Journal of Elementology ISSN 1644-2296

Chwastowska-Siwiecka, I. and Miciński, J. (2023)
'Characteristics and applications of marine algae in the agri-food industry and animal nutrition'
Journal of Elementology, 28(3), 855-874,
available: https://doi.org/10.5601/jelem.2023.28.3.3044

RECEIVED: 23 July 2023
ACCEPTED: 19 September 2023

REVIEW PAPER

Characteristics and applications of marine algae in the agri-food industry and animal nutrition*

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Abstract

The aim of this review article was to present the characteristics and properties of marine algae and their potential applications in agriculture, biofuel production, the food industry, and livestock nutrition. Algae are autotrophic aquatic organisms with a varied morphological structure. The earliest forms of algae evolved in the sea 3.5 billion years ago. These are unicellular organisms or multicellular and tissue organisms. Brown, red and green algae have many industrial applications. The algal cytoplasm contains primary and secondary metabolites, minerals, and vitamins which are essential for bodily functions. Algal polysaccharides, in particular alginic acid, fucoidan, agar, carrageenan, carotenoids, chlorophylls, hyaluronic acid, and porphyran, are widely used in medicine, pharmaceutical industry, cosmetology and in the food industry. Algae can play an important role in sustainable agriculture. They are used in the production of dietary supplements owing to their high nutritional value. Algal biomass is a renewable source of valuable bioactive ingredients for food production, and also for the chemical sector. The use of algae in livestock nutrition has improved animal performance and the quality of animal-derived raw materials intended for processing. Feed additives containing nutrients and filtered algal suspensions deliver health benefits, thus increasing animal productivity and, consequently, farming profits. Algal species and the optimal harvesting times when seaweed is most abundant in nutrients should be analyzed to minimize the potential adverse effects of algae-based diets of human and animal.

Keywords: marine algae, applications, algal biomass, food industry, animal nutrition

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* This work was financed from the statutory research of Department of Sheep and Goat Breeding University of Warmia and Mazury in Olsztyn.

INTRODUCTION

Food quality is affected by the quality of livestock diets and the health status of animals. The nutritional status of animals is influenced by both the quantity and quality of feed, including feed hygiene and the content of nutrients and feed additives such as minerals and vitamins, which have to meet the energy and protein requirements of different livestock species. Complete and nutritionally balanced rations promote animal health, contribute to protecting the environment (undigested feed components are not deposited in the soil), and increase farming profits (by decreasing feed costs) – Dymek, Skiba (2014).

In recent years, marine algae have attracted considerable interest as additives in livestock nutrition. Algae have been approved for use in animal diets by the Regulation of the Minister of Agriculture and Rural Development of 5 May 2011 on the classification of feedstuffs. Research on the chemical composition of algae and numerous toxicological and nutritional analyses have shown that algal biomass is a valuable feed additive and an alternative protein source that can replace conventional protein sources in animal diets (soybean meal, fish meal, and rice bran) (Becker 2007, Chojnacka et al. 2012). Feeds containing algae boost the immune system, improve fertility, increase weight gains, and improve the overall health of animals. Livestock diets supplemented with algae increase the concentrations of bioactive compounds in meat, milk, and eggs. Algae have been effectively used in diets for poultry, cattle, horses, ornamental birds and aquarium fish. The use of algae in livestock nutrition has improved animal performance and the quality of animal-derived raw materials intended for processing. Feed additives containing nutrients and filtered algal suspensions deliver health benefits, thus increasing animal productivity and, consequently, farming profits. Innovative algal preparations exert stimulatory effects, harness the animals' genetic potential, improve animal welfare and reproductive performance, while maintaining food safety and quality (Chojnacka et al. 2012, Dymek, Skiba 2014, Mirowski 2019).

CHARACTERISTICS AND PROPERTIES OF MARINE ALGAE

Marine algae or seaweed (*Algae* in Latin, *Phykos* in Greek) are autotrophic aquatic organisms of highly variable morphology. Algae are unicellular or multicellular thallophytes and eukaryotes (Muszyńska et al. 2016). This group of autotrophic, mostly thalloid and non-vascular organisms also includes prochlorophytes and bacteria (Kozieł, Włodarczyk 2011).

In the Far East, algae have been long regarded as a valuable source of food, and they have been used for medicinal purposes and in the production of cosmetics. In Western Europe, algae gained recognition only at the turn of the 19th and 20th centuries, when scientists discovered that seaweed is a rich source of iodine and alginic acid (Kępska, Olejnik 2014). Algae can be used as a remedy for various health conditions, from treating the common cold to inhibiting cancer development, and in recent years, their popularity has increased considerably in Europe, including Poland (Godlewska et al. 2014). Algae are produced mainly for human consumption, and more than 2 million tons of fresh algae (nori, wakame, and kobu) are consumed each year in the Far East. Each year, around 1.5 million tons of algae are processed industrially (phytocolloids, alginates, agar, and carrageenan), mostly in the USA, Norway, France, the United Kingdom, and Japan, as well as in Chile, China, Russia, India, and other countries (Pielesz 2010). The first commercial microalgal cultivation systems were built in the 1960s in Japan (*Chlorella*) and in the 1970s in Mexico (*Arthrospira* or spirulina). By 1980, more than 1 000 kg of microalgae (mostly *Chlorella*) were produced each month in Asia. New commercial seaweed farms were built in Israel, India and in the USA. In 2006, global microalgal biomass production reached 5 000 kg of dry matter (DM) (Spolaore et al. 2006).

