Int Aquat Res
https://doi.org/10.22034/IAR.2022.1962583.1297

REVIEW

Nutritional, sustainable source of aqua feed and food from microalgae: a mini review

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Received: 14 May 2022 / Accepted: 14 August 2022 / Published online: 19 August 2022

Abstract Microalgae are a sustainable food source for humans and aquatic organisms, and this study explores their nutritional and physiological importance. Marine and freshwater microalgae exist as microscopic photosynthetic organisms. In aquaculture, microalgae are used as food and as live feed for bivalve mollusks, juvenile stages of abalone, crustaceans and some fish species and as zooplankton in food chains. Using microalgae for food and aquatic feed is a sustainable and economically beneficial process. As a source of protein, omega-3, fatty acids and carotenoids, microalgae are more nutrient-dense than traditional forms of animal and aquatic feed, such as millet, grams and other small fish. In addition to being nutritious, they contain antioxidants, antimicrobials and disease-preventative molecules, extending the lifespan of humans and fish.

Keywords Microalgae . Sustainable source . Aquatic feed . Omega-3 . Fatty acids . Carotenoids

Introduction

Human population is growing steadily, which leads to an increased demand for food products and increased use of agrochemicals. The world population in 2017 was 7.6 billion people and projected to rise to 9.8 billion by 2050 (Saxena et al. 2021). Some studies reveal that food production must be doubled by 2050 to meet the expanding demand (Tilman et al. 2011; Alexandratos and Bruinsma 2012). There were many valuations projected to increase the production feed of 25–60% by 2050 (Hunter et al. 2017). It is important to conserve the lands and water bodies that we have or might locate for the production of food and feed. In this review, we analyzed the alternative food scenario for the human and aquaculture demands to their dietary requirements. Another essential part of agriculture is aquaculture, which treated the breeding and harvesting of marine - freshwater species of fish and plants in different water systems like rivers, oceans, ponds and lakes As reported by Godfray et al. (2018), the use of exogenous feed increases aquaculture

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production yield to 66% in 2015. In response to this increase in demand, aquatic products have been used six times as much, growing from 8 million tons to 48 million tonnes. The Hasan and Soto studies in 2017 suggested reducing fishmeal and feed conversion ratios could reduce greenhouse gas emissions from aquaculture. The global fish production (including aquaculture and capture) in 2016 was accounted for 171 million tonnes valuing the industry at USD 362 billion. However, in 2030 this production is projected to reach 209 million while 103 million coming from aquaculture (Godfray et al. 2018). Thanks to these projections, 5.3 and 1.0 million tonnes of fishmeal and fish oil can be produced using 16% of capture fisheries by 2030 (Dineshbabu et al. 2019). The future objective solution should be finding an alternative product that is easy to manufacture and less expensive in order to avoid causing a large part of production to be attributed to aquaculture feed. However, several commercial applications of microalgae have recently been used to improve the nutritional value of aquaculture feed and food. In fish farming, fishmeal is the most important feed. It was obtained from the small fish or the waste of the fish drying after crushed, cooking and pressing to obtain a solid form (Miles and Chapman 2015). As a result, it is better to use waste fish to produce fishmeal than to use whole fish, due to the fact that the whole fish does not meet current demand and the food prospects for the future. The Food and Agriculture Organization of the United Nations (FAO) shows that by 2030 the use of fishmeal will increase by 19% to that used in 2016. However, the use of waste fish and fish oil accounts for 54% of the production of fishmeal (Godfray et al. 2018). At present, researchers are looking for alternatives to fishmeal in order to produce fishmeal from fish. Therefore, using microalgae can be represented as the best alternative to utilize as a dietary supplement in the production of fishmeal, which ensures the reduction of the pressure on fish and fish oil. In this review, the importance of using microalgae as an alternative to feeding aquatic animals as well as the methods of production are discussed, since they are not only cost-effective and sustainable, but also ecologically beneficial.

Microalgae

Algae constitute a large group of photosynthetic organisms, such as eukaryotic microalgae and prokaryotic cyanobacteria (Lee 2018). These microalgae are regarded as ‘living biorefinery’ due to their capacity to offer a large variety of green chemicals, also growth rate and consequently increased biomass yield than the other terrestrial plants, primary and secondary metabolites within photosynthesis method and due to their higher photon conversion efficiency, they can convert carbon dioxide (CO_2) and water into oxygen (O_2) to a renewable energy source (Gouveia 2011; Malcata 2011). Lipids, carbohydrates and proteins are considered the primary metabolites. Secondary metabolites include fatty acids, triglycerides, phenolic substances, flavonoids, tannins, esters, alkaloids and terpenes, which are green molecules with a high added value (De Corato et al. 2018). Microalgae accumulate the most nutrients during the growth phase, producing algal biomass rich in lipids, proteins, and carbohydrates (Packer et al. 2016). In addition to being economically and environmentally benign, they are also sustainable. There are several applications for microalgae that include feed, food, pharmaceuticals, nutraceuticals, and cosmetics. It has been successful in commercializing antioxidants, cosmetic components, polyunsaturated fatty acids (PUFAs), and natural colors derived from microalgae (Spolaore et al. 2006).

Nutrition from microalgae

Aquaculture feed

The microalgae are used as supplement feed in aquaculture due to their toxicological and physiological activities (Milione and Zeng 2008; Nunes et al. 2009; Khatoon et al. 2010; Ghaeni et al. 2011; Komprda et al. 2015; Ozcicek et al. 2017). In aquaculture feed, microalgae can provide color, disease-resistant effects, and immunostimulant properties to fish. The high content of lipids, carbohydrates, fatty acids (docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA)), proteins, pigments (carotenoids, phycobiliproteins and chlorophyll) and vitamins (A, B1, B2, B6, B12, C, E and biotin) favors their uses as an alternative to fishmeal (Tokuşoglu and Ünal 2003; Batista et al. 2013). The most frequently utilized species in aquaculture feed are *Chlorella*, *Tetraselmis*, *Isochrysis*, *Pavlova*, *Phaeodactylum*, *Dunaliella*, *Chaetoceros*, *Nannochloropsis*, *Arthrospira*, *Haematococcus*, *Schizochytrium*, *Skeletonema* and *Thalassiosira* (Yaakob et al. 2014; Madeira et al. 2017). Significant results are obtained by using microalgae as feed in the most hatchery production of zooplankton, fish farming, shrimp, mollusks and crustaceans (Haoujar et al. 2020).

