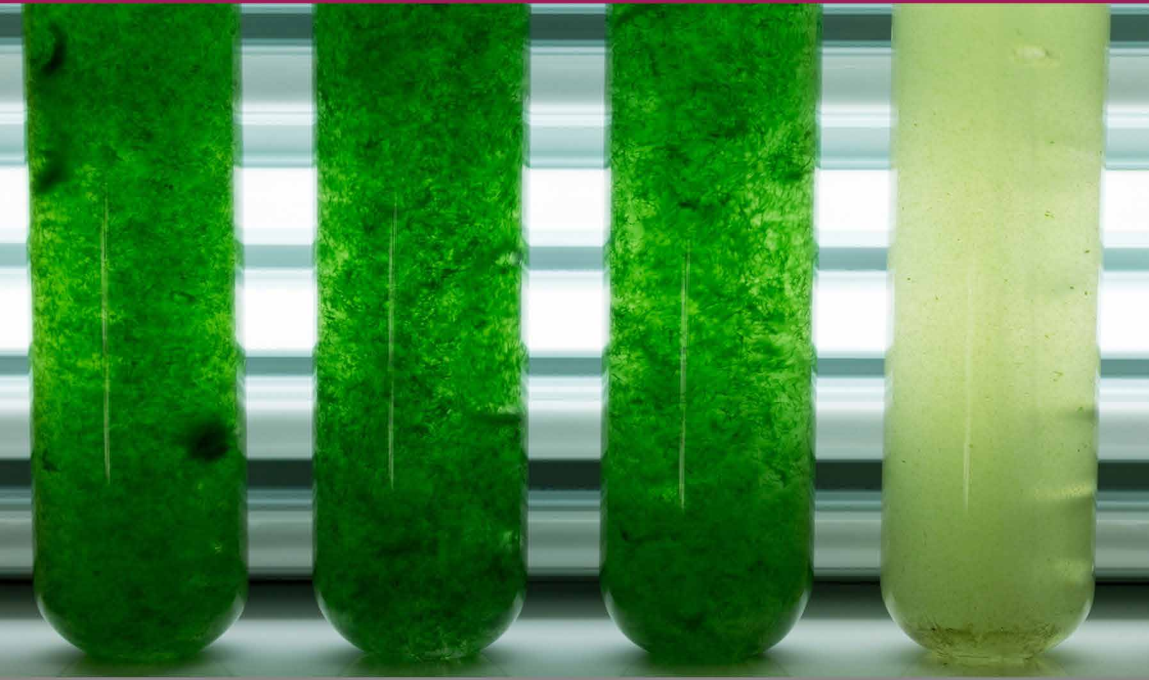
BURLEIGH DODDS SERIES IN AGRICULTURAL SCIENCE

Seaweed and microalgae as alternative sources of protein

Edited by Professor Xin Gen Lei, Cornell University, USA



burleigh dodds
SCIENCE PUBLISHING

Seaweed and microalgae as alternative sources of protein

Contents

© Burleigh Dodds Science Publishing Limited, 2021. All rights reserved.

© Burleigh Dodds Science Publishing Limited, 2021. All rights reserved.

© Burleigh Dodds Science Publishing Limited, 2021. All rights reserved.

© Burleigh Dodds Science Publishing Limited, 2021. All rights reserved.

© Burleigh Dodds Science Publishing Limited, 2021. All rights reserved.

Introduction

With traditional sources of protein considered as major contributors to climate change, there is growing interest in alternative, more ‘climate-smart’ sources of protein. This collection assesses the viability of using macroalgae (seaweed) and microalgae as sustainable protein sources.

Part 1 of the book discusses the different types of macroalgae and microalgae and how they can be used as alternative sources of protein in the food animal sectors. Chapters focus on areas such as using algae in animal feeds, the use of cyanobacteria and eukaryotic microalgae for solar energy conversion, and the extraction of proteins and other functional components from red seaweed. Part 2 focuses on the cultivation and processing of algae, specifically developments in commercial scale farming, developments in algal processing, bioprocessing of microalgal protein and the environmental impacts of seaweed cultivation. Part 3 of the book highlights the use of algae in ruminant, pig, poultry and fish diets.

Part 1 Types of macroalgae and microalgae

The first chapter of the book discusses algae as a potential protein supplement in animal feeds. Chapter 1 begins by highlighting novel protein sources for animal feed and the key factors for selecting alternative protein sources for both human and animal nutrition. The chapter also examines the production of algae for foods and feeds, then goes on to discuss the nutrient composition of different algae. A section on algae as protein supplements in feed is also included. The chapter then provides a summary that emphasises the potential importance of using algae as an alternative in providing nutrients to animals.