Algal species and the optimal harvesting time, when seaweed is most abundant in nutrients, should be analyzed to minimize the potential adverse effects of algae-based diets of humans and animals (Rudawska et al. 2018). Algae containing valuable chemical compounds are used mainly in cosmetic and pharmaceutical industries, as well as in medicine, food processing, agriculture and environmental protection. Seaweed is processed into extracts and meal. Algal extracts are used in the production of creams, lotions and shampoos, whereas seaweed meal is added to face masks, body wraps and weight loss products (Frąc et al. 2009, Muszyńska et al. 2016). Algae are used in the production of over-the-counter medicines and functional foods, including freeze-dried powders, tablets and capsules, as well as in the cosmetic industry. The following seaweed taxa are most widely processed into food, medicinal products and cosmetics: Cyanobacteria (*Arthrospira platensis* and *Arthrospira maxima*), red algae of the genera Porphyra (*Porphyra yezoensis* and *Pyropia tenera*) and Chondrus (*Chondrus crispus*), red algae of the families Gelidiaceae and Gigartinaceae, brown algae (*Fucus vesiculosus*, *Fucus serratus*, and *Ascophylum nodosum*), and green algae (*Chlorella vulgaris* and *Ulva lactuca* (Figure 1) (Muszyńska et al. 2016).

The taxonomic classification of algae poses a challenge due to considerable differences in their morphology. There are 11 main classes of algae, and more than 20,000 of algal species belonging to different kingdoms (Plantae, Protista, and Bacteria) have been identified to date. Algae are classified mainly based on their cell structure, cell wall composition, and biomass color. Eukaryotic algae are divided into Glaucophyta, Pyrrophyta, Euglenida, and

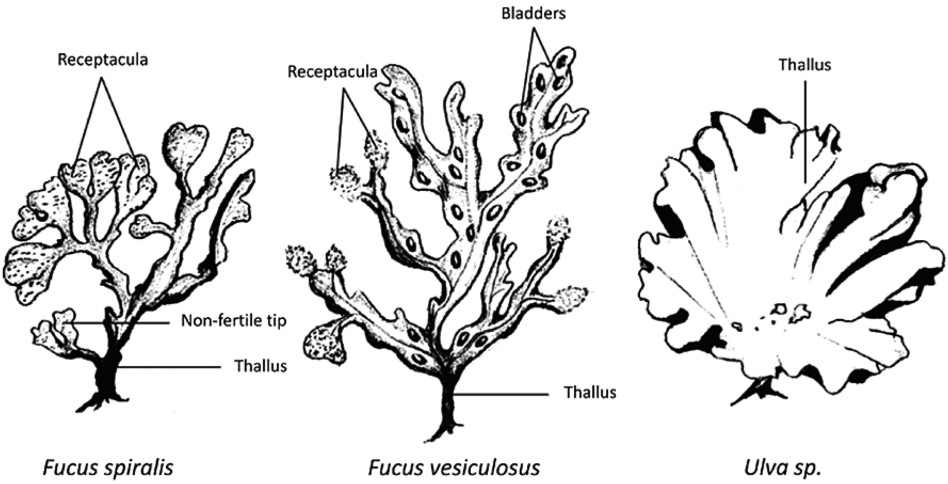

Fig. 1. Structure of brown and green algae (Guden et al. 2018)

Chrysophyta represented by golden algae (Chrysophyceae), haptophytes (Prymnesiophyceae, Haptophyceae), yellow-green algae (Xanthophyceae), diatoms (Bacillariophyceae), eustigmatophytes (Eustigmatophyta), cryptophytes, red algae, brown algae and green algae (Kępska, Olejnik 2014). Algae are harvested in oceans, seas and other natural water bodies, or cultivated in farms (algaculture). Algae colonize all geographical zones, but they are most abundant in the northern hemisphere, where around 1.5 million tons of seaweed are harvested each year. Brown, red, and green algae are most widely used in food production and industry (Frąc et al. 2009). Algal species are characterized by different morphology and properties, and they differ in size from microscopic unicellular organisms (microalgae) to large seaweeds (macroalgae) with a length up to several dozen meters (Urbańska, Kłosowski 2012). Many species of both prokaryotic and eukaryotic algae have natural features that make them desirable as a food source for human consumption. Algae are capable of fast and cost-effective photosynthetic growth, have been shown to exert positive effects on human health, and have a robust set of tools that can lead to domestication and biomass improvements (Diaz et al. 2023). Algal species also differ in nutritional value, and they are harvested with the use of various methods (Table 1).