Zooplanktons

The first aliment for the small fish in farmhouses is zooplankton; they provide live prey for them. As a result of drying, some nutrients, such as proteins, are denatured, so live food is more nutritious than preserved food. They have a small size ranges from 0.1 to 2 mm. Artemia, copepods, rotifers (Brachionus) and cladocerans represented the most used zooplanktons can be cultivated to be addressed as live prey for small fishes. Artemia are particle filter feeders, used in fisheries as live prey due to their high nutrition (Herawati et al. 2014). Rotifers lack PUFA, for that it's necessary to alimented with microalgae diet. Yeast-fed rotifers lack ascorbic acid and polyunsaturated fatty acids, but microalgae can improve their fatty acid content (Cahu et al. 2003; Seychelles et al. 2009). The microalgae using as feed for the zooplankton needs a specific place for their culturing in the hatcheries. Microalgae witch used as feed for zooplankton are growing in ponds or tanks. However, the growing technique of zooplankton in microalgae culture is called green-water aquaculture. Specific criteria are necessary to choose the appropriate microalgae like as; j) cell with small size, jj) easy to digest, jjj) does not contain any toxic substances and jv) easy to grow with v) high nutritional value. The most algae frequently applied as feed for zooplanktons have a range of around 25 µm size; such as *Nannochloropsis*, *Tetraselmis*, *Chlorella*, *Isochrysis* and *Dunaliella* (Le et al. 2019).

Fishes

Recently, several researchers have been interested in using alternative compounds that are rich in unsaturated fatty acids as a substitute for fish oils. Consequently, microalgae have become the focus of attention as a good industry in the future. In hatcheries, the small fishes can be alimented by some species of microalgae like live prey by Green-water aquaculture. Some kinds that can use microalgae as feed: flounders, halibut, seabass, Atlantic cod, Seabream and striped mullet (Tredici et al. 2009). There are already some microalgae being used in aquaculture-related applications, which facilitates their use as aquaculture feeds. *Haematococcus pluvialis* is an essential species of microalgae that can produce and marketed worldwide because it is rich in astaxanthin. Astaxanthin is an element that makes a pink color to salmon fish as well as improves the nutrient profile and the price of fish instead of using the pinkening of the salmonids flesh (Spolaore et al. 2006; Raja et al. 2007; Ambati et al. 2014). In 2018, the United States Food and Drug Administration (US FDA) affirmed the utilization of *H. pluvialis* algae meal in the salmonid feed (FDA, 2018). *Dunaliella salina* considered the principal source of natural β-carotene used as a color for the seafood-market. Among the carotenoids, it was a naturally fat-soluble stereoisomeric pigment rich in pro-vitamin A (Chen et al. 1993). A diet based on microalgae addressed to ornamental goldfish (*Carassius auratus*) makes it possible to approve their pigment value and their marketing (Gouveia and Rema 2005). Whose aim is to improve the color of the muscles, sea bream, lobster, carp and shrimp have benefited from an algal diet (Sousa et al. 2008). A diet based on *Pavlova* sp., is allowing an increase of DHA / EPA in clams, mussels, oysters and brood stock. And on the other hand, *Nannochloropsis* sp., is used in fish hatcheries for its high EPA level. Several studies show that the use of a mixed diet allows presenting a complete and balanced diet that improves growth and survival rates for mussels, oysters, scallops and clams (Brown 2002; Haoujar et al. 2020). The best method of drying microalgae is freeze-drying since it contains the most nutrients while spray-drying or air-drying shrinks in size, shrinks at high temperatures, and loses quality (Lubzens et al. 1995; Cañavate and Fernández-Díaz 2001).

Shrimp

The diet for shrimp in its second stage of larval growth based on microalgae and in the third stage is consists of microalgae combined with zooplankton (Tacon 1987). DHA and arachidonic acid-rich feed increases hemocytes, bactericides and antioxidant properties (higher phenol oxidase and superoxide dismutase activity) (Nonwachai et al. 2010). Besides, an algal diet allows shrimp larvae to have a balanced survival rate, optimal growth and maximum development in good quality water because of pH stabilization and oxygen production (Muller-Feuga 2013). And as an example, the diet based on *Dunaliella salina* is allowed to report the survival rate to 60% up to 5 days while the food which lacked this microalgae reached mortality of 100% for 48 hours for black tiger shrimp (Madhumathi and Rengasamy 2011). *Skeletonema*, *Isochrysis*, *Chlorella*, *Chaetoceros* and *Tetraselmis* were examined as desirable feed for shrimp larva (Muller-Feuga 2013).

Sea urchins

The *Chaetoceros gracilis* helps the urchin larvae to survive in the sea conditions, while the mixture of *C. gracilis* and *I. galbana* is favored the larvae growing and metamorphosis (Cárcamo et al. 2005; Qi et al. 2018). A variety of life stages of larvae, larval posts, and broodstock are fed microalgae as nutrient feed in hatcheries (Kaparapu 2018). Many types of mollusk as the blue mussel (*Mytilus edulis*), New Zealand green shell ™ mussel (GSM, *Perna canaliculus*), flat oysters (*Ostrea edulis*, *Ostrea chilensis* and others) and Pacific oyster (*Crassostrea gigas*) depend on algae for their feed (Packer et al. 2016). A significant development at the level of genetic transformation in microalgae has recently been recognized. *Chlamydomonas reinhardtii* represents the organism most studied for the transformation of transgenes into the nucleus and chloroplast (El-Sheekh 2000; Purton 2007; Neupert et al. 2012; Wittkopp 2018). These microalgae can produce biomolecules with j) immune properties; for example of fatty acids and anti-p57 antibodies against bacterial kidney disease in salmonids, jj) disease resistance and jjj) bactericides in the form of bovine lactoferricin with broad-spectrum antimicrobial peptide (Siripornadulsil et al. 2007; Li and Tsai 2009; Hamilton et al. 2014).

Human food

Microalgae were used to survive during famines in China before 2000 years ago. Microalgae may market like capsules, tablets and liquids. In addition, it can be used to make pasta, candy bars, drinks, snack foods, and gum (Yamaguchi 1996; Liang et al. 2004). Microalgae have different biochemical properties and can act as food supplements and use as a source of food coloring. Besides, they are rich in protein, fiber, carbohydrates and enzymes. The vitamins: A, C, B1, B2, B6, niacin and minerals like iron, calcium, potassium, iodine are potentially abundantly found in microalgae.

Chlorella, *Aphanizomenon flos-aquae*, *Arthrospira* and *Dunaliella salina* are the most commercial strains that can be used in different applications.

