Phycologia

ISSN: 0031-8884 (Print) 2330-2968 (Online) Journal homepage: https://www.tandfonline.com/loi/uphy20

An introduction to farming and biomass utilisation of marine macroalgae

Alejandro H. Buschmann & Carolina Camus

PHYCOLOGIA
2019, VOL. 58, NO. 5, 443–445
https://doi.org/10.1080/00318884.2019.1638149

International Phycological Society
Taylor & Francis
Taylor & Francis Group

Check for updates

An introduction to farming and biomass utilisation of marine macroalgae

Alejandro H. Buschmann and Carolina Camus

Centro i-mar and CeBiB, Universidad de Los Lagos, Puerto Montt 5480000, Chile

ABSTRACT
The interest in seaweeds by humans seems to have originated over 1700 years ago when several seaweed species became used in ethnic cuisines. These initial applications enabled the start of farming in Japan, China and Korea. However, in Western countries, demand for seaweed polysaccharides began only after World War II, when the demand for agar, alginate and carrageenans developed. At the present time, many researchers and entrepreneurs predict a promising future for innovation in the seaweed industry. In this context, this special issue covers some advances and constraints that seaweed farming and the utilisation of its biomass face today.

ARTICLE HISTORY
Received 26 June 2019
Accepted 26 June 2019
Published online 11 September 2019

KEYWORDS
Biomass utilization; Marine macroalgae; Seaweed farming

Since at least the Neolithic period, humans along the coasts of the world harvested seaweed which constituted a significant component of their diets (e.g. Dillehay *et al*. 2008; Erlandson *et al*. 2015). In recorded history, interest in seaweeds by humans seems to have originated over 1700 years ago (Yang *et al*. 2017). During the past couple of centuries, several seaweed species became used in ethnic cuisines and the first seaweed gelling agents were extracted (e.g. Abbott 1996; Delaney *et al*. 2016). These initial applications enabled the start of farming in Japan, China and Korea. However, in Western countries, demand for seaweed polysaccharides began only after World War II, when the demand for agar, alginate and carrageenans was developed (e.g. Bixler & Porse 2011; Hafting *et al*. 2015). As seaweed aquaculture matures in the 21st century, many researchers and entrepreneurs predict a promising future for innovation in the seaweed industry. Developments will not only be associated with food products and polysaccharides, but also more valuable products such as functional foods, cosmeceuticals, nutraceuticals, pharmaceuticals, and perhaps also lower value products such as biofuels that have a high biomass requirement. The `biorefinery concept´, where seaweed biomass is used in an integral way with low waste production and reduced environmental impacts, seems to be the only viable approach for progress in industrial development (e.g. Buschmann *et al*. 2017).

According to FAO statistics (FAO 2016), yields of seaweed production through aquaculture are several times higher than the harvesting of natural populations (Table 1). Harvesting natural resources can produce considerable ecological, social and economic consequences if not well managed. For this reason, farming is an alternative that requires an understanding of its interaction with the biotic and abiotic environment. At present, the most important cultivated seaweed taxa are *Eucheuma* spp. and *Kappaphycus alvarezii* for carrageenans; *Gracilaria* spp. for agar; and *Saccharina japonica* (formerly *Laminaria japonica), Undaria pinnatifida, Pyropia* spp. (formerly *Porphyra*) and *Sargassum fusiforme* (see Table 1 for authorities), all of which are used as food. These species are cultivated mostly in the sea, but some (e.g. kelps and nori) require an additional hatchery phase to grow the microscopic stages and to seed ropes or nets before deployment into the sea.

The number of species that are commercially cultivated is relatively low, posing a challenge to find new species that can offer novel products (Hafting *et al*. 2015). However, not only are new species needed, but extensive research is needed to incorporate modern technologies to understand how seaweeds perform under various culture conditions, how to optimise light and nutrient uptake, and how environmental stressors and enemies (e.g. pathogens and grazers) can affect productivity. Research is also needed to incorporate the assessment of genetic diversity, gene expression and inheritance of relevant traits to allow the development of strains and cultivars with known agronomic traits, as have been developed for thousands of years in terrestrial agronomy (Valero *et al*. 2017). Also relevant is the need for industrialisation that includes novel and energy-efficient technologies for seeding, harvesting and post-harvest operations. Finally, to make seaweed farming commercially relevant, emphasis should be placed on new product development, increased efficiency of biomass processing to achieve economic profitability, and minimisation of the production of unutilised residues (Neori *et al*. 2007). These are economic passives that a sustainable industry cannot afford to ignore. All of these topics cannot be covered in one journal issue. It is our hope that the articles found in this special issue of *Phycologia* will serve to both advance and enhance seaweed farming.