Algae are a source of essential nutrients, including carbohydrates, proteins, lipids, micronutrients, macronutrients and vitamins (Or-Rashid et al. 2008, Nagarajan et al. 2021, da Rosa et al. 2023). Brown algae contain 75-90% water, 30-50% minerals, 30-50% carbohydrates, 7-15% protein, 2-5% lipids and 2-10% cellulose. Carbohydrates account for up to 60% of all bioactive compounds in seaweed (Pielesz 2011). Algal carbohydrates include glycosaminoglycans (GAGs), also known as mucopolysaccharides, which are composed of amino sugars and uronic sugars, as well as fucans, mannitol,

Table 1

Classification of algae (Chojnacka et al. 2012)

<table>
<tr><td colspan="5">Algae</td></tr>
<tr><td colspan="2">Microalgae</td><td colspan="3">Macroalgae</td></tr>
<tr><td>Eukaryotes</td><td>Prokaryotes</td><td>Chlorophytes</td><td>Brown algae</td><td>Red algae</td></tr>
<tr><td colspan="5">Biomass production methods</td></tr>
<tr><td colspan="2">– Harvesting from the seas
– Farming in natural waters (algaculture)</td><td colspan="3">– Cultivation systems:
✓ photobioreactors
✓ ponds</td></tr>
<tr><td colspan="5">Composition</td></tr>
<tr><td colspan="2">– polysaccharides
– protein
– polyunsaturated fatty acids
– dyes
✓ chlorophyll
✓ carotenoids
✓ phycobilisome
– polyphenols
– minerals
– stimulators of plant growth:
✓ cytokinins</td><td colspan="3">– polysaccharides
– protein
– polyunsaturated fatty acids
– dyes
✓ chlorophyll
✓ carotenoids
✓ phycobilisome
– polyphenols
– minerals
– stimulators of plant growth:
✓ cytokinins</td></tr>
</table>

sorbitol, carrageenans (natural hydrocolloids) and agar, which is used as a natural thickening and gelling agent. Seaweed is also a rich source of proteins and amino acids, such as glycoproteins, metalloproteins, and exogenous amino acids (alanine, asparagine, glycine, lysine, serine, isoleucine, leucine, methionine, phenylalanine, threonine, tryptophan, and valine) – Godlewska et al. (2014). Algal lipids provide essential fatty acids, including arachidonic acid, eicosapentaenoic acid (EPA), docosahexaenoic acid (DHA), and the rarely occurring *γ*-linolenic acid (GLA) (Schroeder et al. 2013, da Rosa et al. 2023). As regards vitamins, algae synthesize carotenoids, including *β*-carotene (a precursor of vitamin A), and they contain B vitamins (including vitamins B_1, B_2, B_5, B_6, and B_{12}), and vitamins E, C, and D. Seaweed is a rich source of readily available macronutrients and micronutrients, such as iron, manganese, magnesium, copper, iodine, bromide, zinc, calcium, sodium, potassium and phosphorus, which occur in metal-organic compounds. Algae also contain polyphenols, which are potent anti-inflammatory agents and free radical scavengers; natural pigments, such as phycoerythrin, phycocyanin and chlorophyll, which protect plants against UV damage, as well as biogenic compounds with antibacterial properties (Spolaore et al. 2006, Pielesz 2011, Godlewska et al. 2014, Kępska, Olejnik 2014).

Macroalgae or seaweed can be classified as functional foods. In many parts of the world, these algae have been consumed and used in traditional medicine for many centuries (Chandini et al. 2008). Brown algae differ in shape, and they are the largest seaweeds with a length of up to 35-45 m.

Brown algae grow mainly in shallow waters and along rocky shores. These thallophytes form long monoaxial or multiaxial hyphae, often with pseudoparenchymatic structures. Kelp (*Laminaria japonica*) and wakame (*Undaria pinnatifida*) have been a part of the local cuisine and traditional medicine in many Asian and coastal countries for centuries (Rudawska et al. 2018). The nutritional content of Spirulina microalgae determined by Japanese scientists is presented in Table 2.

Table 2

Proximate composition of Spirulina (Shimamatsu 2004)

Composition	Content (per 100 g dry wt)
Moisture (g)	3.00
Protein (g)	61.40
Fat (lipids) (g)	8.50
Fiber (g)	3.00
Ash (g)	7.70
N-free extract (g)	16.40
Pigments	
Phycocyanin (g)	16.20
Carotenoids (mg)	477.00
Chlorophyll-*a* (g)	1.20
Vitamins	
Provitamin A (mg)	214.0
Vitamin B_1 (thiamin) (mg)	1.98
Vitamin B_2 (riboflavin) (mg)	3.63
Vitamin B_6 (mg)	0.59
Vitamin B_{12} (mg)	0.11
Vitamin E (mg)	11.80
Niacin (mg)	13.20
Folic acid (µg)	42.00
Pantothenic acid (mg)	0.88
Inositol (vitamin B_8) (mg)	74.00
Minerals	
Phosphorus (mg)	914.00
Iron (mg)	57.40
Calcium (mg)	171.00
Potassium (g)	1.77
Sodium (g)	1.05
Magnesium (mg)	257.00

