Biologically Active Compounds in Seaweed Extracts - the Prospects for the Application

Katarzyna Chojnacka*, Agnieszka Saeid, Zuzanna Witkowska and Łukasz Tuhy

Institute of Inorganic Technology and Mineral Fertilizers, Wroclaw University of Technology ul. Smoluchowskiego 25, 50-372 Wroclaw, Poland

Abstract: The paper covers the latest developments in research on the utilitarian properties of algal extracts. Their application as the components of pharmaceuticals, feeds for animals and fertilizers was discussed. The classes of various biologically active compounds were characterized in terms of their role and the mechanism of action in an organism of human, animal and plant.

Recently, many papers have been published which discuss the methods of manufacture and the composition of algal extracts. The general conclusion is that the composition of extracts strongly depends on the raw material (geographical location of harvested algae and algal species) as well as on the extraction method. The biologically active compounds which are transferred from the biomass of algae to the liquid phase include polysaccharides, proteins, polyunsaturated fatty acids, pigments, polyphenols, minerals, plant growth hormones and other. They have well documented beneficial effect on humans, animals and plants, mainly by protection of an organism from biotic and abiotic stress (antibacterial activity, scavenging of free radicals, host defense activity etc.) and can be valuable components of pharmaceuticals, feed additives and fertilizers.

Keywords: Algal extracts, feed additives, fertilizers, pharmaceuticals, biologically active compounds.

1. INTRODUCTION

The resource for the manufacture of algal extracts can be the biomass of seaweeds harvested from surface waters. This is beneficial for water reservoirs because they would help to reduce the load of biogenic compounds and would clean the coast from unwanted biomass. Additionally, using extracts instead of fresh or dry algal biomass provides a chance to reduce the content of toxic elements or compounds accumulated from waters by the seaweeds.

Algae and consequently their extracts can be the treasure trove of biologically active compounds. Their beneficial properties for humans, animals and plants were recognized in the past and are appreciated nowadays, in the development of new biotechnological products.

Products with functional properties containing organic compounds derived from natural sources, rather than being a product of heavy organic synthesis are increasingly demanded by consumers. Currently, recipients of products have higher demands, expecting that they will be on one hand "bio" and "organic", but on the other - will be a concentrate of compounds with desired properties. This poses a particular challenge for modern biotechnology.

The paper presents state-of-the-art in the current developments in the field of algal extracts. The particular attention was paid to biologically active compounds, useful as the components of pharmaceuticals, feeds and fertilizers.

*Address correspondence to this author at the Institute of Inorganic Technology and Mineral Fertilizers, Wroclaw University of Technology ul. Smoluchowskiego 25, 50-372 Wroclaw, Poland; Tel. +4871-3204325; Fax: +4871-3203469; E-mail: katarzyna.chojnacka@pwr.wroc.pl

2. BIOLOGICALLY ACTIVE COMPOUNDS IN ALGAL EXTRACTS

2.1. Polysaccharides

Seaweeds contain many different polysaccharides, which chemical structure relates to the corresponding taxonomic classification of algae and their cell structure [1, 2]. Sulfated polysaccharides inhibit activity of many bacterial species as well as viruses [3]. Polysaccharides can act as prebiotics (substances that stimulate the growth of beneficial bacteria in the digestive track) and exert growth-promoting and health-improving effects [4]. Many of them are soluble dietary fibers which have positive effect on digestive track of animals (i.e. alginic acid). Also, seaweed-derived polysaccharides are effective and non-toxic antioxidants [5, 6]. The contents of polysaccharides show seasonal variations. The total level of these compounds in seaweeds is up to 76% of dry weight [7]. Among many different algal polysaccharides, the most important are galactans, fucoidan, laminarin and alginates [1].

Sulfated galactans are found both in the intercellular matrix and in the cell wall. Galactan is a macromolecule containing disaccharide-based repeating units: [→3)-β-D-Gal*p*-1→] and either [→4)-α-Gal*p*-(1→] or 3,6-anhydro-α-Gal*p* [1]. Depending on the optical configuration of the second unit, agarans (D) and carrageenans (L) are distinguished. The substituents of the main chain of galactans are sulfate

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groups, methoxyl groups, pyruvic acid acetals and glucosyl side chains. These groups can be irregularly distributed through the macromolecule [1]. Galactans have anti-tumor and antiviral properties.

