Sky Journal of Microbiology Research Vol. 1(3), pp. 22 - 31, April, 2013
Available online http://www.skyjournals.org/SJMR
ISSN 2315-876X ©2013 Sky Journals

Review

Algae: A potent antioxidant source

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Accepted 23 April, 2013

There is a current worldwide interest in finding new and safe antioxidants from natural sources. Algae can biosynthesize, metabolize, accumulate and secrete a great diversity of primary and secondary metabolites including carotenoids, phenolic compounds, phycobilins, sulphated compounds and vitamins. All of these compounds have commercial applications in medicine, pharmaceutical, nutraceutical, cosmetic, agricultural and food industries. Keeping in view the presence of these antioxidant compounds there is a great potential of algae that can be used in pharmaceutics and other industries.

Key words: Algae, antioxidants, carotenoids, photosynthesis, phycocyanin, vitamins.

INTRODUCTION

Algae are photosynthetic organisms which constitute a total of 25 to 30 species, with a great diversity of forms and sizes. They can exist from unicellular microscopic organisms (microalgae) to multicellular of great size (macroalgae). Algae can be an interesting natural source of novel compounds with biological activity. Some algae are organisms that live in complex habitats submitted to extreme environmental conditions (salinity, temperature, nutrients, UV-Vis irradiation, etc.). To survive in these adverse conditions, they must adapt rapidly by producing a great variety of secondary (biologically active) metabolites, which cannot be found in other organisms (Gonulol et al., 2009; Welker et al., 2012). Among the various compounds found in the algae, antioxidants are probably the substances that have attracted major interest of the health and pharmaceutical industry (Table 1).

Substance that effectively prevents or delays the adverse effects caused by free radicals, even when the amount of the substance is less than the substance to be oxidized is generally defined an antioxidant. Commercial antioxidant supplements such as butylated hydroxyl anisole (BHA), butylated hydroxyl toluene (BHT), α-tocopherol and propyl gallate have been used to reduce oxidative damages (Gulçin et al., 2002). However, it is suspected that these synthetic antioxidants are responsible for a number of side-effects such as liver damage and carcinogenesis. As a result, consumers have become more health conscious and investigators are increasingly seeking natural antioxidant alternatives for use in foods or medicinal materials. Recently many researchers are interested in finding natural antioxidants having safety and effectiveness, which can be substituted the synthetic antioxidants, BHA and BHT. One such natural source for producing antioxidants is algae (Hirata et al., 2000; Benedettia et al., 2004; Karawita et al., 2007; Lee et al., 2008; Moo-Puc et al., 2011).

Algal antioxidants

As algae are photosynthetic organisms, they produced free radicals and other oxidative reagents when they are exposed to high oxygen concentrations and light. It is considered because of absence of structural damage that these organisms are able to generate the necessary compounds to protect themselves against oxidation

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Abbreviations: BHA, butylated hydroxyl anisole; **BHT,** butylated hydroxyl toluene.

Table1. Antioxidant compounds from algae and their health benefits.

S. No	Antioxidant compounds	Perceived Health Benefits	Reference
1.	β-carotene , lutein	Protective against breast cancer	(Yang et al., 2010)
2.	Bromophenol	α glycosidase inhibition	(Kim et al., 2010)
	Carrageenan,	Anti - tumor	(Haijin et al., 2003) (Moo-Puc et al., 2011)
	oligosaccrides Fucoidan	Anti – HIV	
		Ameliorates hyperoxaluria Anticancer	(Veena et al., 2007)
		Protection against neurogenerative disorder	(Luo et al., 2009)
3.	Fucophlorethols	Chemopreventive	(Parys et al., 2010)
4.	Fucoxanthin	Antiangiogenic	(Sugawara et al., 2006)
		Protective effects against retinol deficiency	(Sangeetha et al., 2009)
5.	Galactan sulphate	Antiviral	(Talarico et al., 2004) (Yasuhara – Bell and Lu 2010)
6.	Phenolic functional groups and MAAs (mycosporine – like amino acids)	Antiproliferative	(Yuan et al., 2005)
7.	Phlorotannins	Anti – inflammatory	(Shin et al., 2006)
		Bactericide	(Nagayama et al., 2002)
		Inhibits H_2O_2 mediated DNA damage Hypertension	(Ahn et al., 2007)
		Photochemopreventive effect	(Cha et al., 2006) (Hwang et al., 2006)
8.	Phycoerythrin	Amelioration of diabetic complications	(Yabuta et al., 2010)
9.	Polyphenols	Vascular chemoprotection	(Kang et al., 2003)
		Antimicrobial	(Apostolidis and Lee 2010)
		α glycosidase inhibition	(Jimenez et al., 2010)
10.	Porphyran, shinorine	Antiaging	(Zhang et al., 2003;Rastogi et al., 2010)