THE APPLICATION OF ALGAE IN FOOD PROCESSING, COSMETIC AND PHARMACEUTICAL INDUSTRIES

Algae are a rich source of valuable compounds that are used in many branches of food processing, cosmetic and pharmaceutical industries. Algae-based cosmetics and creams supply the skin with nutrients, promote skin regeneration and scar healing. Algal carbohydrates exert strong moisturizing and protective effects, whereas algal lipids regenerate and protect the skin. Seaweed also contains vitamins and minerals, which strengthen blood vessels, rejuvenate the skin and restore skin elasticity. Due to their high nutritional value, algae are highly suitable for the production of functional foods. Seaweed is a rich source of protein, essential amino acids and vitamins. *Spirulina*, green algae of the genus *Chlorella*, and *Aphanizomenon flos-aquae* are most widely used in the food industry. Algae remove toxins from the body, promote digestion and protect the gastric mucosa. They enhance memory and concentration, and are helpful in the management of diabetes, rheumatic diseases and hypertension. Algae have the potential to fight bacterial, fungal and viral infections. They alleviate inflammations, pain and fever (Kępska, Olejnik 2014, Kępińska-Pacelik, Biel 2022). Algae contain compounds with anticarcinogenic properties, including carotenoids, flavonoids and phenolic compounds, and their potential is harnessed in the development of novel cancer therapies (Sheih et al. 2010, Godlewska et al. 2014).

Alginic acid is a polysaccharide found in the cell walls of brown algae (Phaeophyceace) and the slime layer surrounding the cell wall of some bacterial species, including *Azotobacter vinelandii*, *Pseudomonas aeruginosa* and *Pseudomonas fluorescens*. Alginates (salts of alginic acid) are used in food, pharmaceutical and automotive industries and in dental prosthetics. In the food processing sector, sodium alginate is used as a thickening, gelling and stabilizing agent in salad dressings, low-fat mayonnaise, frozen fish products, jam, jelly and ice-cream. Sodium alginate is also applied as a clarifying agent in the production of juice, wine, beer and mead. In Europe, sodium alginate is a food additive denoted with number E401. In the pharmaceutical industry, alginates (salts of alginic acid with cations such as sodium, potassium, magnesium, calcium, and ammonium) are used to produce ointments, creams and pastes. Alginate extracted from brown algae has the largest number of industrial applications. The structure of alginate is determined by algal species, geographic origin and variety (including seasonal varieties) (Muszyńska et al. 2016). In the food processing industry, algal biomass is added to pasta or even chewing gum, and it is also used as a natural food colorant. Seaweed is also an alternative protein source. *Chlorella* and *Spirulina* were the first algal genera to be used in the production of superfoods in Japan, Taiwan, and Mexico (Cuellar-Bermudez et al. 2015, Kępińska-Pacelik, Biel 2022). For example, some species of algae, such as *Chlorella*, *Arthrospira* and *Aphanizomenon*, are an appealing food source for human consumption since they contain a high level of essential amino acids (EAAs) as well as other health-enhancing nutrients (Kusmayadi et al. 2021). *Chlorella* is also used as a coloring ingredient in shortbread biscuits, and it is added to milk and yogurt to increase their nutritional value (Guccione et al. 2014).

ALGAL BIOFUELS

The use of algae as a source of energy is not a new concept, and algal biofuels attract growing interest on the market of alternative fuels. Algae farming for biofuel production can mitigate climate change by reducing the demand for fossil fuels and absorbing significant quantities of atmospheric CO_2 (Frąc et al. 2009, Diaz et al. 2023). Algal biomass can be converted to solid, liquid and gaseous biofuels. Freshwater algae have relatively low nutritional requirements, and they are the most promising source of biomass for the production of biodiesel and other biofuels due to rapid photosynthesis, high biomass yield and high lipid content (up to 77% on a DM basis). As a rich source of lipids, proteins, carbohydrates and other metabolites, algae can be effectively converted to biodiesel. The production of biodiesel consists of several stages, and the most important stage is transesterification, during which tri-, di- and monoacylglycerols react with alcohol in the presence of a base (KOH, NaOH) or acid (H_2SO_4) catalyst. During transesterification, lipids are converted into fatty acid methyl esters (biodiesel) and glycerol (by-product). Biodiesel is purified by removing residues of glycerol, free fatty acids, the catalyst and methanol (Frąc et al. 2009, Schroeder et al. 2013,). According to Schroeder et al. (2013), due to high biomass productivity, the production cycle of algal biodiesel lasts only 3-5 days, which is significantly shorter in comparison with conventional oilseed crops (3 months to 3 years). According to estimates, some species of microalgae can produce 10-20 times more biofuel than oilseed crops such as rapeseed (Table 3).

Algal biomass can be also converted to bioethanol and biogas. Both cultured algae and naturally growing seaweed can be used for this purpose. Algae absorb large amounts of carbon dioxide during growth, thus reducing the concentrations of greenhouse gases in the atmosphere. In a study by Kuligowski et al. (2010), biogas output in the anaerobic digestion of *Macrocystis pyrifera* and *Durvillea antarctica* reached 180.4 ml g^{-1} of dry biomass, with methane concentration of 65%. The biogas output of a digester stocked with a mixture of manure and maize silage was only somewhat higher at 216 ml g^{-1}, with methane concentration of 60-65%. Algae also remove CO_2 from the produced biogas. Carbon dioxide is pumped into the cultivation tank, and sludge from the anaerobic digester can be used as natural fertilizer.