The next chapter focuses on solar energy conversion, oxygen evolution and carbon assimilation in cyanobacteria and eukaryotic microalgae. Chapter 2 starts by discussing the evolution and diversity of the photoautotrophic cyanobacteria and microalgae. It then moves on to examine photosynthesis and conversion of solar energy, focusing on areas such as light-harvesting antenna and pigments, the importance of chlorophyll and how phycobilins can fill the gap of chlorophylls. The chapter also discusses carotenoids and how they can facilitate excitation energy transfer and photoprotection. A section on the functions of photosystems in converting light energy into chemical energy is also provided, which is then followed by an analysis of photosynthetic CO_2 assimilation and the potential of cyanobacteria and microalgae.

The final chapter of Part 1 examines the extraction of proteins and other functional components from red seaweed (*Rhodophyta*). Red seaweeds are a major industrial source of agar and carrageenan. They also contain high amounts

© Burleigh Dodds Science Publishing Limited, 2021. All rights reserved.

of other polysaccharides and higher amounts of proteins than brown seaweeds. Some species of red seaweed also contain polyphenols with antioxidant activities as well as being a source of carotenoids and phycobiliproteins. However, there are currently no commercial-scale methods for extracting those bioactive compounds. Chapter 3 provides an overview of various methods for extracting all these functional compounds from red seaweeds. Whereas the main emphasis is on the extractions of proteins, extractions of polysaccharides (carrageenan and agar) and antioxidants (phenolic compounds) are covered. Multi-extraction approaches for extractions of bioactive compounds from red seaweeds are also described.

Part 2 Cultivation and processing

Part 2 opens with a chapter that discusses the developments in commercial scale farming of microalgae and seaweeds. Chapter 4 highlights how expanding markets for microalgae and macroalgae products have led to increased development of commercial farming operations. While microalgae and macroalgae, or seaweed, have historically been harvested in many parts of the globe, more recent developments seek to improve productivity, decrease production costs, increase scale, and mitigate environmental impacts of cultivation. The chapter includes some of those recent developments and identifies future focus areas for research and development.

Chapter 5 considers the developments in algal processing. The chapter outlines various developments in processing technologies used for the treatment of algal biomass with discussion of scalability, cost, time, and efficacy. Topics cover methods for harvesting and dewatering algae, drying algal biomass, biomass disruption, and nutrient recovery, including case studies with lessons learned. The final section presents biomass applications and product considerations. While there is no universally adopted approach for processing algal biomass, these studies provide the foundation for making informed decisions, considering the unique properties of the algae and the integrity of the desired end products.

The subject of Chapter 6 is bioprocessing of microalgal protein and their applications in the cosmetic, nutraceutical and food industries. Microalgae have long been recognised for their nutritional value and high protein contents. They are highly productive and can be grown without competing for arable land or freshwater resources. Most microalgal protein contains all essential amino acids and is hence more suitable as a meat replacement than any other plant protein. Microalgal products are also readily suitable for cosmetic and nutraceutical applications due to their significant health benefits. The chapter provides an overview of the use of various protein-rich microalgae in food, feed, nutraceuticals, and cosmetics. The latest technical advances in protein

© Burleigh Dodds Science Publishing Limited, 2021. All rights reserved.

extraction from microalgae are presented, together with an overview of current knowledge on bioavailability and digestibility of microalgal proteins.

Chapter 7 addresses the environmental impacts of seaweed cultivation, focusing specifically on kelp farming and preservation. The chapter starts with a short overview of the life cycle assessment (LCA) methodology, and how it can be used to quantify the environmental impacts of seaweed supply chains. After a discussion of the overall environmental impacts of the preserved seaweed supply chain, the chapter focuses on specific life cycle stages: spore preparation and seeding of juvenile seaweed onto string in the hatchery, seaweed cultivation, harvesting preservation and storage of harvested seaweed. The chapter ends with a summary and discussion of future trends in the subject.

Part 3 Applications

The first chapter of Part 3 examines the nutritional and anti-methanogenic potentials of macroalgae for ruminants. Chapter 8 begins by discussing the nutritional value of macroalgae, then goes on to examine its digestibility as a feed or feed ingredients. The livestock production sector is facing challenges to find alternative feed resources and nutritional strategies to mitigate enteric methane (CH_2) emissions from ruminants. Recently, marine macroalgae have emerged as potential anti-methanogenic feed ingredients due to their ability to suppress enteric CH_4 production in ruminants. The anti-methanogenic properties of macroalgae have been ascribed to the contents of secondary metabolites, such as halogenated compounds e.g. bromoform in red species, and polyphenols or isoprenoids in brown species. The chapter also analyses the anti-methanogenic properties of macroalgae. A section on the processing and seasonal effects of these properties is also provided, before concluding with an analysis of potential future research trends and a section that emphasises the importance of using macroalgae as alternative ruminant feeds.