hence, algae is a potent antioxidant compounds that could also be suitable for protecting our bodies against the damaging effect of reactive oxygen species produced as a result of normal metabolism of the body. Algal antioxidants are of very different nature such as carotenoids and vitamin E (α-tocopherol) are fat-soluble fraction, whereas vitamins, phycobiliproteins and polyphenols are the powerful water-soluble antioxidants (Table 2) (Ikeda et al., 2003; Ina Kamei 2006).

Carotenoids

Carotenoids are among the most common pigments in nature. Most naturally occurring carotenoids are hydrophobic tetraterpenoids that contain a C40 methyl-branched hydrocarbon backbone (Figure 1). The polyene chains of carotenoids, consisting of conjugated double bonds, are responsible for the pigmentation of carotenoids and their ability to absorb photons in visible wavelengths. Carotenoids are synthesized by all photosynthetic organisms as well as by many non-photosynthetic bacteria and fungi. More than 600 known carotenoids were reported in nature and about 50 have provitamin- A activity (Del Campo et al., 2007). There are two main classes of naturally occurring carotenoids: carotenes, which are hydrocarbons that are either linear or cyclized at one or both ends of the molecule (such as β- carotene, α-carotene); and xanthophylls, which are oxygenated derivatives of carotenes. All xanthophylls produced by higher plants, for example violaxanthin, antheraxanthin, zeaxanthin, neoxanthin and lutein are also synthesized by green algae. However, in contrast to land plants, specific green algae possess additional xanthophylls such as loroxanthin astaxanthin and canthaxanthin (Baroli and Niyogi 2000; Grunewald et al., 2001). In addition, diatoxanthin, diadinoxanthin, and fucoxanthin are produced in brown algae and dinoflagellates (Lohr and Wilhelm, 2001).

In the algae the carotenoids seem to function primarily

Table 2. Antioxidant compounds in algae and potential algal sources for utilization.

Sr. no	General category	Example compounds	Algal source	Reference
1.	Carotenoids	β-carotene	*Chondrus crispus* *Mastocarpus stellatus* Brown algae Red algae	Lohrmann et al. (2004)
		Lycopene		Nguyen and Schwartz (1999)
2.	Phenolic compounds	Stypodiol, Isoepitaondiol, Taondiol	Taonia atomaria	Nahas et al. (2007)
		Terpenoids	*Cystoseira* sp.	Foti et al. (1994)
3.	Phycobilin pigments	Phycoerythrin, phycocyanin	Red algae in general	Romay et al. (2003); Sekar and Chandramohan (2008); Soni et al. (2009); Yabuta et al. (2010)
4.	Polyphenols	Catechin, Epicatechin, Gallate Flavonoids Phlorotannins	*Halimeda* sp.	Devi et al. (2008)
5.	Sulphated polysaccharides	Fucoidan, Alginic acid,	*Turbinaria conoides*	Chattopadhyay et al. (2010)
		Laminaran		Luo et al. (2009)
		Fucoidan	*Laminaria japonica*	Rocha de Souza et al.(2007)
		Sulphated galactans (lambda carrageenan)	Most red algae	Barahona et al. (2011) Costa et al. (2010)
		Galactans	Some marine red	Josephine et al. (2008)
		Sulphated Glycosaminoglycan	algae *Sargassum wightii*	Athukorala et al. (2006)
		Porphyran	*Porphyra* sp.	
6.	Vitamins	Ascorbate	*Chondrus crispus* *Mastocarpus stellatus*	Lohrmann et al. (2004)
			Sargassum sp.	García-Casal et al. (2009)
		Vitamin A	*Kappaphycus alvarezii*	Kumar et al. (2008)

as photoprotective agents and as accessory light harvesting pigment, thereby protecting the photosynthetic apparatus against photo damage. They also play a role in phototropism and phototaxis. Some microalgae can undergo a carotenogenesis process, in response to various environmental and cultural stresses (e.g. light, temperature, salts, nutrients), where the alga stops growth and changes dramatically its carotenoid metabolism, accumulating secondary carotenoids as an adaptation to severe environments (Bhosale, 2004).

