemañ et al. 2019; Hayashi et al. 2013; Rebours et al. 2014). Therefore, Section 3.2 will attempt to summarize the main findings of these authors and complement them with recent Peruvian publications and projects focused on seaweed culture.

As previously mentioned, the most exploited red algae in Peru are C. chamissoi and Porphyra/Pyropia. Most of their biomass comes from natural beds. In the case of *C. chamissoi*, overexploitation has led to a decrease in the populations together with size reduction and lower gel quality. Scallop cultivation in the north of Peru has also affected the populations of this carrageenophyte (Hayashi et al. 2013). Given this threat, cultivation of C. chamissoi was explored during the early 2000s and from 2012 to 2014 (Rebours et al. 2014). This last attempt at cultivation ceased in 2015 according to the FAO (2020). However, recent studies have started to examine the factors affecting carpospore cultures of C. chamissoi (Arbaiza et al. 2019; Castañeda et al. 2018), and a project is currently being implemented for its vegetative propagation (Figure 5E) in Paracas Bay with fishermen (Paul Baltazar, Universidad Científica del Sur, 2020, pers. comm.). As suggested by Alemañ et al. (2019), the investment for C. chamissoi cultivation must be focused on human consumption due to the Peruvian gastronomic boom. Prices of *C. chamissoi* have experienced an increase of around 400% due to the few existing beds, the short time allowed for plant regeneration, and the effort involved in small-scale harvesting (Hayashi et al. 2013). Fresh *C. chamissoi* is sold at US\$ 2.99–3.59 kg⁻¹, while *C. chamissoi* flour packages (200 g) cost US\$ 4.19 (Noriega 2011). Also, the current legislation does not regulate the harvesting of this or other red seaweeds in Peru.

Cultivation of *Porphyra/Pyropia* has just started, with studies of the effects of photoperiod and a liquid commercial foliar fertilizer (Bayfolan®) on its biomass under semi-controlled conditions (Arbaiza et al. 2018). This is part of a larger project involving the establishment of a culture system in Pisco (central Peru) together with fishermen associations. The resulting biomass is planned to be used as flour in the bakery industry (Toribio-Chahua 2017). As previously mentioned, *Porphyra/Pyropia* is consumed saltdried. It is sold as sheets (250 g) for US\$ 0.45 by fishermen, and the same amount costs US\$ 2.69 (almost six times the original price) in the capital (Noriega 2011).

Attempts at cultivating the agarophyte *G. lemaneiformis* were performed with governmental support in the late 1990s. Despite the initial success of the cultures in the Bay of San Nicolas (central Peru), seaweeds were negatively impacted by the "El Niño" phenomena of 1997–1998. Increased temperature, grazers, and epiphytism caused



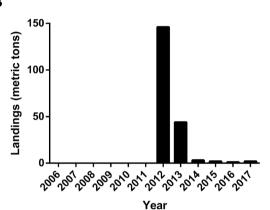


Figure 6: Landings of harvested seaweed in Peru from 2006 to 2017. (A) Total landings. (B) Aquaculture landings. From PRODUCE (2015, 2017).

high rates of mortality on the farms. Since then, no more attempts at *G. lemaneiformis* culture have been reported (Hayashi et al. 2013).

Important populations of L. nigrescens, L. trabeculata and M. pyrifera can be found along the southern coast of Peru. Their importance relies on the ecosystem services they provide, such as elevated secondary production, coastal erosion defence, direct applications, and biodiversity repositories, among others (Carbajal and Gamarra 2018; Smale et al. 2013). Drift brown seaweeds, but also plants harvested directly from natural beds, are collected and air-dried for at least two days in order to get final moisture content of 15-20%. A higher content usually reduces their price. Dried seaweeds are then sold to processing companies that export them (Noriega 2011). Rebours et al. (2014) reported four companies that purchase seaweeds from the local communities: two Peruvian companies, one Chilean, and one Chinese-owned company. During years where "El Niño" does not affect brown seaweed populations, about 3000 tonnes of dry L. nigrescens and dry L. trabeculata is exported to Asia. Due to overexploitation, the prices of dried seaweeds have been increased from US\$60 to US\$400 t⁻¹ between 2006 and 2008 (Rebours et al. 2014). In 2008, Peru banned the direct harvesting of these species to protect their natural populations along the Peruvian coast (RM N° 839-2008-PRODUCE). The next year, the government allowed the collection of only beach-cast material (RM N° 264–2009–PRODUCE; IMARPE 2020). Nevertheless, illegal harvesting is still reported and a scientific-based management plan for these resources is urgently needed (Noriega 2011). Apart from the cultivation of *M. pyrifera* in San Nicolas Bay by the company PSW (Murias 2010), no other attempts at brown seaweed aquaculture have been reported (Alemañ et al. 2019).

Green seaweeds have not been subjected to major cultivation studies in Peru. This might be explained by the scarce use they have in the country and their high natural biomass, as explained in Section 2. Efforts to implement new cultivation technologies for *Ulva* spp. and *Codium* spp. have been reported (PSW 2020), but the results are not currently available.

4 Conclusions

Studies on Peruvian seaweed diversity started more than 200 years ago. With some exceptions, these works have not been updated and sustained over the years and have lagged behind the neighbouring countries like Chile and Brazil. However, during the last eight years, there has been a "reemergence" of seaweed taxonomic research assisted by the development of molecular approaches. Despite the increase in algal publications during this period, little is still known about the taxonomy and diversity of Chlorophyta and Phaeophyceae, as these groups have not been extensively studied compared to red algal families such as Halymeniaceae, Phyllophoracea and Rhodomelaceae. Also, the seaweed diversity of subtidal habitats remains largely unexplored. Molecular systematic, genomic and transcriptomic studies with Peruvian seaweeds are currently available, mostly for Rhodophyta. These works will not only help to uncover the real seaweed diversity of Peru and understand basic aspects of these organisms, but also provide essential information for their culture, management, application and preservation (Huete-Pérez and Quezada 2013). While basic research on seaweeds (e.g., growth and developmental studies) must be encouraged, the information must also be linked with culture studies and new applications for seaweed biomass (Charrier et al. 2017). Peru needs to stop relying only on natural beds, as this can lead to overexploitation of the seaweed resources (which is already known for some

species) with profound consequences for Peruvian fisheries and the Peruvian seaweed industry. Although the government has established some regulations for brown seaweed collection, these have been ineffective and a science-based management system is needed for the sustainable exploitation of marine macroalgae, involving scientists, policy makers and coastal communities. Seaweed aquaculture can become an alternative source of income for coastal communities, and it can provide several ecosystem services. Peru is starting to prioritize cultivation projects on its coast, bringing together universities, companies and fishermen, in an effort to diversify its production. These projects (and future ones) must consider "phyconomic" issues (Hurtado et al. 2019) in order to assure short and long-term success. Diversification of seaweed species for culture and utilization has just started to be explored with studies on noncommercial species such as C. filiformis, U. lactuca and Rhodymenia howeana. Also, species from the PP, which have received little attention, represent a big opportunity for Peruvian basic and applied phycology.

Finally, Peruvian scientific and non-scientific communities need to work together for a better understanding and adequate management of seaweed resources. The challenge now is to sustain this "re-emergence" of phycological studies and improve its accessibility to the international scientific community as well as to the whole of society. Through this manner, the seaweed resources of Peru can be preserved for the benefit of the country and the world.

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