The issue starts by describing the progress, challenges and future directions of seaweed farming in the Western Hemisphere, particularly in the USA (Kim *et al*. 2019) and Latin America (Alemañ *et al.* 2019). Latin America has a strong potential for the development of seaweed aquaculture

CONTACT Alejandro H. Buschmann abuschma@ulagos.cl

Table 1. Seaweed production (tonne) by aquaculture and exploitation of wild stands during 2016 (biomass values and taxonomy after FAO 2016).

Brown algae	Aquaculture landing	Wild land harvesting
Alaria esculenta (Linnaeus) Greville	76	–
Ascophyllum nodosum (Linnaeus) Le Jolis	–	68,291
Durvillaea antarctica (Chamisso) Hariot	–	8015
Laminaria digitata (Hudson) J.V. Lamouroux	–	49,413
Saccharina japonica (Areschoug) C.E. Lane, C. Mayes, L. Druehl & G.W. Saunders	8,219,210	58,111
Laminaria hyperborea (Gunnerus) Foslie	–	10,422
Lessonia nigrescens Bory	–	155,741
Lessonia trabeculata Villouta & Santelices	–	49,802
Macrocystis pyrifera (Linnaeus) C. Agardh	1	35,092
Saccharina latissima (Linnaeus) C.E. Lane, C. Mayes, Druehl & G.W. Saunders	33	–
Sargassum fusiforme (Harvey) Setchell	189,910	–
Undaria pinnatifida (Harvey) Suringar	2,069,682	2679
Other brown algae	33,622	–
Red algae		
Chondracanthus chamissoi (C. Agardh) Kützing	–	2125
Eucheuma denticulatum Trono & Ganzon-Fortes	214,026	–
Eucheuma spp.	10,518,771	–
Gelidium spp.	–	2302
Gigartina skottsbergii Setchell & N.L. Gardner	–	22,199
Gracilaria spp.	4,149,524	26,423
Gracilaria verrucosa (C. Agardh)	450	–
Gymnogongrus furcellatus Kützing	–	239
Kappaphycus alvarezii (Doty) Doty ex P.C. Silva	1,527,217	–
Mazzaella laminarioides (Bory) Fredericq	–	2273
Porphyra linearis Greville	–	11
Porphyra tenera Kjellman	710,425	40
Porphyra spp.	1,352,520	109
Sarcothalia crispata (Bory) Leister	–	30,694
Green Algae		
Caulerpa racemosa (Forsskal) J. Agardh	2	–
Caulerpa spp.	585	–
Codium fragile (Suringar) Hariot	4,279	224
Enteromorpha clathrata (Roth) Greville	3,710	–
Monostroma nitidum Wittrock	7,158	1029
Ulva pertusa Kjellman	–	106
Ulva spp.	–	1070
TOTAL	**29,001,210**	**526,410**

due to its vast coastline, which encompasses different ecosystems with a wide variety of seaweed species. However, almost all of their production is based on harvesting natural beds from Chile, Peru and Mexico. Alemañ *et al*. present the status of seaweed production (from both natural beds and aquaculture production) in Latin American countries, emphasising the challenges and future requirements for success. The US began seaweed aquaculture in the 1980´s for fuel production, but the first attempts did not result in commercial production. Since 2010, seaweed cultivation has been rapidly expanding in the US but only in limited areas. Kim *et al*. (2019) review the past and current status of the industry in the US and discuss potential opportunities and challenges for its full development.

In contrast with the development of seaweed cultivation on the American continent, the cultivation of seaweeds (i.e. *Kappaphycus* and *Eucheuma*) in Southeast Asia and East Africa, dominate global aquaculture production. Despite its success, there remain several lessons to be learned, as described in Hurtado *et al.* (2019), who introduce the term 'phyconomy' to refer to marine seaweed cultivation to mirror the term agronomy used for terrestrial plant cultivation. According to these authors, a key challenge for euchematoid cultivation is the delay in the introduction of cultivars or strains with higher productivity and/or resistance to disease. The development of such breeding and strain selection programs is reviewed by Hwang *et al.* (2019) who focus on Korean, Chinese and Japanese experiences. In their review, they emphasise the development of cultivar-related research and applications, with particular reference to key commercial species, i.e. *Saccharina japonica, Pyropia* spp., *Undaria* spp., *Cladosiphon okamuranus* and *Nemacystus decipiens*. An example of such research is provided by Lee & Choi (2019) who used gamma irradiation to generate a mutant of *Pyropia tenera* with improved heat tolerance.