The next chapter addresses developing macroalgae as feed for pigs. Macroalgae are a promising source of nutritional ingredients including proteins, polysaccharides and minerals. The need to increase animal and feed production has increased interest in macroalgae as underutilised resources with promising applications as alternative animal feeds. Chapter 9 summarises the nutritional attributes of macroalgae in terms of macro and micronutrients as a source of protein and other compounds in pig nutrition. The benefits of macroalgae or macroalgal derived extracts in feed are discussed together with future trends and challenges in the development of effective feed formulations.

Moving on from Chapter 9, Chapter 10 examines microalgae and its importance as a source of dietary protein, lipids and other compounds for poultry. The chapter reviews effects of supplemental full- or de-fatted microalgal biomass in diets for broiler chickens, laying hens, and other types of poultry on

© Burleigh Dodds Science Publishing Limited, 2021. All rights reserved.

their production performance, meat and egg qualities, nutrient metabolism, and molecular responses. Different sources of microalgal biomass have shown excellent potential to replace a good amount of soybean meal and/or corn without adverse effects. Meanwhile, microalgae are used to enrich chicken meat and eggs with N-3 polyunsaturated fatty acids and bioactive phytochemicals for adding human health-promoting values to these animal products. The dual application of microalgae for producing biofuels and replacing conventional feed protein stands as propitious mediator to reshape the junction between intensifying animal agriculture and meeting the global needs for energy, food, and environmental sustainability.

Chapter 11 focuses on developing macroalgae and microalgae as feed for fish. The rapid expansion of aquaculture industry is severely restricted by the shortage of key feed ingredients such as fishmeal and fish oil. Application of marine plants (macro and microalgae) as dietary ingredients could potentially overcome the limitation of key feed ingredients used in aquafeed. The chapter summarises the current knowledge of the use of macro and microalgae in aquafeed and their effects on overall fish performance.

© Burleigh Dodds Science Publishing Limited, 2021. All rights reserved.

Chapter 1

Seaweed as a potential protein supplement in animal feeds

Sung Woo Kim, North Carolina State University, USA

1 Introduction

Global meat demand has been steadily increasing due to population and economic growth, putting pressure on feed supply to support animal production (FAO, 2003). Protein supplements are typically the most expensive components in animal feeds (Kim et al., 2019). The price of protein supplements varies largely depending on their source. Traditional protein supplements include oilseeds, animal coproducts, and distillers grains. Soybean meal is currently the most widely used protein supplement in animal feeds. Two hundred and thirty-eight million metric tons (MT) of soybean meal were used in animal feeds globally in 2020, representing almost 70% of all oilseed meal consumed (ASA, 2020; FAS, 2021). The use of soybean meal in animal feeding increased from 165 million MT in 2010 to 238 million MT in 2020, representing an annual increase of 3.8% (Table 1). The use of dried distillers grains (DDGs) in animal feeds has also become popular since 2000, increasing rapidly to 39 million MT in the US (ERS, 2020a).

Improvements in yield have been a major factor enabling crop production to meet this demand. In the United States, for example, soybean yield improved from 2.89 MT/ha in 2010 to 3.56 MT/ha in 2018 (NASS, 2018). However, there has also been a need to expand agricultural land use to support crop production to meet the demand for foods and feeds (NASS, 2018; ERS, 2020b; FAS, 2021). An

http://dx.doi.org/10.19103/AS.2021.0091.01
© Burleigh Dodds Science Publishing Limited, 2021. All rights reserved.

Table 1 Global production of soybean meal (million metric ton)[1]