The main carotenoids produced by microalgae are β -carotene from *Dunaliella salina* and astaxanthin from *Haematococcus pluvialis*. β -carotene serves as an essential nutrient and has high demand in the market as a natural food colouring agent, as an additive to cosmetics and also as a health food (Raja et al., 2007). β -carotene is routinely used in soft-drinks, cheeses and butter or margarines. Is well regarded as being safe and indeed positive health effects are also ascribed to this carotenoids due to a pro-vitamin A activity (Baker and Gunther, 2004).

Lycopene is a red pigment that occurs naturally in certain fruits, vegetables, algae and fungi. It belongs to a large group of pigments known as carotenoids; however, it has no provitamin A activity (Bradbury et al., 2012).

The benefits of astaxanthin are said to be numerous, and include enhancing eye health, improving muscle strength and endurance and protecting the skin from premature ageing, inflammation and UVA damage, is a strong coloring agent and has many functions in animals such as growth, vision, reproduction, immune function, and regeneration. Some reports support the assumption that daily ingestion of astaxanthin may protect body tissues from oxidative damage as this might be a

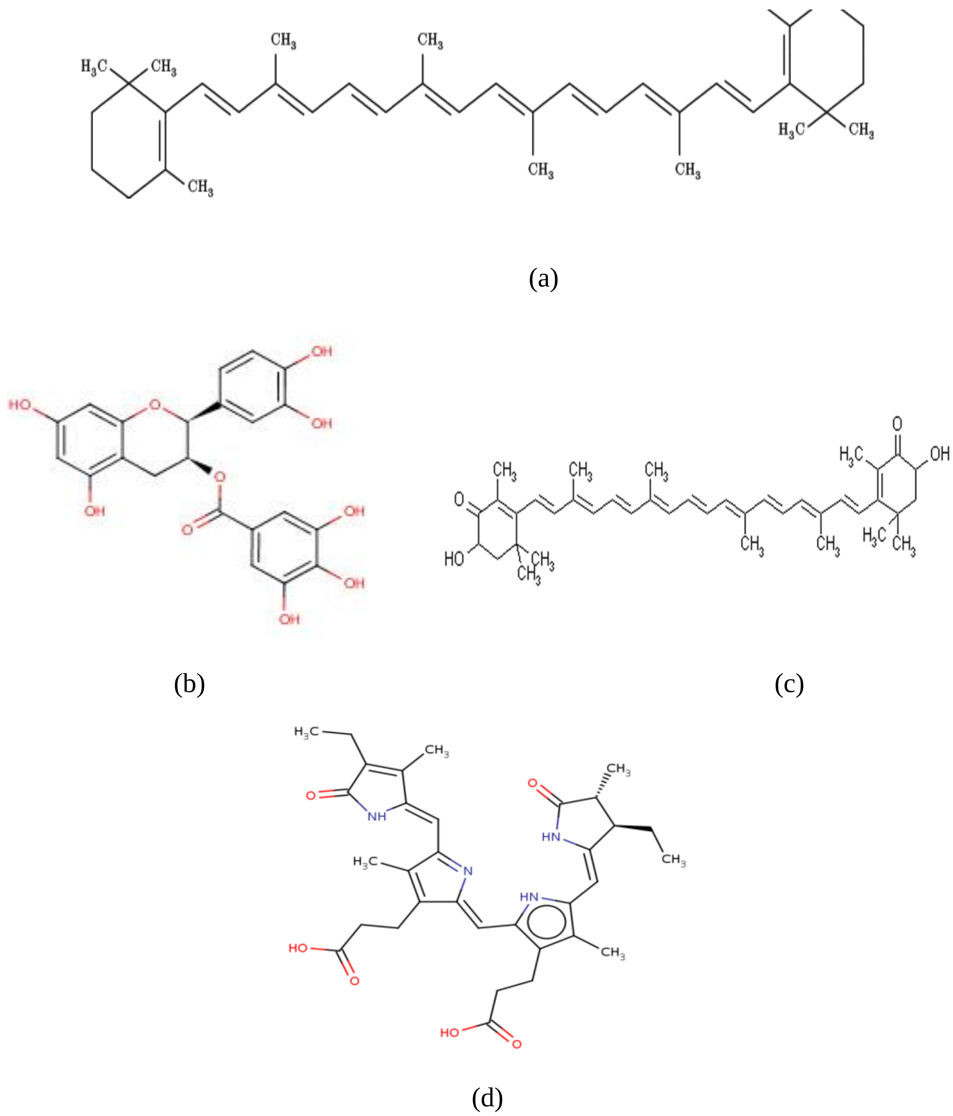

Figure 1. Chemical structures of (a) β –carotene (b) catechin (c) astaxhanthin (d) Phycocyanobilin.

practical and beneficial strategy in health management. It has also been suggested that astaxanthin has a free radical fighting capacity worth 500 times that of vitamin E (Dufosse et al., 2005).

Phycobilin pigments

Aside chlorophylls, as the primary photosynthetic pigment, microalgae also form various accessory or secondary pigments, such as phycobiliproteins. These natural pigments are able to improve the efficiency of light energy utilization of the algae and protect them against solar radiation and related effects. Their function as antioxidants in the plant shows interesting parallels with their potential role as antioxidants in foods and humans (Van den Berg et al., 2000).

Cyanobacteria (blue-green algae), Rhodophyta (red algae) and cryptomonads algae contain phycobiliproteins, which are major components of a complex assemblage of photosynthetic light-harvesting antenna pigments - the phycobilisomes. Phycobiliproteins are formed by a protein backbone covalently linked to tetrapyrrole chromophoric prosthetic groups, named phycobilins (Figure 1). The main natural resources of phycobiliproteins are the cyanobacterium *Spirulina*