Table 3

Production of microalgae and selected oilseed crops (with different oil content) that can cater to 50% of the demand for transport fuels in the USA (Frąc et al. 2009, Schroeder et al. 2013)

Crop	Oil yield (L ha^{-1})	Land-use requirements (M ha)
Microalgae (70% oil content, DM basis)	136,900	2
Microalgae (30% oil content, DM basis)	58,700	4.5
Oilseed rape	1190	223
Coconut tree	2689	99
Oil palm	5950	45
Maize	172	1540
Soybean	446	594

According to Kępska and Olejnik (2014), some microorganisms, including molds, yeasts, bacteria and algae, can absorb heavy metals. These organisms can be used to remove environmental pollutants and recover valuable metals such as silver and gold. Microorganisms can be immobilized to increase the efficiency of heavy metal removal from the aquatic environment, and enable their multiple use. Microalgae for wastewater treatment are usually obtained from natural water bodies, and they are harvested manually or with the use of dedicated combine harvesters. Purification processes generally involve dead biomass which does not require nutrition or sterile handling conditions. Harmful algal blooms can be readily used for this purpose.

ALGAE AS FERTILIZERS

Marine algae are also used as fertilizers. Seaweed has been long recognized for its beneficial effects on plant growth. Algal biomass was initially applied to fertilize crops in coastal regions with easy access to seaweed. The development of algae extraction methods was a major breakthrough that promoted the widespread use of algae in agriculture. Seaweed extracts differ in physicochemical properties (colour, aroma, viscosity) and fertilizing effects, depending on the extraction method and species-specific traits. Algal extracts are usually obtained by thermal processing with the addition of sodium and potassium solutions, and nearly all extracts are derived from brown algae. Commercial products based on extracts from *Ascophyllum nodosum*, *Laminaria* spp., *Saragassum* spp., and *Durvillaea* spp. are obtained by the above method (Matysiak et al. 2012). Seaweed extracts supply crops with nutrients, increase yields, and boost plant resistance to environmental stressors such as drought, freezing temperatures, pathogens, and pests. Crops fertilized with algal extracts can take up more nutrients from the soil.

Green and red algae are also used in the production of algal extracts (Matysiak et al. 2010). The chemical composition of seaweed extracts is determined by the harvesting date. Young algae harvested in spring are more abundant in cytokinins and nutrients, whereas seaweed harvested in fall has a higher content of polyphenols and compounds with antifungal properties. Plant hormones, mainly cytokinins, have biostimulatory effects. Algae are also a rich source of micronutrients and macronutrients that are essential for plant growth (Matysiak et al. 2010). Brown algae (Phaeophyceae) of the genera *Ascophyllum*, *Fucus*, and *Laminaria* are most widely used as fertilizers. These macroalgae are the largest seaweeds in the world. In coastal regions, fresh or composted brown algae have been used in agriculture since ancient times. Algae found many more applications after the invention of seaweed processing methods, and hydrothermal liquefaction techniques revolutionized the use of algae in the farming sector, including as foliar fertilizers. In crop production, brown algae are used as plant growth regulators, osmoprotectants, soil amendments, and, less frequently, as nutrient sources. Seaweed, in particular brown algae, is a rich source of bioactive substances that stimulate plant growth and exert positive effects on soil-dwelling microorganisms (Rudawska et al. 2018).

ALGAE IN ANIMAL NUTRITION

Algal biomass has numerous industrial applications, including the production of sodium, iodine and potassium (brown algae), as well as agar, alginate and carrageenan hydrocolloids. Nine algal species are most widely used as raw materials for processing: *Laminaria* spp., *Fucus* spp., *Ascophyllum nodosum*, *Chondrus crispus*, *Porphyra* spp., *Ulva* spp., *Sargassum* spp., *Gracilaria* spp., and *Palmaria palmata* (Chojnacka 2014). Annual sales on the global algae market are estimated at USD 6 billion, mainly in food processing, plant protection, feed additive and cosmetic sectors (Pulz, Gross 2004). The algae industry is divided into macroalgae and microalgae sectors. The raw materials for each sector originate from different sources: macroalgae are harvested from surface waters, whereas microalgae are grown in culture systems (Bixler, Porse 2011). Macroalgae are processed into hydrocolloids (agar-agar, alginates, carrageenan), whereas microalgae are used in the production of health foods, cosmetics, dietary supplements, feed additives and pharmaceuticals (Spolaore et al. 2006). Macroalgae are also a source of polyphenols with antioxidant and antibacterial properties, which are added to meat products to prevent spoilage (Chojnacka et al. 2012).

In Europe, seaweed has been a source of animal nutrition since the Roman times. In Iceland, France and Norway, algae were added to feed to increase its nutritional value. In 2004, algae-based animal feeds had a 1% share of the global algae market (mainly *Ascophyllum nodosum*) (Chojnacka et al.