Year	Argentina	Brazil	Canada	China	EU	India	Mexico	Paraguay	USA	Other	Total
09/10	26.6	26.1	1.0	38.6	10.0	6.2	2.9	1.2	37.8	14.7	165.2
10/11	29.3	28.2	1.1	43.6	9.7	7.5	2.9	1.3	35.6	15.9	175.0
11/12	27.9	29.5	1.1	48.3	9.2	8.2	2.9	0.7	37.2	15.8	180.9
12/13	26.1	27.3	1.2	51.5	10.0	8.6	2.9	2.3	36.2	16.1	182.2
13/14	27.9	28.5	1.2	54.6	10.3	7.0	3.2	2.8	36.9	18.1	190.4
14/15	30.9	31.3	1.3	59.0	11.4	6.2	3.3	2.9	40.9	21.3	208.5
15/16	33.2	30.8	1.5	64.5	11.8	4.4	3.5	3.0	40.5	22.8	216.0
16/17	33.3	31.3	1.4	69.7	11.4	7.2	3.6	2.9	40.6	24.5	225.9
17/18	28.4	34.3	1.5	71.3	11.8	6.2	4.2	3.0	44.7	27.4	232.7
18/19	31.2	33.4	1.6	67.3	12.8	7.7	4.4	3.1	44.3	28.7	234.4
19/20	33.8	34.0	1.5	66.9	12.6	6.4	4.7	3.0	44.9	30.1	237.8

[1] Data were adapted from FAS (2021).

© Burleigh Dodds Science Publishing Limited, 2021. All rights reserved.

estimated 11% of the land is used globally for crop production, covering about 40% of the land potentially available for agriculture (FAO, 2003). However, there are clear limitations to further expansion of agriculture land due partly to the availability of water (McDaniel et al., 2017; Sloat et al., 2018). About 10% of land currently used for agriculture could face water shortages (Fitton et al., 2019). Limitations in available agriculture land and water will potentially limit further expansion of animal production and could even threaten the existing level of production (Sloat et al., 2018). There is, therefore, a need to consider alternative nutrient sources to support growing animal production.

It is important to note that there are a number of challenges in using alternative protein sources. Protein sources from plants contain compounds that interfere with nutrient digestion or impairing animal intestinal health. These compounds are collectively called antinutritional factors and include trypsin inhibitor, lectin, glycinin, β-conglycinin, raffinose family oligosaccharide, and β-galactomannan (Kim et al., 2003; Hong et al., 2004; Taliercio et al., 2014). While the digestive tract of mature animals can cope with most of these antinutritional factors, this is not true for young animals which suffer inflammatory response and oxidative damage in the intestinal epithelium, leading to impaired nutrient digestion and absorption and ultimately reduced growth (Zhao et al., 2014; Yin et al., 2017; Chen et al., 2017; Sun and Kim, 2017).

To avoid problems with antinutritional factors, animal-based protein supplements, mostly rendered animal coproducts, have been used extensively in feeding young animals. These coproducts include meat meal, meat and bone meal, poultry coproduct meal, fish meal, blood coproducts (blood meal, blood cells, and blood plasma), and milk coproducts (dried skim milk, whey protein concentrates, and casein) which are mostly free of typical antinutritional factors. However, the use of rendered animal coproducts has been limited by restrictions in supply. Global production of fish meal, as an example, has fallen from 7 million MT in 1995 to 5 million MT in 2019 (Tacon et al., 2011; Rabobank, 2019). Some rendered animal by-products have also been banned for their potential associations with zoonotic diseases and are less acceptable to consumers (Kim et al., 2019).

2 Novel protein sources for animal feeds

With these limitations in the amount and types of protein supplements available, animal nutritionists have been seeking alternative sources to replace conventional protein supplements. Key factors for selecting alternative sources include safety for both animals and consumers, nutritional value and palatability to animals, affordability and availability in large quantities, consistency in composition, and environmental sustainability (Hard, 2004; Jędrejek et al., 2016; Dee et al., 2018).

© Burleigh Dodds Science Publishing Limited, 2021. All rights reserved.

Emerging candidates for alternative protein supplements include:

- insect protein,
- single cell-based protein, and
- seaweed.

Larvae of selected insects such as black soldier flies and yellow mealworms can accumulate proteins (35%–55%) and lipids (10%–40%) and have been extensively reviewed (Rumpold and Schlüter, 2013; Makkar et al., 2014; DiGiacomo and Leury, 2019). Single-cell protein is derived from microorganisms (cells), including bacteria, fungi, microalgae, and yeast, with the latter being most developed (Spark et al., 2005; Shen et al., 2009; Espinosa et al., 2020). Reviews of the use of single-cell proteins include Kim et al. (2019) and Jones et al. (2020). The focus of this chapter is on the use of seaweed in animal feeds.

3 Seaweed production for foods and feeds

Seaweed is the common name for a wide range of multicellular macroalgae growing in the marine environment. Seaweed is often classified into three groups:

- Chlorophyta (also known as green macroalgae),
- Phaeophyta (also known as brown macroalgae), and
- Rhodophyta (also known as red macroalgae).

Seaweed has a crucial role in maintaining marine ecology as a source of nutrients and oxygen (Krause-Jensen and Duarte, 2016).