A significant quantity of *Arthrospira* reproduction is effectuating in China and India. For human nutrition, *Arthrospira* was used due to its content of protein and its high added value (De Oliveira Rangel-Yagui et al. 2004; Soletto et al. 2005). Also, she has different health-promoting effects like the regulation of hypertension, increases development of intestinal *Lactobacillus*, alleviation of hyperlipidemia and diminution of serum glucose levels (Yamaguchi 1996; Liang et al. 2004). Additionally, because Chlorella has taste-and-flavor-adjusting properties, it can also be used as a food additive (Yamaguchi 1996). For β-carotene production, *D. salina* is the most useful strain that can produce more than 14 % of dry weight (Metting 1996). However, Cognis Nutrition and Health, the world's largest yielder of *Dunaliella*, suggests that strain powder as an element of dietary complements and functional foods addressed to human consumption. *Spirulina* is considered as nutritional research due to its protein contents, biological value and digestibility. According to various study studies, *A. flos-aquae* prefers good overall health (Pugh and Pasco 2001). Compared to plant materials, meat and daily, *Spirulina* is considered a high source of protein. Due to their low levels of sulfur-containing essential amino acids, it was a high source of protein. Therefore, it can be compared to another plant as a protein source if the culture conditions are modified to provide high sulfate levels. This strain represents a source of vitamins A and B12 (Jassby 1988). It utilized in Europe, Asia and North America in the form of powder and tablets with accepted therapeutic effects (for immune responses, antiviral activities and radioprotection) (Belay et al. 1993).

As have already mentioned, microalgae are sources of proteins, carotenoids, vitamins and fatty acids that favor their use in the formulation of health food products. The comparison of several compositions of human food sources based on microalgae is detailed in Table 1.

Table 1 The nutrition profile of various microalgae generally utilized in food and aqua-feed

Biomolecule (% dwt)	*Spirulina*	*Chlorella*	*Dunaliella*	*Chlamydomonas*	*Scenedesmus*	*Haematococcus*	*Porphyridium*	*Isochrysis*	*Nannochloropsis*	*Schizochytrium*	References
Class	Cyanophyceae	Trebouxiophyceae	Chlorophyceae	Chlorophyceae	Chlorophyceae	Chlorophyceae	Porphyridiophyceae	Coccolithophyceae	Eustigmatophyceae	Fungi Class	
					Proteins						(Uriarte et al. 1993; Ju et al. 2012; Safi et al. 2013; Pagels et al. 2019)
Total proteins	53.21	46.53	40.46	48.00	43.66	30.87	33.55	41.00	29.70	21.00	
Total carbohydrate	16.40	15.84	20.44	17.00	25.39	37.93	40.87	14.46	22.84	22.50	
					Amino acids (g/100 protein)						(Jiang et al. 2004; Stamm 2015, Sarker et al. 2016; Matos et al. 2017; Andrade et al. 2018; Koyande et al. 2019)
Leucine	9.26	14.22	13.41	14.00*	12.27	6.43	12.40	9.43	22.77	7.43	
Valine	8.69	9.40	9.73	16.00*	10.86	5.11	5.32	6.00	20.08	5.43	
Lysine	6.46	13.53	10.75	39.00*	11.13	4.10	11.70	6.14	22.77	4.52	
Phenyl alanine	6.53	8.46	9.71	31.00*	9.39	3.44	10.64	8.00	18.42	4.90	
Methionine	4.43	6.17	5.52	16.00*	5.82	1.38	9.43	7.14	13.25	1.04	
Tryptophan	2.45	3.55	2.95	80.00*	2.92	0.00	5.91	3.14	7.87	5.39	
Threonine	6.94	7.61	8.55	41.70*	9.65	3.82	14.36	5.86	16.19	4.29	
Histidine	2.65	4.47	3.65	8.30*	4.30	2.57	2.36	2.14	8.75	2.22	
					Lipids						(Patil et al. 2007; Sarker et al. 2016; Shi et al. 2018; Tredici et al. 2009; Molino et al. 2018)
Total lipids	8.86	15.82	15.51	21.00	16.02	23.07	9.02	17.72	20.39	43.05	
DHA	0.30	2.60	0.36	ND	ND	ND	0.20	2.49	1.1(TFA)	7.60	
EPA	0.25	0.40	0.60	ND	0.41	ND	3.13	0.22	3.47	0.08	
					Carotenoids						(Del Campo et al. 2004; Panis and Carreon 2016; Shah et al. 2016; Dineshbabu et al. 2019)
Beta carotene	0.14	0.014	0.102	ND	0.070	0.05	ND	ND	0.048	0.00	
Lutein/Fucoxanthin	ND	0.40	ND	ND	0.54	ND	ND	1.8	ND	ND	
Astaxanthin	ND	0.203	0.083	20.85**	0.150	3.07	ND	ND	0.640	1.25	
C- Phycocyanin	9.27	NP	NP	NP	NP	NP	1.20	NP	NP	NP	
C-phycoerythrin	1.79	NP	NP	NP	NP	NP	4.22	NP	NP	NP	
					Vitamins (mg/kg dwt)						(Fabregas and Herrero 1990; Brown et al. 1999; Tokuşoglu and Ünal 2003)
Vitamin E	85.00	434.50	116.30	ND	ND	ND	ND	471.60	350.00	0.00	
Vitamin B1	24.00	17.55	29.00	ND	ND	4.00	ND	14.00	70.00	0.02	
Vitamin B3	144.50	82.50	79.30	ND	ND	60.00	ND	77.70	ND	140.00	
Vitamin B6	13.70	7.70	2.20	ND	ND	3.00	ND	1.80	9.50	14.00	
Vitamin B12	13.45	0.60	0.70	ND	ND	1.00	ND	0.60	0.85	0.54	

Note: * g in 1000 g of dry weight; ** mg per chlorophyll a; ND: No data available; NP: Not present

Fig. 1 Earthrise Farms *Arthrospira* production plant (Calipatria, CA, USA)

Health foods

Microalgae for human nutrition are nowadays available in a variety of forms such as tablets, capsules and liquids. Pasta, candy bars, gums, snack foods and beverages can also contain them. As well as its health-promoting properties, the microalgae may alleviate hyperlipidemia, protect against renal failure, suppress hypertension, stimulate the growth of intestinal *Lactobacillus* and lower blood glucose levels (Liang et al. 2004; Soletto et al. 2005). Due to their diverse chemical properties, they can be used as nutritional supplements or as food colors. *Chlorella*, *Arthrospira*, *Aphanizomenon flos-aquae* and *D. salina* dominate commercial applications.