Fucoidan is a sulfated polysaccharide found in brown seaweeds. The macromolecule contains α-1,3-linked sulphated L-fucose as main sugar unit and sulfate ester groups [8, 9]. The chemical composition depends on the algal source and harvesting time. The amount of fucoidan in algae is about 10% of dry mass. The absorption and bioavailability of fucoidan depends on its molecular weight. Compared to high molecular fucoidan (HMF), low molecular fucoidan (LMF) is bioavailable in higher degree [8]. Many of biological effects of these polysaccharides are related to their ability to change surface properties of the cell. It has anti-inflammatory, antiviral, anti-tumor and antioxidative activities [8, 9]. Antiviral properties of fucoidan participate in inhibition of viral-induced syncytium formation.

Laminarin is one of the major polysaccharides found in brown algae. It has a chemical structure consisting of β-(1→3)-linked glucose in the main chain and random β-(1→6)-linked side-chains [10]. The content of laminarin in seaweeds is about 10% of dry weight, but seasonally it can reach up to 32% [7]. Laminarin is a dietary fibre and can act as a prebiotic. Also, it has antiviral and antibacterial properties [10]. Antioxidative acitivity of laminarin depends on its molecular weight and chemical structure [5].

Alginates are absent in terrestrial plants. They can be extracted from brown seaweeds, in which they constitute up to 47% of dry biomass [7]. Alginates can be found both in acidic and salt forms. The acid form, known as an alginic acid, is a polymer consisting of two types of hexuronic acid monomers linked by 1–4 bonds [11]: β-D-mannuronic acid and α-L-guluronic acid. They have thickening, stabilizing and general colloidal properties [12], but also strong antibacterial and anti-inflammatory activities.

2.2. Proteins

Structure and biological properties of proteins extracted from seaweeds are not as widely documented as of polysaccharides. Usually the content of proteins in seaweeds is less than 5% [3]. The lowest content of proteins have brown seaweeds. Most species of algae contain all of the essential amino acids. For example, in *Enteromorpha* spp.: 9 of the 10 amino acids essential for vertebrates were detected in higher levels than in an equivalent weight of soy beans [13]. Very important bioactive proteins that can be extracted from macroalgae are lectins, which bind with carbohydrates and participate in many biological processes like intercellular communication. They have also antibacterial, antiviral or anti-inflammatory activities [14].

2.3. Polyunsaturated Fatty Acids (PUFAs)

Phospholipids and glycolipids are the main classes of lipids found in seaweeds. When the decrease of environmental temperature occurs, seaweeds can accumulate polyunsaturated fatty acids (PUFAs). The species that live in cold regions contain more PUFAs than species living in higher temperatures [7]. Long chain PUFAs (LC-PUFAs) are of particular interest, because they are very important for human health maintenance and they are synthesized only by plants [15]. These lipids consist of at least 20 carbon atoms with at least two double bonds. When the first double bond is located in the third carbon atom, the lipid molecule is referred as omega-3 (n-*3* LC-PUFA). The research [13] showed that n-*3* LC-PUFA constituted 10.38 % of total fatty acids found in *Enteromorpha* spp.

2.4. Pigments

Seaweed pigments can be divided into three major groups: chlorophylls, carotenoids and phycobiliproteins. Carotenoids are organic pigments present in chloroplasts and chromoplasts [2]. They are produced by marine algae, plants, fungi and by some bacteria [5, 16] and are the most widespread pigments in the nature. Pigments are polyenes soluble in lipids. Different species of algae contain different kinds of carotenoids, which are very strong antioxidants. These properties are based on the fact that they are able to quench singlet oxygen and scavenge free radicals [5]. The most important carotenoids are β-carotene, fucoxanthin and tocopherol. The content of β-carotene in algal dry mass ranges from 36 to 4500 mg/kg. Fucoxanthin comprises even 70% of total carotenoid content [7]. Supercritical CO_2 extraction gives an opportunity to extract these compounds from different seaweeds (e.g. *Chlorella vulgaris*, or *Dunaliella salina*) with extraction yield ranging up to 90% [17].