(*Arthrospira*) for phycocyanin (blue) and the rhodophyte *Porphyridium* for phycoerythrin (red). Phycocyanin is currently used in Japan and China as a natural colouring, in food products like chewing gums, candies, dairy products, jellies, ice creams, soft drinks (*e.g*. Pepsi® blue and also in cosmetics such as lipsticks, eyeliners and eye shadows. In a recent study, phycocyanin was considered a more versatile blue colorant than gardenia and indigo, providing a bright blue color in jelly gum and coated soft candy, despite its lower stability towards heat and light (Jespersen et al., 2005).

Phenolic and polyphenols compounds

Polyphenolic secondary metabolites are a large and diverse group of chemical compounds which exist both in terrestrial plants and in aquatic macrophytes. Phenolic compounds can act as antioxidants by chelating metal ions, preventing radical formation and improving the antioxidant endogenous system (Al-Azzawie and Mohamed-Saiel, 2006). The term “phenolic compound” describes several hundred molecules found in edible plants that possess on their structure a benzenic ring substituted by, at least, one hydroxyl group (Manach et al., 2004). These phenolic compounds are commonly found in plants, including seaweeds (Duan et al., 2006). Polyphenols represent a diverse class of compounds including flavonoids (i.e. flavones, flavonols, flavanones, flavononols, chalcones and flavan-3-ols), lignins, tocopherols, tannins and phenolic acids (Thomas and Kim, 2011). Phlorotannins from brown algae have up to eight interconnected rings. They are therefore more potent free radical scavenger than other polyphenols derived from terrestrial plants, including green tea catechins, which only have three to four rings (Hemat, 2007).

Flavonoids, the largest groups of phenolic compounds are known to contain a broad spectrum of chemical and biological activities including antioxidant and free radical scavenging properties (Kahkonen et al., 1999). Flavonoids include flavonols, flavones, catechins, proanthocyanidins, anthocyanidins and isoflavonoids (Ndhlala et al., 2007).

In the brown algae (Phaeophyceae), the only group of tannins present is the phlorotannins. They are polymers of phloroglucinols (1,3,5-trihydroxybenzene, and may constitute up to 15% of the dry weight of brown algae (Wang et al., 2012).