Another challenge that seaweed cultivation is facing is the availability of suitable space in nearshore areas for the installation of new cultivation systems. This is needed to satisfy the increasing demand for biomass required for biofuels and processing of the resulting seaweed biomass. In response, an interest in developing offshore seaweed aquaculture has emerged, particularly in European countries. Azevedo *et al.* (2019) demonstrate the feasibility of cultivating *Saccharina latissima* at its southern distribution limit under exposed offshore conditions in Portugal, emphasising the need for technological and biological innovation for such challenging conditions.

Related to the processing of seaweed biomass, the concept of 'biorefinery' as applied to seaweeds has proven to be a promising move forward for the production of a wide range of products, including food, agrochemicals, biomaterials and biofuels. Here, Zollmann *et al.* (2019) present the challenge of developing industrially relevant and environmentally-friendly green seaweed biorefineries, including a survey of potential products and their co-production, using both traditional and emerging processing technologies.

Given global climate change, aquaculture will face environmental challenges similar to natural ecosystems. However, the inclusion of seaweed cultivation with other marine resource farms could result in the amelioration of potentially negative effects of global climate change, such as the increasing periodicity of green tide events (e.g. Cui *et al.* 2019). To alleviate the effects of ocean acidification on shellfish aquaculture, Fernández *et al.* (2019) propose incorporating the naturally generated chemical refuge of seaweed photosynthesis into shellfish aquaculture by co-cultivation.

Successful seaweed aquaculture requires an understanding of key concepts in nutrient uptake and assimilation, and Roleda & Hurd (2019) apply these to seaweed polyculture and Integrated Multi-Trophic Aquaculture (IMTA). A contribution by Shannon & Abu-Ghannam (2019) reviews recent developments in seaweed applications for human health from an epidemiological perspective and as functional food ingredients. The issue ends with a review of an award-winning book on seaweeds as food (Cornish 2019).

We hope that the articles in this special volume will be useful to researchers, students, entrepreneurs and the public in general who have interest in producing seaweeds or transforming seaweed biomass into novel products. This issue of *Phycologia* provides a timely assessment of seaweed aquaculture and emerging, environmentally-friendly technologies that recognise the need for progress towards truly sustainable seaweed aquaculture.

ACKNOWLEDGEMENTS

As guest editors, we acknowledge the hard work of authors, reviewers, and David Garbary, Editor-in-Chief of *Phycologia*, for supporting this work.

FUNDING

This work was supported by CONICYT-Chile (PIA, FB-0001).

ORCID

Alejandro H. Buschmann http://orcid.org/0000-0003-3246-681X

REFERENCES

Abbott I.A. 1996. Ethnobotany of seaweeds: clues and uses of algae. *Hydrobiologia* 326/327: 15–26. DOI: 10.1007/BF00047782.

Alemañ A.E., Robledo D. & Hayashi L. 2019. Development of seaweed cultivation in Latin America: current trends and future prospects. *Phycologia* 58: 462–471. DOI: 10.1080/00318884.2019.1640996.

Azevedo I.C., Duarte P.M., Marinho G.S., Neumann F. & Sousa-Pinto I. 2019. Growth of *Saccharina latissima* (Laminariales, Phaeophyceae) cultivated offshore under exposed conditions. *Phycologia* 58: 504–515. DOI: 10.1080/00318884.2019.1625610.

Bixler H.H.J. & Porse H. 2011. A decade of change in the seaweed hydrocolloids industry. *Journal of Applied Phycology* 23: 321–335. DOI: 10.1007/s10811-010-9529-3.

Buschmann A.H., Camus C., Infante J., Neori A., Israel A., Hernández-González M.C., Pereda S.V., Gomez-Pinchetti J.L., Golberg A., Tadmor-Shalev N., *et al.* 2017. Seaweed production: overview of global state of exploitation, farming and emerging research activity. *European Journal of Phycology* 52: 391–406. DOI: 10.1080/09670262.2017.1365175.

Cornish L. 2019. [Book review] *Those curious and delicious seaweeds: a fascinating voyage from biology to gastronomy* by José Lucas Peréz Lloréns *et al.* *Phycologia* 58: 578–579. DOI: 10.1080/00318884.2019.1634929.