The high protein content and excellent nutritional value of *Arthrospira* make it a popular ingredient in human nutrition (De Oliveira Rangel-Yagui et al. 2004; Desmorieux and Decaen 2005; Soletto et al. 2005). China and India produce a significant amount of *Arthrospira*. Located in Hainan province in China, Hainan Simai Enterprising Ltd. is the largest producer worldwide. The algal powder is produced at this company every year, which makes up 25% of the country's total output and nearly 10% of the world's. Earthrise Farms owns the largest plant in the world, covering 440,000 m^2 (located at Calipatria, CA, USA; Fig.1). In Fig. 2, their production process is presented. In over 20 countries, they distribute tablets and powder containing *Arthrospira*. This microalgae is widely used in nutraceuticals.

Spirulina products are produced in Alaska, Hawaii and Myanmar, for example. In Hawaii, a company named Cyanotech Corp. produces *Spirulina Pacifica* products that range from pure powder to packaged bottles. With the development of Cyanotech Corp.'s process, the oxidation of carotenes and fatty acids is eliminated from the drying process, which occurs with standard dryers. Closed drying systems maintain low oxygen concentrations through nitrogen and carbon dioxide flushing. Using a very cold ocean water crown that's 600 meters deep offshore, the process dehumidifies and dries microalgal products in less than 6 seconds (Fig. 3).

Over 70 companies manufacture *Chlorella*; Taiwan *Chlorella* Manufacturing and Co. (Taipei, Taiwan) is the largest, producing 400 t of dried biomass every year. Significant production is also achieved in Klötze, Germany (130 – 150 t dry biomass per year) with a tubular photobioreactor. There are 500,000

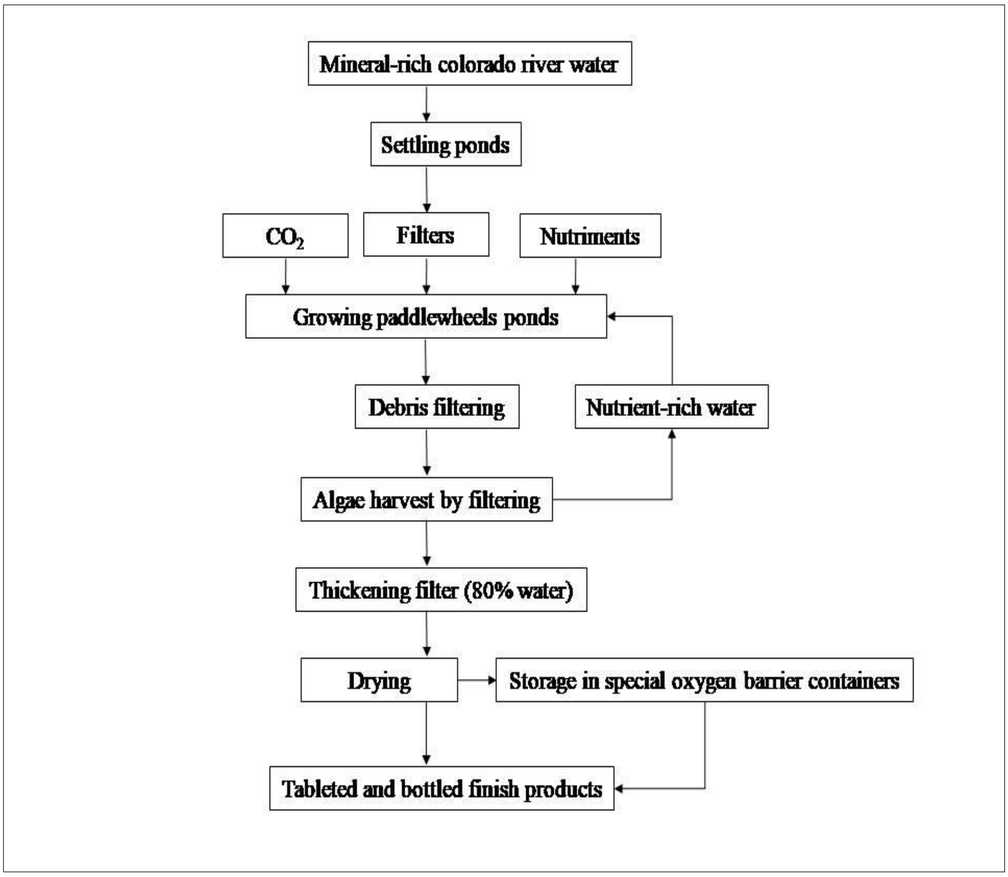

Fig. 2 Earthrise Farms microalgal production process (Mostafa 2012)

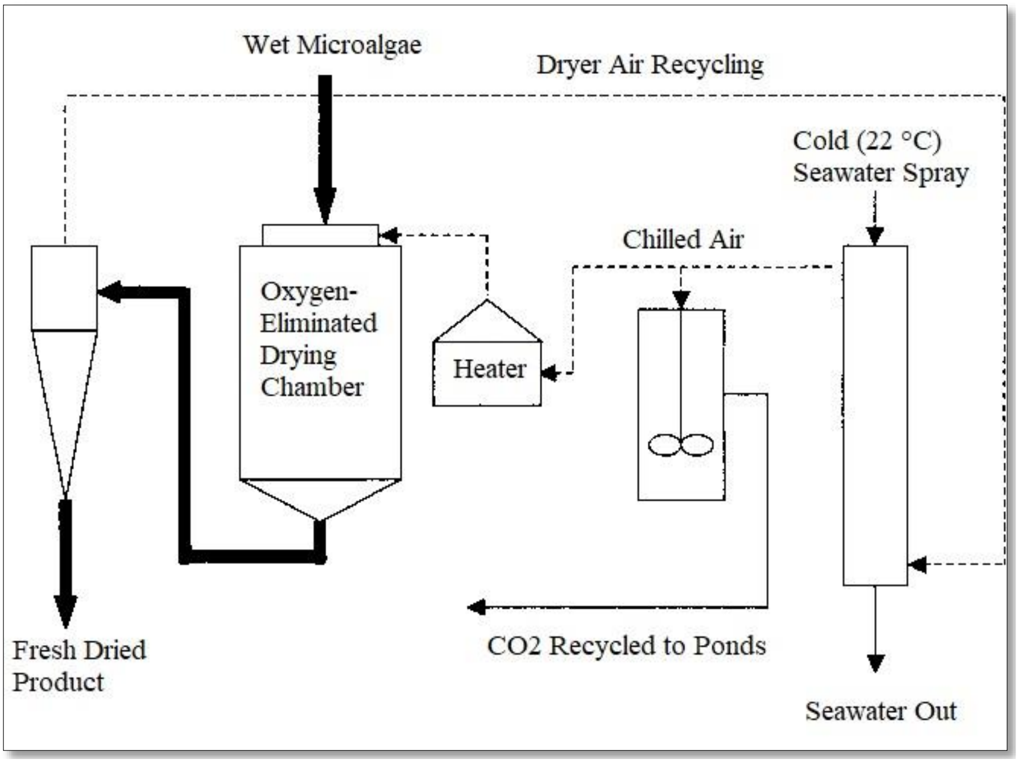

Fig. 3 Cyanotech process for drying microalgae biomass (Mostafa 2012)