Phycobiliproteins are water soluble pigments produced by cyanobacteria (blue-green algae), red algae and cryptomonads [18]. They constitute a few percent of algal dry weight. Phycobiliproteins have not only antioxidant, but also anti-inflammatory, antiviral and neuroprotective properties [7].

2.5. Polyphenols

Polyphenols are produced by most plants, including seaweeds [19]. Among polyphenols phenolic acids, flavonoids, isoflavones, cinnamic acid, benzoic acid, quercetin and lignans can be mentioned [20, 21]. Polyphenols are strong antioxidants [22]. Seaweeds produce these compounds to protect them from external conditions such as stress and herbivores [23]. Reactive oxygen species, generated in organisms as an integral part of metabolism, are highly reactive and can cause cellular dysfunction and cytotoxicity [24]. Polyphenols can donate hydrogen to free radicals and produce non-reactive radicals [21]. Seaweed extracts contain appreciable amounts of polyphenols, but their content is strongly dependent on the extraction method. *Ascophyllum* spp. have significantly more polyphenols than other seaweeds, while *Ulva* spp. have the lowest content of these compounds [20, 25].

Phlorotannins are the group of tannin compounds, which belong to the polyphenolic substances. Although tannins are widespread among both terrestrial and marine plants, phlorotannins, eg. eckol or dieckol, have been found only in brown seaweeds [19, 21]. The phlorotannins are polyphenols formed by polymerization of phloroglucinol through the acetate-malonate pathway [2, 23]. These polymers have many biological activities in organisms, eg. are involved in host defense mechanisms [26]. Phlorotannin content varies

from 1 to 10% of the algal dry mass [26]. The molecular skeleton of phlorotannins consists of even 8 phenol rings [27], while terrestrial plants produce tannins consisting of only 3 to 4 rings [19]. Phenol rings act as electron traps for free radicals [21]. Consequently, phlorotannins have very strong anitioxidant properties because of their unique structure [19]. For example, phlorotannins isolated from *Eisenia bicyclis* have shown even 10 times higher antioxidant activity in comparison with ascorbic acid and α-tocopherol [21]. Phlorotannins also have strong antimicrobial activities. They can attack microbiological proteins, which can result in inhibition of bacteria [21].

2.6. Minerals

Algae are a rich source of minerals [28]. Their content in the biomass is sometimes as high as 40% [29]. This is because seaweeds accumulate metal ions from salt water and concentrate those substances as carbonate salts in their fronds [30]. Researchers examined the mineral content in concentrates from seaweeds harvested from Japanese beaches. The highest concentrations of potassium (2.71 g/L), magnesium (0.19 g/L) and calcium (0.16 g/L) ions were detected in extract from *Sargassum ringgoldianum* subsp. *coreanum*. *Codium fragile* was shown to be a rich source of sodium ions (1.21 g/L) [31]. *Kappaphycus alvarezii* contains high levels of magnesium and calcium ions [32]. Their concentrations in extracts were 581.20 mg/L and 460.11 mg/L, respectively.

2.7. Plant Growth Hormones

Plant growth hormones found in seaweed extracts are mainly responsible for plant growth stimulation and the increase of the intensity of photosynthesis. Cytokinins (plant growth regulators) protect plants from the consequences of temperature changes [33, 34]. They are synthesized by biochemical modification of adenine. Among many important functions, being responsible for controlling of bud and cell division, seem to be the most important. Within this group of hormones, zetaine and indole-3-propionic acid (IPA) were the main compounds identified in seaweed extracts [35]. Cytokinins were found in *Protococcus, Chlorella*, and *Scenedesmus* spp. [33].

Other plant hormones present in seaweed extracts – auxins, were shown to initiate root formation and inhibit its elongation. Plants are able to synthesize these compounds from tryptophan or indole [33]. The concentrations of auxins in seaweed extracts are different and strongly depend on the species. Some authors reported their presence in extract from *Ascophyllum nodosum* in the concentration of 50 mg IAA/g of dry mass (IAA - indole-3-acetic acid) [36]. Other researchers have shown that IAA is also present in extracts from *Porphyra perforata*, *Botryocladia* spp., *Enteromorpha* sp. and in cyanobacteria [36].