Sulphated polysaccharides

Polysaccharides are the most abundant among the natural products produced by plants and they widely exist in plants, animals, microorganisms and algae (Paulsen, 2002; Yang and Zhang 2009). These polymeric carbohydrate structures, usually composed of various monosaccharides linked with different glucosidic bonds (Holdt and Kraan 2011). Depending on the structure, polysaccharides can have distinct functional properties from their building blocks. Sulphated polysaccharides are among the most abundant and broadly studied polysaccharides from non-animal origin (Pereira et al., 2002). Most naturally occurring sulphated polysaccharides are complex mixtures of molecules showing wide variations in their structure as well as their activities (Alban et al., 2002). They are widespread in nature. Seaweeds are recognized as a major source of sulphated polysaccharides with various biological activities. Thus, sulphated polysaccharides are of special interest in the search of natural products.

Fucoidan is a type of complex sulphated polysaccharides , mainly found in the cell-wall matrix of various brown seaweed species (Teruya et al., 2007; O’Connell et al., 2008; Kim et al., 2010). It contains substantial percentages of L-fucose and sulfate ester groups (Matou et al., 2002; Li et al., 2008; Jiang et al., 2010). Fucose is a hexose deoxy sugar with the chemical formula $C_6H_{12}O_5$ and is the fundamental sub unit of the fucoidan polysaccharides. For the past decade fucoidan has been extensively studied due to its numerous biological activities. Recently researches for new drugs have raised interest in fucoidans. In the past few years, several fucoidans’ structures have been isolated, and many aspects of their biological activity have been elucidated (Aisa et al., 2005; Li et al., 2008).

Vitamins and minerals

Extraction of vitamins from natural sources has received increasing attention due to the high antioxidant activity associated to this family of compounds. Besides its well-known antioxidant activity, recent studies have demonstrated that certain synthetic vitamins are less effective than natural vitamins (Kelman et al., 2012).

Microalgae biomass represents a valuable source of nearly all essential vitamins (*e.g.* A, B1, B2, B6, B12, C, E, nicotinate, biotin folic acid and pantothenic acid) and a balanced mineral content (*e.g*. Na, K, Ca, Mg, Fe, Zn and trace minerals) (Becker, 2004). The high levels of vitamin B12 and Iron in some microalgae, like *Spirulina*, makes them particularly suitable as nutritional supplements for vegetarian individuals. The vitamin content of an alga depends on the genotype, the stage in the growth cycle, the nutritional status of the alga, the light intensity (photosynthetic rate). The vitamin content is

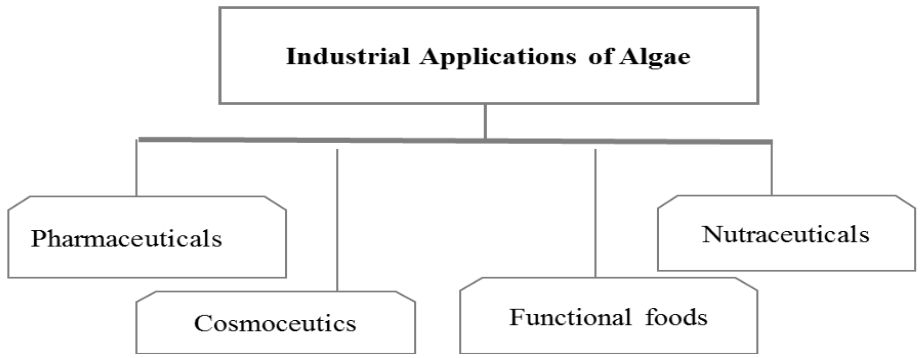

Figure 2. Industrial applications of algae.

therefore amenable to manipulation by varying the culture conditions as well as by strain selection or genetic engineering. However, vitamins cell content fluctuates with environmental factors, the harvesting treatment and the biomass drying methods (Garcia et al., 2009).