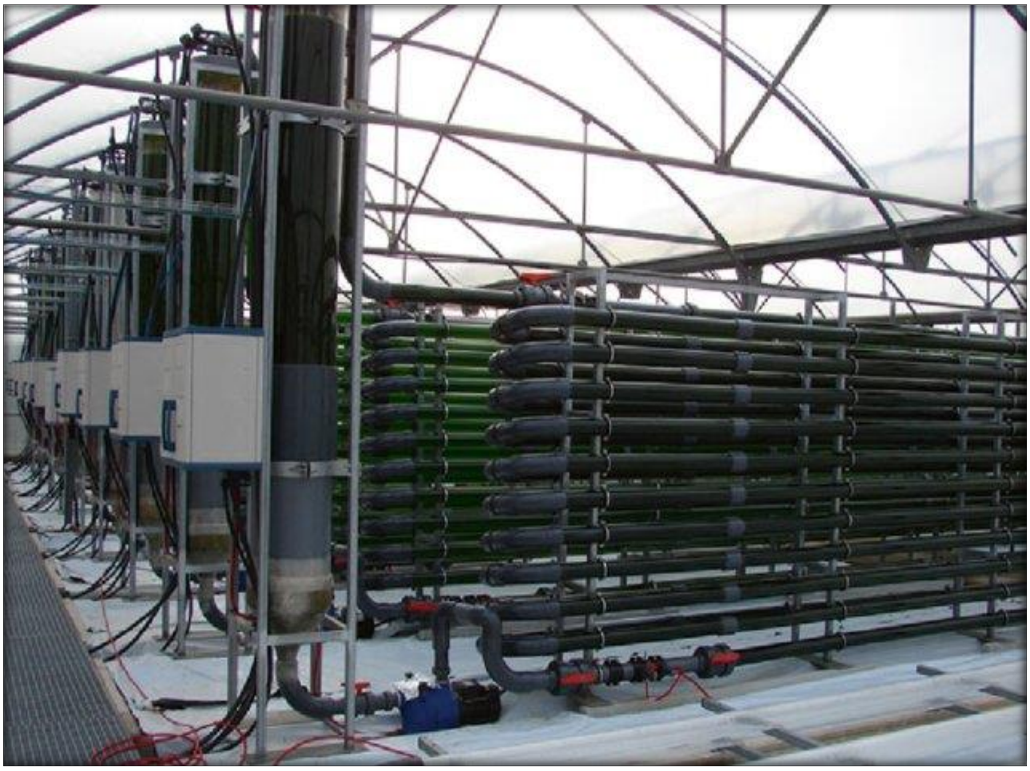

Fig. 4 Glass tube photobioreactor (700 m3) producing Chlorella biomass (Klötze, Germany)

m of horizontal running glass tubes arranged vertically with a volume of 700 m^3 and a total length of 500,000 m (Fig. 4). In the world, *Chlorella* is sold for over US$ 38 billion annually (Yamaguchi 1996). *Chlorella* contains numerous antiinflammatory agents such as free radical scavengers, immunostimulants and blood lipid reducing agents. Furthermore, other benefits have been studied (preventing ulcers, wounds and constipation; preventing atherosclerosis and hypercholesterolemia and preventing cancer) (Yamaguchi 1996; Jong-Yuh and Mei-Fen 2005; Salih and Haase 2012).

Conclusion

Increasing demand for fish and livestock meat also increases the need for feed. Furthermore, consumers today want food that is not only tasty but also nutritious, so fish and meat must be improved nutritionally. Microalgae can significantly enhance the nutritional profile of feeds and feed supplements. Microalgae and related products will be economically viable, profitable and global with foolproof technology and improvements in cultivation and harvesting. Depending on the type of nutrition desired, microalgal species used for feed production may vary; for example, *Spirulina* sp. *Haematococcus* spp. is recommended for protein supplementation and also useful for carotenoid enhancement.

In addition to being nutritionally superior, microalgae feed is also faster to grow, requires less land, has no need for arable land and can be grown in seawater. Furthermore, it reduces the amount of fish sacrificed as well as grains for aquaculture and animal feed. In the coming years, microalgae will be needed by an increasing population as a food or dietary supplement. In addition to providing significant nutrients, antioxidative properties and disease preventative properties, microalgae are also ecologically sustainable.

Conflicts of interest The authors declare no conflict of interest.

Funding This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Authors contributions All authors contributed equally, and finally, read and approved the final manuscript.

References

Alexandratos N, Bruinsma J (2012) World agriculture towards 2030/2050: the 2012 revision. DOI:10.22004/ag.econ.288998

Ambati RR, Phang S-M, Ravi S, Aswathanarayana RG (2014) Astaxanthin: sources, extraction, stability, biological activities and its commercial applications—a review. Mar Drugs 12:128–152. DOI:10.3390/md12010128

Andrade LM, Andrade CJ, Dias M, Nascimento C, Mendes MA (2018) *Chlorella* and *spirulina* microalgae as sources of functional foods. Nutraceuticals Food Suppl 6:45–58. DOI:10.15406/mojfpt.2018.06.00144

Batista AP, Gouveia L, Bandarra NM, Franco JM, Raymundo A (2013) Comparison of microalgal biomass profiles as novel functional ingredient for food products. Algal Res 2:164–173. DOI:10.1016/j.algal.2013.01.004

Belay A, Ota Y, Miyakawa K, Shimamatsu H (1993) Current knowledge on potential health benefits of *Spirulina*. J Appl Phycol 5:235–241. DOI:10.1007/BF00004024