There are nearly 6000 species of seaweeds with a limited number of species used as food and feed sources. Currently, almost 30 million MT/year of seaweed is produced globally, mainly for biomass and food production, with only 1% used for animal feeds (Rajauria, 2015). Seaweed has long been cultured and used as food in Asian countries in particular (FAO, 2018). Production of cultured seaweed increased twofold from 14.3 MT in 2006 to 29.4 MT in 2015. China and Indonesia are major producers accounting for 47% and 38% of global production, respectively, followed by the Philippines (5.3%) and the Republic of Korea (4.1%), as shown in Fig. 1 (FAO, 2018).

Cultured seaweeds from China and Korea are mainly used for foods, whereas those from Indonesia and the Philippines are mainly for the extraction of carrageenan and agar used as an ingredient in food processing and other applications (FAO, 2018). The major cultured seaweed in China is *Saccharina japonica* (a brown seaweed), whereas Korea mainly produces *Pyropia tenara* (a red seaweed) (Abbot, 1988). Major cultured seaweeds from Indonesia and

© Burleigh Dodds Science Publishing Limited, 2021. All rights reserved.

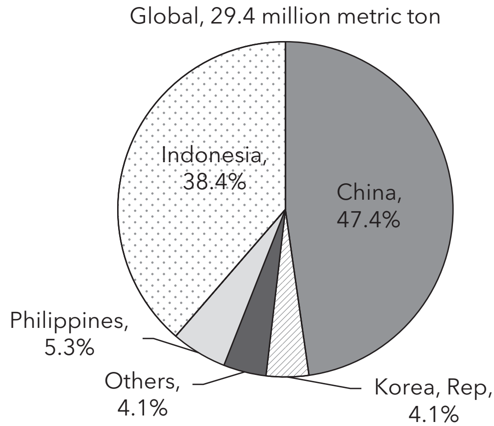


Figure 1 Global production of cultured seaweeds (FAO, 2018).

the Philippines are *Eucheuma* and *Kappaphycus* (Hurtado et al., 2017; Lucas and Southgate, 2012). In the northern Atlantic regions, *Ascophyllum nodosum* (a brown seaweed) is not cultured but extensively harvested for biomass and animal feeds (Anderson et al., 2006; Braden et al., 2007).

4 Nutrient composition of seaweeds

The nutrient composition of seaweeds varies significantly depending on species. On a dry matter basis, seaweeds are mainly composed of carbohydrates (30%–55%), minerals (20%–30%, mainly ash), and protein (7%–30%) with minor amounts of fat (1%–9%) and phenolic compounds (MacArtain et al., 2007; Kumar et al., 2015; Makkar et al., 2016; Ganesan et al., 2020). In general, green and red seaweeds have higher protein content than brown seaweeds (Cabrita et al., 2016). Nutrient composition within a species can also vary depending on season and environmental conditions. Protein and carbohydrate contents are generally highest in young seaweed at the end of winter, whereas fat and ash contents are highest in the spring (Dawes, 1987; Kumar et al., 2015).

Excluding water, carbohydrates are the major component of seaweed, comprising alginates, carrageenans, and agar (MacArtain et al., 2007; Rioux et al., 2007). Seaweed also contains β-glucans (Bobadilla et al., 2013; Nakashima et al., 2018). These are indigestible polysaccharides with a potential role as prebiotics (O'Sullivan et al., 2010; Charoensiddhi et al., 2020; Lopez-Santamarina et al., 2020). Seaweeds contain high levels of minerals such as K (1.5%–4.5%), Na (0.5%–4%), and Ca (0.4%–2%), while the content of other minerals varies depending on the type of seaweeds (Holdt and Kraan, 2011). According to Cabrita et al. (2016), Lorenzo et al. (2017), and Circuncisão et al. (2018), green seaweeds are generally high in Mg (about 2% in green seaweeds

© Burleigh Dodds Science Publishing Limited, 2021. All rights reserved.

Index

© Burleigh Dodds Science Publishing Limited, 2021. All rights reserved.

© Burleigh Dodds Science Publishing Limited, 2021. All rights reserved.

© Burleigh Dodds Science Publishing Limited, 2021. All rights reserved.

© Burleigh Dodds Science Publishing Limited, 2021. All rights reserved.

© Burleigh Dodds Science Publishing Limited, 2021. All rights reserved.

© Burleigh Dodds Science Publishing Limited, 2021. All rights reserved.

© Burleigh Dodds Science Publishing Limited, 2021. All rights reserved.

© Burleigh Dodds Science Publishing Limited, 2021. All rights reserved.