POTENTIAL APPLICATIONS OF ANTIOXIDANTS

Algae are an enormous biological resource, representing one of the most promising sources for new products and industrial applications (Figure 2) (Pulz and Gross, 2004). They can be used to enhance the nutritional value of food and animal feed, due to their well-balanced chemical composition. Moreover, they are cultivated as a source of highly valuable molecules such as polyunsaturated fatty acids, pigments, antioxidants, pharmaceuticals and other biologically active compounds. The application of microalgal biomass and/or metabolites is an interesting and innovative approach for the development of healthier food products. Microalgal biotechnology is similar to conventional agriculture, but has received quite a lot of attention over the last decades, because they can reach substantially higher productivities than traditional crops and can be extended into areas and climates unsuitable for agricultural purposes (e.g. desert and seashore lands). Microalgae production is an important natural mechanism to reduce the excess of atmospheric CO_2 by biofixation and recycling of fixed C in products, ensuring a lower greenhouse effect, reducing the global environmental heating and climate changes. Microalgae cultivation also presents less or no seasonality, are important as feed to aquaculture and life-support systems, and can effectively remove nutrients (or pollutants) (e.g nitrogen and phosphorus) from water. Microalgal systems for sunlight driven environmental and production applications can clearly contribute to sustainable development and improved management of natural resources. Lately, microalgae have been seen with a great potential as a sustainable feedstock for biodiesel production, in substitution for oil from vegetable crops (Spolaore et al., 2006), and also for hydrogen production (Dutta et al., 2005).

Human health

The United States Food and Drug Administration approved the use of astaxanthin as a feed additive for aquaculture in 1987 and subsequently in 1999 astaxanthin were approved as a nutraceutical (Guerin et al., 2003).

Nutrition

In recent years, there has been a growing interest in the so-called functional foods because they can provide physiological benefits additional to nutritional and energetic, as, for instance, antihypertensive, antioxidant or anti-inflammatory. In the search for feasible new sources of natural antioxidants that can be used in the food industry, algae have been suggested as possible raw materials. These organisms are widely known and consumed in certain countries, and numerous health benefits have been associated with their use. Therefore, algae are potentially a great source of natural compounds that could be used as ingredients for preparing functional foods. Different compounds with antibacterial, antiviral and anti fungal activity can be found in these types of organisms along with compounds with antioxidant activity (Molina et al., 2003; Christaki et al., 2011; Lee et al., 2013). Antioxidants can play an important role in food technology because of their usefulness against lipid peroxidation (Senorans et al., 2003).