Brown MR (2002) Nutritional value and use of microalgae in aquaculture. Av En Nutr , Cancun, Quintana Roo, Mexico

Brown MR, Mular M, Miller I, Farmer C, Trenerry C (1999) The vitamin content of microalgae used in aquaculture. J Appl Phycol 11:247–255. DOI:10.1023/A:1008075903578

Cahu C, Infante JZ, Takeuchi T (2003) Nutritional components affecting skeletal development in fish larvae. Aquaculture 227:245–258. DOI:10.1016/S0044-8486(03)00507-6

Cañavate JP, Fernández-Díaz C (2001) Pilot evaluation of freeze-dried microalgae in the mass rearing of gilthead seabream (*Sparus aurata*) larvae. Aquaculture 193:257–269. DOI:10.1016/S0044-8486(00)00492-0

Cárcamo PF, Candia AI, Chaparro OR (2005) Larval development and metamorphosis in the sea urchin *Loxechinus albus* (Echinodermata: Echinoidea): effects of diet type and feeding frequency. Aquaculture 249:375–386. DOI:10.1016/j.aquaculture.2005.03.026

Chacón-Lee TL, González-Mariño GE (2010) Microalgae for "healthy" foods—possibilities and challenges. Compr Rev Food Sci Food Saf 9:655–675. DOI:10.1111/j.1541-4337.2010.00132.x

Chen BH, Chuang JR, Lin JH, Chiu CP (1993) Quantification of provitamin a compounds in Chinese vegetables by high-performance liquid chromatography. J Food Prot 56:51–54. DOI:10.4315/0362-028X-56.1.51

De Corato U, De Bari I, Viola E, Pugliese M (2018) Assessing the main opportunities of integrated biorefining from agro-bioenergy co/by-products and agroindustrial residues into high-value added products associated to some emerging markets: A review. Renew Sustain Energy Rev 88:326–346. DOI:10.1016/j.rser.2018.02.041

De Oliveira Rangel-Yagui C, Danesi EDG, de Carvalho JCM, Sato S (2004) Chlorophyll production from *Spirulina platensis*: cultivation with urea addition by fed-batch process. Bioresour Technol 92:133–141. DOI:10.1016/j.biortech.2003.09.002

Del Campo JA, Rodriguez H, Moreno J, Vergas MA, Rivas J, Guerrero MG (2004) Accumulation of astaxanthin and lutein in *Chlorella zofingiensis* (Chlorophyta). Appl Microbiol Biotechnol 64:848–854. DOI:10.1007/s00253-003-1510-5

Desmorieux H, Decaen N (2005) Convective drying of spirulina in thin layer. J Food Eng 66:497–503. DOI:10.1016/j.jfoodeng.2004.04.021

Dineshbabu G, Goswami G, Kumar R, Sinha A, Das D (2019) Microalgae–nutritious, sustainable aqua-and animal feed source. J Funct Foods 62:103545. DOI:10.1016/j.jff.2019.103545

El-Sheekh MM (2000) Stable chloroplast transformation in *Chlamydomonas reinhardtii* using microprojectile bombardment. Folia Microbiol (Praha) 45:496–504. DOI:10.1007/BF02818717

Fabregas J, Herrero C (1990) Vitamin content of four marine microalgae. Potential use as source of vitamins in nutrition. J Ind Microbiol Biotechnol 5:259–263. DOI:10.1007/BF01569683

Ghaeni M, Matinfar A, Soltani M, Rabbani M (2011) Comparative effects of pure spirulina powder and other diets on larval growth and survival of green tiger shrimp, *Peneaus semisulcatus*. Iran J Fish Sci 10:208–217. URI: http://hdl.handle.net/1834/11334

Godfray HCJ, Aveyard P, Garnett T, Hall JW, Key TJ, Lorimer J, Pierrehumbert RT, Peter S, Marco S, Jebb SA (2018) Meat consumption, health, and the environment. Sci 361. eaam5324. DOI:10.1126/science.aam5324

Gouveia L (2011) Microalgae as a feedstock for biofuels. In: microalgae as a feedstock for biofuels. Springer, pp 1–69. DOI:10.1007/978-3-642-17997-6_1

Gouveia L, Rema P (2005) Effect of microalgal biomass concentration and temperature on ornamental goldfish (*Carassius auratus*) skin pigmentation. Aquac Nutr 11:19–23. DOI:10.1111/j.1365-2095.2004.00319.x

Gutiérrez-Salmeán G, Fabila-Castillo L, Chamorro-Cevallos G (2015) Aspectos nutricionales y toxicológicos de *Spirulina* (*arthrospira*). Nutr Hosp 32:34–40. DOI:10.3305/nh.2015.32.1.9001

Hamilton ML, Haslam RP, Napier JA, Sayanova O (2014) Metabolic engineering of *Phaeodactylum tricornutum* for the enhanced accumulation of omega-3 long chain polyunsaturated fatty acids. Metab Eng 22:3–9. DOI:10.1016/j.ymben.2013.12.003

Haoujar I, Abrini J, Chadli H, Essafi A, Nhhala H, Chebbaki K, Cacciola F, Senhaji NS (2020) Effect of four diets based on three microalgae on the growth performance and quality of mediterranean mussel flesh, *Mytilus galloprovincialis*. Int Aquat Res 12:137–145. DOI:10.22034/IAR(20).2020.1892283.1007

Hasan MR, Soto D (2017) Improving feed conversion ratio and its impact on reducing greenhouse gas emissions in aquaculture. Improv feed convers ratio its impact reducing greenh gas emiss aquac. http://www.fao.org/3/a-i7688e.pdf

Herawati VE, Hutabarat J, Radjasa OK (2014) Nutritional content of artemia sp. fed with *Chaetoceros calcitrans* and *Skeletonema costatum*. Hayati J Biosci 21:166–172. DOI:10.4308/hjb.21.4.166

Hunter MC, Smith RG, Schipanski ME, Atwood LW, Mortensen DA (2017) Agriculture in 2050: recalibrating targets for sustainable intensification. Biosci 67:386–391. DOI:10.1093/biosci/bix010

Jassby A (1988) Spirulina: a model for microalgae as human food. Algae Hum Aff 149–179. DOI:10024288523

Jiang Y, Fan K-W, Tsz-Yeung Wong R, Chen F (2004) Fatty acid composition and squalene content of the marine microalga *Schizochytrium mangrovei*. J Agric Food Chem 52:1196–1200. DOI:10.1021/jf035004c