Among plant hormones, gibberellins were also isolated from seaweed extracts. They are produced in developing seeds from glyceraldehydes-3-phosphate. Gibberellins were identified in extracts from *Fucus vesiculosus* and *Fucus spiralis* [33]. Trace quantities of these compounds were also detected in extract from *Ascophyllum nodosum* [25]. The main role of gibberellins is to initiate seeds germination.

Abscisic acid (ABA) synthesized from carotenoids by more than 60 species of algae (e.g. *Chlorella* spp., *Haematococcus pluvialis)* is another plant growth regulator. ABA is mostly responsible for synthesis of proteins required for response to drought [25]. Although abscisic acid was determined in many groups of seaweeds, in some extracts lunularic acid was found as a compound which plays the same role as ABA in higher plants. It is supposed that algae produce a complex responsible for growth inhibition consisting of several components which act as ABA in algae [33].

Betaines, which are not conventional plant hormones, were also found in algal extracts [37]. Their minor function is to protect plants from drought and frost [25]. Besides, they can act as a source of nitrogen for plants. Another role of this plant regulator is to enhance chlorophyll content in leaves by decreasing its degradation. Extracts from brown algae *Ascophyllum nodosum* are also proved to be rich in betaines [25, 36].

3. USING SEAWEED EXTRACTS AS COMPONENTS OF PHARMACEUTICALS, FEEDS AND FERTILIZERS

Algal extracts were firstly manufactured to obtain highly concentrated product with long shelf life [26]. For agricultural uses, seaweed extracts were first applied in 1949. While liquefying seaweeds, in some cases even 100% of particular biologically active substances can be extracted [16]. Among different valuable compounds in algal extracts there are sulfated polysaccharides, carotenoid pigments, phycosterols, bioactive peptides [19, 38], polyunsaturated fatty acids (PUFA) [15, 39], betaines, taurine [39], polyphenols (especially phlorotannins) [27,39], minerals [19], vitamins [21] and others [40-42] (Table **1**). Some of biologically active substances, like phlorotannins, occur only in seaweeds [19, 21]. The biochemical composition of seaweed extract depends on geographical location of harvested algae and on the extraction method [16, 43].

3.1. Pharmaceuticals

Algae are a natural source of bioactive molecules with a broad range of biological activities, such as antibiotics, antivirals, anti-tumorals, antioxidants and anti-inflammatories [44]. A large number of algal extract products have been found to have antimicrobial activity [41, 45]. Many of the structures were identified as fatty acids and hydroxyl unsaturated fatty acids, glycolipids, steroids, phenolics and terpenoids. Lauric acid, palmitic acid, linolenic acid, oleic acid, stearic acids are known to be potential antibiotic or antifungal agents [44]. Some halogenated with bromine, chlorine and even iodine metabolites like diterpenes, triterpenes have been reported to possess diverse biological activities as antibacterial, ichtyotoxic, antioxidant, antimalarian, insecticidal and cytotoxic [45].

Polysaccharides possess immunological properties ranging from nonspecific stimulation of host immune system, resulting in anti-tumor, antiviral and anti-infection effects to antioxidant, anti-mutagenic or hematopoietic activity [28, 46, 47]. These properties were found in the blue-green filamentous alga *Spirulina* extract, which can inhibit viral replica-

tions and cancer development, and enhance antibodies production [48]. The antiviral polysaccharides should have very low cytotoxicity towards mammalian cells if they are to be used for medicinal purpose. Polysaccharides have shown good immunomodulatory properties associated with anti-tumor effects. A role of sulfated polysaccharides from algae as anti-neoplastic agent has been suggested. Several investigations have reported that sulfated polysaccharides have anti-proliferative activity in cancer cell lines as well as inhibitory activity against tumors [49]. A polysaccharide (sarg) extracted from the brown marine alga *Sargassum stenophyllum* could effectively inhibit vasculogenesis as well as developmental angiogenesis in chick embryos [50].