2012). In the USA, the value of microalgae-based feed additive market reached USD 300 million in 2004 (Pulz, Gross 2004). Approximately 10 000 algal species have been identified to date, and around 5% of these are used in food and feed production. The nutritional value of algae and the use of algae-based feeds in aquaculture (oysters and fish) have been described in the literature (Brown et al. 1997). Seaweed is a promising ingredient in bird nutrition, and most research has been conducted on poultry models. Poultry diets can be safely enhanced with 5-10% algae as an alternative protein source (Spolaore et al. 2006). Seaweed is also used in aquaculture, and around 30% of global algae production is processed into aquaculture feed (Chojnacka et al. 2012). In dairy cattle, increased productivity leads to energy deficit during gestation and lactation. To address this problem, cow diets are supplemented with various types of fat, including tallow, vegetable oil, fat by-products and fish oil. Both rumen-protected and rumen unprotected fats are used in cattle nutrition. Rumen-protected fats remain insoluble at normal rumen pH, and they are added to cattle diets in the form of calcium soaps of fatty acids (Kupczyński et al. 2011*a*, Mirowski 2019). Seaweed is abundant in omega-6 and omega-3 fatty acids, mostly docosahexaenoic acid (DHA), and it is an alternative source of polyunsaturated fatty acids (PUFAs) in cattle nutrition (Kupczyński et al. 2011*a*,*b*).

Because of their high nutritional value, algae have been added to animal diets for more than two decades. Algae are considered to be valuable feed components because they accumulate micronutrients and macronutrients (Chojnacka et al. 2012). Micronutrients such as Mn, Mg, Fe, I, Cu and Zn occur as metal-organic compounds, which increases their bioavailability. The same applies to macronutrients such as N, P, K and Na. Some freshwater macroalgae, including species of the genera *Ulva* and *Cladophora*, accumulate large quantities of alkaline earth metals, mainly calcium and magnesium. Photosynthesis leads to the deposition of calcium carbonate on the surface of algae growing in alkaline waters, and the biomass of these algae can be used as a source of supplemental calcium and magnesium in animal diets. Algae are also a rich source of selenium and iodine in livestock nutrition. Marine microalgae are added to pig, cattle, poultry and sheep diets, and to the feed of fish (tilapia, carp, rainbow trout, white sturgeon and red seabream). According to Schroeder et al. (2013), the addition of algae to livestock diets increases the nutritional value of animal-derived products. Dietary supplementation with seaweed meal have been shown to increase the iodine content of chicken eggs and milk yields in dairy cows. Algae are an alternative source of PUFAs, which enhance the color of meat and increase feed conversion efficiency. In addition, the supplementation of algae as animal feed provides plentiful benefits, such as improved growth and body weight, reduced feed intake, enhanced immune response and durability towards illness, antibacterial and antiviral action as well as enrichment of livestock products with bioactive compounds (Kusmayadi et al. 2021).

Chojnacka et al. (2012) reviewed the literature on feeding trials involving macroalgae and microalgae in selected livestock species, and their impact on animal performance.

Pigs

Pig diets supplemented with 0.25-0.5% microalgae (*Schizochytrium* spp.) significantly increased the content of DHA in pork. The inclusion of brown algae (*Laminaria digitata*) in piglet diets at 0.12% and 0.19% (DM basis) increased iodine levels in their muscles, liver, kidneys and heart. Organic iodine was more readily available than non-organic iodine.

Poultry

Algae are a rich source of compounds with antimicrobial properties, such as astaxanthin, and the inclusion of microalgae (*Hematococcus pluvalis*) in broiler diets at 350, 1800, and 8950 mg kg^{-1} suppressed the growth of *Capylobacter* and *Clostridium perfingens*. The inclusion of *Spirulina platensis* in poultry diets at 14% and 17% had no negative effect on the weight, composition and histopathology of chicken organs or the overall quality of their meat - it only intensified its color. A research study investigating the performance of broilers whose diets were supplemented with 10%, 20%, and 30% of green algae (DM basis) (*Enteromorpha intestinalis, Ulva lactuca, Ulva taeniata, Caulerpa taxifolia, Codium flabellatum, Codium iyengarii, Halimeda tuna, Bryopsis pennata*, and *Caulerpa scalpeliformis*) revealed that the inclusion level of 10% promoted the highest weight gains, decreased fat content and increased protein levels in the blood and liver, relative to the control group. In turn, the inclusion of *Chlorella* spp. at 6% and 15% had no adverse effect on weight gains.

The addition of *Nannochloropsis oculata* microalgae to laying hen diets at 20% increased the content of unsaturated fatty acids and carotenoids in egg yolks. In turn, diets containing 12% *Chlorella* spp. (120 g) increased egg yolk pigmentation without compromising the quality of eggshells or feed conversion efficiency. The dietary inclusion of *Pithophora* spp. (green algae) at 7.5% increased egg yolk pigmentation, but had no influence on egg production, the feed conversion ratio or spleen weight relative to the reference group fed a maize-soybean-based diet. A 10% inclusion of *Enteromorpha* spp. (DM basis) in layer diets had no effect on laying performance, feed intake, eggshell weight or thickness, but the cholesterol content of eggs was 5% lower in the experimental group than in the control group. The supplementation of hen diets with *Fucus serratus* and *Fucus esiculosus* brown algae at 15% (DM basis) increased the concentration of fucoxanthin metabolites in egg yolks by 15-20%. The inclusion of *Crypthecodinium cohnii* microalgae in duck diets at 0.5% had no effect on weight gains, excreta composition or the chemical composition, color, pH, shelf life and the aroma of breast muscles.