Jong-Yuh C, Mei-Fen S (2005) Potential hypoglycemic effects of *Chlorella* in streptozotocin-induced diabetic mice. Life Sci 77:980–990. DOI:10.1016/j.lfs.2004.12.036

Ju ZY, Deng D-F, Dominy W (2012) A defatted microalgae (*Haematococcus pluvialis*) meal as a protein ingredient to partially replace fishmeal in diets of pacific white shrimp (*Litopenaeus vannamei*, Boone, 1931). Aquaculture 354:50–55. DOI:10.1016/j.aquaculture.2012.04.028

Kaparapu J (2018) Application of microalgae in aquaculture. Phykos 48:21–26

Kent M, Welladsen HM, Mangott A, Li Y (2015) Nutritional evaluation of australian microalgae as potential human health supplements. PloS One 10:e0118985. DOI:10.1371/journal.pone.0118985

Khatoon N, Sengupta P, Homechaudhuri S, Pal R (2010) Evaluation of algae based feed in goldfish (*Carassius auratus*) nutrition. In: proceedings of the zoological society. Springer, pp 109–114. DOI:10.1007/s12595-010-0015-3

Komprda T, Škultéty O, Křížková S, Zomikova G, Rozikova V, Krobot R (2015) Effect of dietary *Schizochytrium* microalga oil and fish oil on plasma cholesterol level in rats. J Anim Physiol Anim Nutr 99:308–316. DOI:10.1111/jpn.12221

Koyande AK, Chew KW, Rambabu K, Tao Y, Chu DT, Show PL (2019) Microalgae: A potential alternative to health supplementation for humans. Food Sci Hum Wellness 8:16–24. DOI:10.1016/j.fshw.2019.03.001

Kumar K, Dasgupta CN, Das D (2014) Cell growth kinetics of *Chlorella sorokiniana* and nutritional values of its biomass. Bioresour Technol 167:358–366. DOI:10.1016/j.biortech.2014.05.118

Le TH, Hoa NV, Sorgeloos P, Van Stappen G (2019) Artemia feeds: a review of brine shrimp production in the Mekong Delta, Vietnam. Rev Aquac 11:1169–1175. DOI:10.1111/raq.12285

Lee RE (2018) Phycology. Cambridge university press

Li S-S, Tsai H-J (2009) Transgenic microalgae as a non-antibiotic bactericide producer to defend against bacterial pathogen infection in the fish digestive tract. Fish Shellfish Immunol 26:316–325. DOI:10.1016/j.fsi.2008.07.004

Liang S, Liu X, Chen F, Chen Z (2004) Current microalgal health food R and D activities in China. In: Asian pacific phycology in the 21st century: prospects and challenges. Springer, pp 45–48. DOI:10.1007/978-94-007-0944-7_7

Lubzens E, Gibson O, Zmora O, Sukenik A (1995) Potential advantages of frozen algae (*Nannochloropsis* sp.) for rotifer (*Brachionus plicatilis*) culture. Aquaculture 133:295–309. DOI:10.1016/0044-8486(95)00010-Y

Madeira MS, Cardoso C, Lopes PA, Coello D, Afonso C, Bandarra NM, Prates JA (2017) Microalgae as feed ingredients for livestock production and meat quality: A review. Livest Sci 205:111–121. DOI:10.1016/j.livsci.2017.09.020

Madhumathi M, Rengasamy R (2011) Antioxidant status of penaeus monodon fed with *Dunaliella salina* supplemented diet and resistance against WSSV. Int J Eng Sci Technol 3:7249–7260

Malcata FX (2011) Microalgae and biofuels: a promising partnership? Trends Biotechnol 29:542–549. DOI:10.1016/j.tibtech.2011.05.005

Matos J, Cardoso C, Bandarra NM, Afonso C (2017) Microalgae as healthy ingredients for functional food: a review. Food Funct 8:2672–2685. DOI:10.1039/C7FO00409E

Metting FB (1996) Biodiversity and application of microalgae. J Ind Microbiol 17:477–489. DOI:10.1007/BF01574779

Miles RD, Chapman F (2015) The benefits of fish meal in aquaculture diets. University of Florida IFAS Extension, (May 2006), 1–6

Milione M, Zeng C (2008) The effects of temperature and salinity on population growth and egg hatching success of the tropical calanoid copepod, Acartia sinjiensis. Aquaculture 275:116–123. DOI:10.1016/j.aquaculture.2007.12.010

Molino A, Iovine A, Casella P, Mehariya S, Chianese S, Cerbone A, Rimauro J, Musmarra D (2018) Microalgae characterization for consolidated and new application in human food, animal feed and nutraceuticals. Int J Environ Res Public Health 15:2436. DOI:10.3390/ijerph15112436

Mostafa SS (2012) Microalgal biotechnology: prospects and applications. Plant Sci 12:276–314

Muller-Feuga A (2013) Microalgae for aquaculture: the current global situation and future trends. Handb Microalgal Cult Appl Phycol Biotechnol, 2nd Ed Wiley Blackwell West Sussex 615–627. DOI:10.1002/9781118567166.ch33

Neupert J, Shao N, Lu Y, Bock R (2012) Genetic transformation of the model green alga *Chlamydomonas reinhardtii*. In: Transgenic plants. Springer, pp 35–47. DOI:10.1007/978-1-61779-558-9_4

Nonwachai T, Purivirojkul W, Limsuwan C, Chuchird N, Velasco M, Dhar AK (2010) Growth, nonspecific immune characteristics, and survival upon challenge with vibrio harveyi in pacific white shrimp (*Litopenaeus vannamei*) raised on diets containing algal meal. Fish Shellfish Immunol 29:298–304. DOI:10.1016/j.fsi.2010.04.009

Nunes M, Pereira A, Ferreira JF, Yasumaru F (2009) Evaluation of the microalgae paste viability produced in a mollusk hatchery in Southern Brazil. J World Aquac Soc 40:87–94. DOI:10.1111/j.1749-7345.2008.00226.x

Ozcicek E, Can E, Yilmaz K, Seyhaneyıldız Can Ş (2017). Usage of microalgae as a sustainable food source in aquaculture. EgeJFAS 34: 347–354. DOI:10.12714/egejfas.2017.34.3.15

Packer MA, Harris GC, Adams SL (2016) Food and feed applications of algae. In: algae biotechnology. Springer, pp 217–247. DOI:10.1007/978-3-319-12334-9_12