Table 1. Biologically Active Substances in Seaweed Extracts

Biologically Active Substance	Activity
Polysaccharides	prebiotics [4] antimicrobial activity [3] growth-promoting activity [4] health-improving activity [4] antiviral activity [8,19,52] anti-tumor activity [8,19,53] anti-inflammatory activity [8,19] source of soluble dietary fibers [8,10] antioxidants [5,6,8,19] antithrombotic activity [51] anticoagulant activity [51]
Proteins	source of essential amino acids [13] elements of intercellular communication [14] antiviral activity [14] antimicrobial activity [14] anti-inflammatory activity [14] antioxidants [55]
Polyunsaturated fatty acids	health-improving activity [15] antibiotic activity [44] antifungal activity [44]
Pigments	antioxidants [5,59] anti-inflammatory activity [7,58] antiviral activity [7] neuroprotective activity [7,58] anti-obesity activity [58,60] anti-angiogenic activity [58] anticancer activity [57]
Polyphenols	host defense activity [26] strong antioxidants [22,61,63] antimicrobial activity [21] antiviral activity [52] anti-photo aging activity [45,61,64,65] anti-obesity activity [28,52,68] antiallergic activity [69] anticancer activity [28]
Minerals	growth- and health-improving activity [28]
Plant growth hormones	growth stimulants [25,36] protective activities [26,33,34] cell division controllers [35] root formation stimulants [33] host defense activity [25] source of nitrogen for plants [25,26]

In many papers anticoagulant, antithrombotic, immunomodulatory, anticancer and anti-proliferative activities are the most extensively studied biological effects of fucoidans [51]. Fucoidan has antiviral properties toward viruses such as HIV and human cytomegalovirus (HCMV) [52]. Increasing the number of sulfate groups in the fucoidan molecule has been shown to affect the anti-tumor and anti-angiogenic activity [53]. Fucoidan with sulphate content less than 20% showed dramatic decreases in anticancer activity. It was also suggested that fucoidan polymers activate the host immune system against tumor [54].

Additionally, the anticoagulant activity of a sulfated polysaccharide from extracts of brown seaweed *Ecklonia cava* was investigated [55]. A group of pharmaceuticals called anticoagulants can be used as a medication for thrombotic disorders. Structural similarities between sulfated polysaccharides from marine algae and heparin were reported [55].

Antioxidant property was found also in the protein extract, specifically some phycobiliproteins such as C-phycocyanin (CP) and allophycocyanin. It was confirmed that the protection effect against hydroxyurea-teratogenic insult was related to the antioxidant activity of protein extract [56].

Natural pigments have received particular attention, because their beneficial activities, such as anticancer [57], anti-inflammatory, anti-obesity, anti-angiogenic and neuroprotective [58]. Recently, the potential antioxidant compounds were identified as some pigments (fucoxanthin, astaxantin, carotenoids) [59]. Many products formulated on the basis on microalgal pigment content with intended use for anti-obesity, immunity booster and many others can be found on the market [60].

Phenolic properties can be expected to contribute to the antioxidant activity by suppressing lipid peroxidation [61]. Polyphenolic extracts possess therapeutic potential for combating bronchial asthma associated with allergic diseases. The intraperitoneal administration resulted in a significant inhibition of all asthmatic reactions [62]. Tannins have also been reported to show their HIV-1 inhibitory mode of action by inhibiting polymerase and ribonuclease activities of HIV-1RT [52]. *Enteromorpha* exhibited good antioxidant activities of its bioactive compounds (phlorotannins) which anticipate a major breakthrough for a variety of food/medical applications as they have potential for the use of such compounds as natural antioxidants in different pharmaceutical products [63].

Many of polyphenolic compounds found in algal extracts are endowed with photoprotective and anti-photo aging activities that can prevent oxidative stress and damage from

exposure to UV radiation [45, 61, 64, 65]. For example, enzymatic extracts from brown seaweeds strongly inhibited DNA damage [27, 59, 66]. One of the group of compounds synthesized by algae, phlorotannins, are able to absorb UV radiation, acting as photoprotective cells against photodamage [23, 67]. It was found that these properties can also protect against UVB-induced skin carcinogenesis in animals [61]. Phlorotannins derived from *E. cava* such as dieckol and eckol reduce the intracellular reactive oxygen species generated by gamma-ray radiation [23]. Phlorotannin, dieckol, has potential whitening effect and can have potential use in the pharmaceutical and cosmetics industry [52]. Therefore, phlorotannins have profound capabilities to be used as functional ingredients in pharmaceuticals and cosmeceuticals for skin treatment.