Cui J., Zhang J., Monotilla A.P., Huo Y., Shi J., Zhao X., Kang X. & He P. 2019. Assessment of blooming *Ulva* macroalgae production potential in the Yellow Sea, China. *Phycologia* 58: 535–541. DOI: 10.1080/00318884.2018.1551016.

Delaney A., Frangoudes K. & Li S.A. 2016. Society and seaweed: understanding the past and present. In: *Seaweed in health and disease prevention* (Ed. by J. Fleurence & I. Levine), pp. 7–40. Elsevier Academic Press, London, UK.

Dillehay T.T.D., Ramirez C., Pino M., Collins M.B., Rossen J. & Pino-Navarro J.D. 2008. Monte Verde: seaweed, food, medicine, and the peopling of South America. *Science* 320: 784–786. DOI: 10.1126/science.1154849.

Erlandson J., Braje T., Gill K. & Graham M.H. 2015. Ecology of the kelp highway: did marine resources facilitate human dispersal from northeast Asia to the Americas? *Journal of Island and Coastal Archaeology* 10: 392–411. DOI: 10.1080/15564894.2014.1001923.

FAO. 2016. *The state of world fisheries and aquaculture 2016. Contributing to food security and nutrition for all.* Rome, Italy. 200 pp. http://www.fao.org/3/a-i5555e.pdf

Fernández P.A., Leal P.P. & Henríquez L.A. 2019. Co-culture in marine farms: macroalgae can act as chemical refuge for shell-forming molluscs under an ocean acidification scenario. *Phycologia* 58: 542–551. DOI: 10.1080/00318884.2019.1628576.

Hafting J.J.T., Craigie J.S.J.J.S., Stengel D.B.D., Loureiro R.R., Buschmann A.H., Yarish C., Edwards M.D. & Critchley A.T. 2015. Prospects and challenges for industrial production of seaweed bioactives. *Journal of Phycology* 51: 821–837. DOI: 10.1111/jpy.12326.

Hurtado A., Neish I.C. & Critchley A.T. 2019. Phyconomy: the extensive cultivation of seaweeds, their sustainability and economic value, with particular reference to important lessons to be learned and transferred from the practice of eucheumatoid farming. *Phycologia* 58: 472–483. DOI: 10.1080/00318884.2019.1625632.

Hwang E.K., Yotsukura N., Pang S.J., Su L. & Shan T.F. 2019. Seaweed breeding programs and progress in eastern Asian countries. *Phycologia* 58: 484–495. DOI: 10.1080/00318884.2019.1639436.

Kim J.K., Stekoll M. & Yarish C. 2019. Opportunities, challenges and future directions of open-water seaweed aquaculture in the United States. *Phycologia* 58: 446–461. DOI: 10.1080/00318884.2019.1625611.

Lee H.-J. & Choi J.-I. 2019. Enhancing temperature tolerance of *Pyropia tenera* (Bangiales) by inducing mutation. *Phycologia* 58: 496–503. DOI: 10.1080/00318884.2019.1623547.

Neori A., Troell M., Chopin T., Yarish C., Critchley A. & Buschmann A. H. 2007. The need for a balanced ecosystem approach to blue revolution aquaculture. *Environment: Science and Policy for Sustainable Development* 49: 36–43.

Roleda M.Y. & Hurd C.L. 2019. Seaweed nutrient physiology: application of concepts to aquaculture and bioremediation. *Phycologia* 58: 552–562. DOI: 10.1080/00318884.2019.1622920.

Shannon E. & Abu-Ghannam N. 2019. Seaweeds as nutraceuticals for health and nutrition. *Phycologia* 58: 563–577. DOI: 10.1080/00318884.2019.1640533.

Valero M., Guillemin M.L., Destombe C., Jacquemin B., Gachon C., Badis Y., Buschmann A.H., Camus C. & Faugeron S. 2017. Perspectives on domestication research for sustainable seaweed aquaculture. *Perspectives in Phycology* 4: 33–46.

Yang L.E., Lu Q.Q. & Brodie J. 2017. A review of the bladed Bangiales (Rhodophyta) in China: history, culture and taxonomy. *European Journal of Phycology* 52: 1–13. DOI: 10.1080/09670262.2017.1309689.

Zollmann M., Robin A., Prabhu M., Polikovsky M., Gillis A., Greiserman S. & Golberg A. 2019. Green technology in green macroalgal biorefineries. *Phycologia* 58: 516–534. DOI: 10.1080/00318884.2019.1640516.