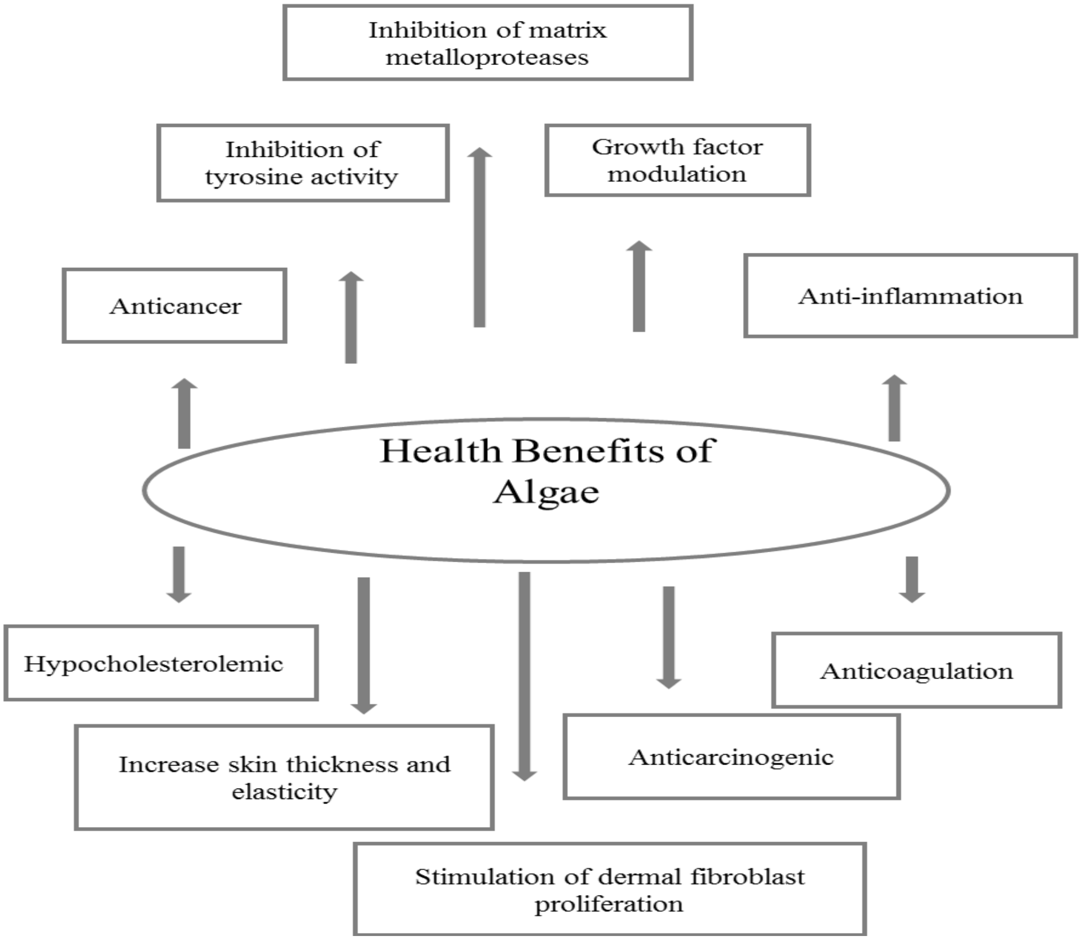

Figure 3. Health benefits of algae.

All over the world commercial production of microalgae for human nutrition is already a reality. Numerous combinations of microalgae or mixtures with other health foods can be found in the market in the form of tablets, powders, capsules, pastilles and liquids, as nutritional supplements (Table 2). They can also be incorporated into food products (*e.g.* pastas, biscuits, bread, snack foods, candies, yoghurts, soft drinks), have beneficial health effects that are associated with microalgal biomass, probably related to a general immune-modulating effect. In spite of some reluctance for novel foods in the past, nowadays there is an increasing consumer demand for more natural food products, presenting health benefits. Functional foods supplemented with microalgae biomass are sensorially much more convenient and variable, thus combining health benefits with attractiveness to consumers. The pathway of health benefits of algae is shown in Figure 3 (Pulz and Gross, 2004).

Live stock

Using even very small amounts of micro algal biomass can positively affect the physiology of animals by improved immune response, resulting in growth promotion, disease resistance, antiviral and antibacterial action, improved gut function, probiotic colonization stimulation, as well as by improved feed conversion, reproductive performance and weight control. The external appearance of the animals may also be improved, resulting in healthy skin and a lustrous coat, for both farming animals (poultry, cows, breeding bulls) and pets (cats, dogs, rabbits, ornamental fishes and birds). Since feed corresponds to the most important exogenous factor influencing animal health and also the major expense in animal production, the use of alternative high quality protein supplements replacing conventional protein sources is encouraged. Considering that animal feed stands at the beginning of the food chain, increasing public and legislative interest is evident, especially considering intensive breeding conditions and the recent trend to avoid *“chemicals”* like antibiotics (Breithaupt, 2007). The large number of nutritional and toxicological evaluations already conducted has demonstrated the suitability of algae biomass as a valuable feed supplement. In fact, 30% of the current world algal production is sold for animal feed applications (Becker, 2004).

Cosmetics

Components of algae are frequently used in cosmetics as thickening agents, water-binding agents and antioxidants. Cosmetics companies claim benefits on the skin or health in general from contents like carrageenan, other algal polysaccharides, algal proteins or lipids, vitamin A, vitamin B1, iron, phosphorus, sodium, copper, magnesium, calcium, or other elements; some companies promise that algal extracts inhibit oxidative degeneration of collagen and hyaluronic acid and that they have anti-aging properties. From a scientific point of view, many of the promised effects have to be judged as not scientifically proven and unsubstantiated. Typical species that are used for cosmetics are *Chondrus crispus*, *Mastocarpus stellatus*, *Laminaria* spp., *Porphyra* spp., *Ulva lactuca*, *Ascophyllum nodosum*, *Alaria esculenta*, *Spirulina platensis*, *Nannochloropsis oculata*, *Chlorella vulgaris* and *Dunaliella salina* (Hallmann, 2007).

Conclusion

Natural antioxidants, found in algae, are important bioactive compounds that play an important role against various diseases and again processes through protection of cells from oxidative damage. It is a valuable source of neuroprotective agents. It provides a useful alternative to non - natural substances. Additionally the combination of the exceptional nutritional value of microalgae with colouring and therapeutically properties, associated with an increase demand of natural products, make microalgae worth exploring for utilization in the future in feed, food, cosmetic and pharmaceutical industries, with recognized advantages comparing with the traditional ingredients.

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