Pagels F, Guedes AC, Amaro HM, Kiijoa A, Vasconcelos V (2019) Phycobiliproteins from cyanobacteria: Chemistry and biotechnological applications. Biotechnol Adv 37:422–443. DOI:10.1016/j.biotechadv.2019.02.010

Panis G, Carreon JR (2016) Commercial astaxanthin production derived by green alga *Haematococcus pluvialis*: A microalgae process model and a techno-economic assessment all through production line. Algal Res 18:175–190. DOI:10.1016/j.algal.2016.06.007

Patil V, Källqvist T, Olsen E, Vogt G, Gislerod HR (2007) Fatty acid composition of 12 microalgae for possible use in aquaculture feed. Aquac Int 15:1–9. DOI:10.1007/s10499-006-9060-3

Pugh N, Pasco DS (2001) Characterization of human monocyte activation by a water soluble preparation of *Aphanizomenon flos-aquae*. Phytomedicine 8:445–453. DOI:10.1078/S0944-7113(04)70063-X

Purton S (2007) Tools and techniques for chloroplast transformation of *Chlamydomonas*. In: Transgenic microalgae as green cell factories. Springer, pp 34–45. DOI:10.1007/978-0-387-75532-8_4

Qi S, Zhao X, Zhang W, Wang C, He M, Chang Y, Ding J (2018) The effects of 3 different microalgae species on the growth, metamorphosis and MYP gene expression of two sea urchins, *Strongylocentrotus intermedius* and *S. nudus*. Aquaculture 492:123–131. DOI:10.1016/j.aquaculture.2018.02.007

Raja R, Hemaiswarya S, Balasubramanyam D, Rengasamy R (2007) Protective effect of *Dunaliella salina* (Volvocales, Chlorophyta) against experimentally induced fibrosarcoma on wistar rats. Microbiol Res 162:177–184. DOI:10.1016/j.micres.2006.03.009

Safi C, Charton M, Pignolet O, Pontalier PY, Vaca-Garcia C (2013) Evaluation of the protein quality of *Porphyridium cruentum*. J Appl Phycol 25:497–501. DOI:10.1007/s10811-012-9883-4

Salih FM, Haase RA (2012) Potentials of microalgal biofuel production. J Pet Technol Altern Fuels 3:1–4. DOI:10.5897/JPTAF11.029

Sarker PK, Kapuscinski AR, Lanois AJ, Livesey ED, Bernhard KP, Coley ML (2016) Towards sustainable aquafeeds: complete substitution of fish oil with marine microalga *Schizochytrium* sp. improves growth and fatty acid deposition in juvenile Nile tilapia (*Oreochromis niloticus*). PloS One 11:e0156684. DOI:10.1371/journal.pone.0156684

Saxena A, Mishra B, Tiwari A (2021) Development of diatom entrapped alginate beads and application of immobilized cells in aquaculture. Environ Technol Innov 23:101736. DOI:10.1016/j.eti.2021.101736

Seychelles LH, Audet C, Tremblay R, Fournier R, Pernet F (2009) Essential fatty acid enrichment of cultured rotifers (*Brachionus plicatilis*, *Müller*) using frozen-concentrated microalgae. Aquac Nutr 15:431–439. DOI:10.1111/j.1365-2095.2008.00608.x

Shah M, Mahfuzur R, Liang Y, Cheng JJ, Daroch M (2016) Astaxanthin-producing green microalga *Haematococcus pluvialis*: from single cell to high value commercial products. Front Plant Sci 7:531. DOI:10.3389/fpls.2016.00531

Shi H, Luo X, Wu R, Yue X (2018) Production of eicosapentaenoic acid by application of a delta-6 desaturase with the highest ALA catalytic activity in algae. Microb Cell Factories 17:1–15. DOI:10.1186/s12934-018-0857-3

Siripornadulsil S, Dabrowski K, Sayre R (2007) Microalgal vaccines. In: Transgenic microalgae as green cell factories. Springer, pp 122–128. DOI:10.1007/978-0-387-75532-8_9

Soletto D, Binaghi L, Lodi A, Carvalho JCM, Converti A (2005) Batch and fed-batch cultivations of *Spirulina platensis* using ammonium sulphate and urea as nitrogen sources. Aquaculture 243:217–224. DOI:10.1016/j.aquaculture.2004.10.005

Sousa I, Gouveia L, Batista AP, Raymundo A, Bandarra NM (2008) Microalgae in novel food products. Food Chem Res Dev 75–112. URI: http://hdl.handle.net/10400.5/2434

Spolaore P, Joannis-Cassan C, Duran E, Isambert A (2006) Commercial applications of microalgae. J Biosci Bioeng 101:87–96. DOI:10.1263/jbb.101.87

Stamm M (2015) Effects of different microalgae supplements on fatty acid composition, oxidation stability, milk fat globule size and phospholipid content of bovine milk. URI: http://hdl.handle.net/10138/157470

Tacon AG (1987) Larval shrimp feeding. Crustacean tissue suspension: a practical alternative for shrimp. FAO Report

Tilman D, Balzer C, Hill J, Befort BL (2011) Global food demand and the sustainable intensification of agriculture. Proc Natl Acad Sci 108:20260–20264

Tokuşoglu Ö, Ünal MK (2003) Biomass nutrient profiles of three microalgae: *Spirulina platensis*, *Chlorella vulgaris*, and *Isochrisis galbana*. J Food Sci 68:1144–1148. DOI:10.1111/j.1365-2621.2003.tb09615.x

Tredici MR, Biondi N, Ponis E, Rodolfi L, Zittelli GC (2009) Advances in microalgal culture for aquaculture feed and other uses. In: New technologies in aquaculture. Elsevier, pp 610–676. DOI:10.1533/9781845696474.3.610

Uriarte I, Farias A, Hawkins AJS, Bayne BL (1993) Cell characteristics and biochemical composition of *dunaliella primolecta* butcher conditioned at different concentrations of dissolved nitrogen. J Appl Phycol 5:447–453. DOI: 10.1007/BF02182737

Wittkopp T (2018) Nuclear transformation of *Chlamydomonas reinhardtii* by electroporation. BIO-Protoc 8

Yaakob Z, Ali E, Zainal A, Mohamad M, Takriff MS (2014) An overview: biomolecules from microalgae for animal feed and aquaculture. J Biol Res-Thessalon 21:6. DOI:10.21769/BioProtoc.2837

Yamaguchi K (1996) Recent advances in microalgal bioscience in Japan, with special reference to utilization of biomass and metabolites: a review. J Appl Phycol 8:487–502. DOI:10.1007/BF02186327

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