According to Elkin et al. (2023), the addition of high amounts of omega-3 fatty acids to laying hen diets can impair laying performance or even completely inhibit egg production. Omega-3 fatty acids inhibit the secretion of substrates in the liver of birds, in particular triglycerides which belong to the fraction of low-molecular-weight lipoproteins that participate in yolk formation in the follicular sac, and are transported from the liver to the ovaries. Microalgal oil is added to the diets of laying hens as a rich source of DHA. Elkin et al. (2023) reported that the supplementation of hen diets with microalgal oil at 40 g kg^{-1} of feed decreased yolk size in more than 50% of eggs and, in some cases, completely inhibited egg production. The content of omega-3 long-chain fatty acids in eggs exceeded daily levels recommended for healthy adults by the Dietary Guidelines for Americans by at least 50%. According to the cited authors, the addition of microalgal oil to hen diets should not exceed 20 g kg^{-1} of feed to maintain high laying performance and deliver health benefits for consumers.

Ruminants

Daily supplementation of sheep diets with brown algae (*Laminaria digitata* and *Laminaria hyperborea*) and green algae (*Entermorpha intestianalis*) at 3-5 kg (wet basis) had a beneficial influence on the animals' growth and development, which indicates that macroalgae may offer an alternative source of nutrients in sheep production. The inclusion of macroalgae in lamb diets at 1% (DM basis) increased feed intake and, consequently, hot carcass weight. In another study, ram diets were supplemented with 20% (DM basis) *Ulva lactuca* green algae which are characterized by low energy value and high nitrogen content. The study revealed that algae can be incorporated into cereal-based diets to reduce their energy value and increase nitrogen content.

Kupczyński et al. (2011a) analyzed the effects of dairy cattle diets supplemented with *Schizochytrium* spp. and *Crypthecodinium cohnii* microalgae on rumen fermentation processes, methane production, biohydrogenation of PUFAs and the fatty acid profile of milk fat. Kupczyński et al. (2011*b*) added rumen unprotected cod liver oil and marine microalgae (DHA Gold) to the total mixed ration (TMR) given to Holstein-Friesian cows, and analyzed the impact of these additives on the chemical composition of milk. At the end of the 8-week experiment, the content of fat, protein, lactose and total solids in the milk of experimental cows was 3.81%, 3.22%, 4.89% and 12.14%, respectively. In a study by Boeckaert et al. (2008), the supplementation of cow diets with *Schizochytrium* spp. at 43 g kg^{-1} of feed (DM basis) considerably decreased DM intake (by approx. 10%), milk yield and the fat content of milk (from 47.9 to 22.5 g kg^{-1} of milk) between experimental days 2 and 20. At the inclusion level of 10 g kg^{-1} of feed, the algal supplement significantly decreased the fat content of milk and desirably modified its fatty acid profile by increasing CLA and DHA levels. In the work of Franklin et al. (1999), rumen-protected and rumen unprotected seaweed (*Schizochytrium* spp., Omega Tech, Inc.) added to cattle diets in the daily amount of 910 g over a period of six weeks induced a similar, significant decrease in the fat content of milk (from 3.70% to 2.95%), but had no effect on protein content.

AbuGhazaleh et al. (2009) demonstrated that daily supplementation of dairy cattle diets with 150 g of seaweed (S-type Gold Algae, Martek Inc.) over a period of 21 days increased the content of fat (3.43%), total protein (3.42%) and lactose (4.61%) in milk relative to control group cows whose diets were enriched with 150 g of fish oil (fat – 3.17%, total protein – 3.35%, lactose – 4.53%). Fievez et al. (2007) found that two edible algal preparations (*Aquagrow*-DHA and TV-20 *C. cohnii*) with a high content of omega-3 PUFAs inhibited the production of methane, which decreases the energy efficiency of milk and beef production.

According to Sheih et al. (2010), algal protein is a low-cost alternative in the production of peptides with antioxidant properties. The by-products from the production of *Chlorella vulgaris* extracts are often used in animal nutrition. Algal protein can be hydrolyzed with the use of pepsin. The residues from the extraction process contain more than 50% of protein. They have a low commercial value, but can be a rich source of protein in animal diets. These by-products could be also a novel source of antioxidants.

Brown algae play the most important role among all algae in animal nutrition on account of their large size and easy harvesting. Brown algae are also used in the production of food, cosmetics, pharmaceuticals and organic fertilizers. *Ascophyllum nodosum* of the class Phaeophyceae is the dominant species of brown algae in the North Atlantic (Figure 2). *Ascophyllum nodosum* contains numerous inflated vesicles, and it can be harvested year-round (http://algavita.pl/ascophyllum-nodosum/).

Brown algae are harvested in clean sea water with the use of dedicated methods. They are dried at high temperature and ground. Brown algae are processed into meal, which is used in the production of premixes, mineral

Fig. 2. *Ascophyllum nodosum* (https://en.wikipedia.org/wiki/Ascophyllum)

and vitamin supplements, and feed additives for cattle, sheep, horses, pigs, poultry, fur-bearing animals, dogs, cats and aquatic organisms (fish, shrimp) (Figure 3). Animal species differ in their demand for bioactive compounds (such as iodine, potassium, sodium, vitamin C and *β*-carotene), and these requirements should be considered in the formulation of nutritionally balanced diets (http://algavita.pl/ascophyllum-nodosum/).

Fig. 3. *Ascophyllum nodosum* meal (photograph by I. Chwastowska-Siwiecka)

Ascophyllum nodosum (knotted wrack) is a rich source of nutrients, including polysaccharides, fatty acids, polyphenols and peptides (Plaza et al. 2008, Tierney et al. 2010). *Ascophyllum nodosum* is a brown algae species with the highest content of total polysaccharides (42-70% on a DM basis) (Holdt, Kraan 2011), and it contains unique polysaccharides (phytocolloids), such as alginic acid (25-28%), fucoidan (11.6%), laminarin (4.5%) and mannitol (7.5%) (O'Sullivan et al. 2010, Holdt, Kraan 2011). These polysaccharides do not occur in terrestrial plants (Khan et al. 2009), and most of them are a source of dietary fiber that cannot be digested by the human body. Therefore, these algal polysaccharides can be potentially used in the production of functional prebiotics that deliver health benefits to humans and animals (Christaki et al. 2010, O'Sullivan et al. 2010, Holdt, Kraan 2011). *Ascophyllum nodosum* is low in lipids (2-7% on a DM basis), but it contains sufficient amounts of omega-3 fatty acids to reduce the risk of cardiovascular diseases in humans (Kumari et al. 2010). This algal species is also abundant in vitamins (A, C, D and E) and minerals (Ca, P, Na and K) – Fitzgerald et al. (2011). The average content of potassium, iodine, iron and vitamin C in *Ascophyllum nodosum* was determined at 2.5%, 900 mg kg^{-1}, 600 mg kg^{-1} and 600 mg kg^{-1}, respectively (http://algavita.pl/ascophyllum-nodosum/). Its protein content ranges from 3% to 15% (Fleurence 2004). *Ascophyllum nodosum* contains acidic amino acids (18-44%) (Harnedy, FitzGerald 2011) and peptides which exert hypotensive effects in the human cardiovascular system (Fitzgerald et al. 2011). This algal species also contains polyphenols, such as phlorotannins (up to 15% on a DM basis), with antioxidant and antibacterial properties (Wang et al. 2009, Holdt, Kraan 2011). *Ascophyllum nodosum* is also a valuable source of carotenoids, in particular photosynthetic pigments, such as chlorophyll and fucoxanthin, which are potent antioxidants (Lordan et al. 2011).

Ascophyllum nodosum has long been used as fertilizer in many coastal regions of the world (Norrie, Hiltz 1999). Simmons-Boyce et al. (2009) reported that dietary supplementation with up to 15% *Ascophyllum nodosum* did not exert any toxic effects. In recent years, these macroalgae have been used as feed additives (Lordan et al. 2011). Numerous research studies have examined the effects of natural feed additives containing *Ascophyllum nodosum* meal and extract on the health and performance of lambs (Saker et al. 2004, Archer et al. 2007), cattle and dairy cows (Anderson et al. 2006, Karatzia et al. 2012), weaned piglets (Dierick et al. 2009), growing-finishing pigs (Gardiner et al. 2008) and chickens (Gravett 2000). The recommended inclusion levels range from 2 kg (German guidelines) to 10 kg of algal meal per ton of feed in dairy cattle and laying hens, and 20 kg in pigs and other livestock species (Scandinavian guidelines) (http://algavita.pl/ascophyllum-nodosum/). In a study by Karatzia et al. (2012), the supplementation of concentrate feed for Holstein cows with 80 g of powdered *Ascophyllum nodosum* per day over a period of 7 weeks did not affect milk yield or the protein and fat content of milk throughout the experiment, relative to the control group. In the experimental group, the protein and fat content of milk increased from 3.2% and 3.8%, respectively (at baseline), to 3.3% and 3.9%, respectively, at the end of the study. Similar observations were made by Čermák et al. (2011), who analyzed the effect of hydrolyzed *Ascophyllum nodosum* in dairy cattle, and by Pompeu et al. (2011), who evaluated the impact of diets supplemented with *Ascophyllum nodosum* in heat-stressed cows.

CONCLUSIONS

Algae can play an important role in sustainable agriculture. They are used in the production of dietary supplements owing to their high nutritional value. In modern agriculture, algae are applied as fertilizers, converted to biofuels, and used in animal nutrition as a rich source of bioactive compounds, such as mucopolysaccharides, essential fatty acids, vitamins, polyphenols, fucoidan, carotenoids and chlorophylls. Algal biomass is a renewable source of valuable bioactive ingredients for food production, the chemical sector, agriculture, medicine, and pharmaceutical and cosmetic industries.

Author contributions

I.CH-S. – conceptualization, visualization and writing – original draft preparation and editing final version; J.M. – writing – review & editing, formal analysis.

Conflicts of interest

The authors ensure that they have neither professional nor financial connections related to the manuscript sent to the Editorial Board.

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