Ability to inhibit digestive enzymes to achieve potential anti-diabetic effect of phenolic-rich extracts from marine macroalgae was proved [28]. Fucosterol (phlorotannins) caused a significant decrease in serum glucose concentration and exhibited an inhibition of sorbitol accumulation in the lenses of rat [52]. Roy *et al*. found in the *in vitro* test that the phlorotannins extracts completely inhibited in dose-dependent relation of α-amylase and α-glucosidase, while in animals the phlorotannins extracts were able to reduce the normal increase in postprandial blood glucose observed 20 min after a meal by 90% and consecutively reduced peak insulin secretion by 40% [68].

Allergic diseases are one of the major public health problems in the developed world. Brown algal *Sargasum hemiphullum* and red algal *Carpopeltis affinis* extracts have been used in Korean folk medicine as a therapeutic treatment of various allergic diseases [69]. Several phlorotannins isolated from *Eisenia arborea* were reported to possess antiallergic properties.

Polyphenol-rich extracts and isolated phlorotannin components have been shown to inhibit proliferation of cancer cells (e.g. colon cancer) and to influence anti-inflamantory responses [28]. Phloroglucinol (phlorotannins) derivatives exerted a higher anti-proliferative activity in human breast cancer cell, induced a significant proliferative inhibition and apoptosis [52]. Polyphenol-rich extracts of *Eucheuma cottonii* was anti-proliferative against oestrogen-dependent and oestrogen-independent human breast-cancer cell but was non-toxic to normal cell lines [70]. Anti-proliferative efficiency of algal extracts was positively correlated with the total polyphenols content. The antioxidant activity of *P. palmate* extracts may be associated with the presence of unique class of secondary metabolites, the mycosporine-like amino acids with functions of UV-absorbing sunscreen molecule [71].

3.2. Feed Additives

In Europe seaweeds were used as animal feed as early as in Roman times. In Iceland, France and Norway domestic animals were fed with algae to enhance nutritional value of feed [14, 26]. In 2004 the use of macroalgae as animal feed comprised 1% of global value of seaweed industry (US$ 10 million, mostly *Ascophyllum nodosum*) [72]. For microalgae as feed additives, the value of the industry in the same year was about US$ 300 million [15]. There is about ten thousand identified species of algae and about 5% of them are used as food for either humans or animals.

Use of algal extracts as feed additives has many benefits, like overall health improvement of feedstock, favorable change in gastrointestinal flora or increased milk production [26]. Also, algal extracts contain compounds, which have significant positive effects on the growth and immune system of aquaculture [1]. Another interesting application of seaweed extracts is pet food. Not only these extracts have advantageous effects on pets health, but they also affect their external appearance (eg. shiny hair) [15].

Recently, prophylactic antibiotics for pigs (feed additives acting as growth promoters) have been banned in most countries and there is an urgent need for new, safe and natural substances that would have antimicrobial properties [15, 73, 74]. Fucoidan and laminarin are of particular interest because of their positive effect on animals (especially pigs) gut flora. Zootechnical research on chickens showed that carrageenans reduce the cholesterol concentration in the blood plasma [75]. The study with newly weaned pigs showed that the inclusion of laminarin-fucoidan extract decreased the counts of *E. coli* in the feaces and improved performance of pigs after weaning [10]. Fucoidan acts a soluble dietary fibre, which has been reported to increase feed intake in pig-feeding studies [74]. In another paper, after the population of shrimp *Penaeus monoron* was infected with White Spot Syndrome virus (common shrimp virus), researchers observed increased survival rate (88-93%) within the group fed with crude fucoidan extracted from either brown seaweed *Sargassum polycystum* or green seaweed *Acirosiphonia orientalis* [76].

Antimicrobial properties and beneficial effect of laminarin on intestinal microflora have been recently showed in zootechnical research on pigs [77]. Laminarin can influence the translocation of bacteria across the epithelium. It also affects the mucus composition and the intestinal pH and by that it can modulate the intestinal metabolism [10].

Alginates can prevent absorption of toxic metal cations and play the role of dietary fibre which cleans the digestive system and prevents substances like toxic metal ions or cholesterol from absorption into the organism. Also, alginates have strong antibacterial properties and stimulate reparative process of wounds [7].

Seaweeds contain substantial amounts of omega-3 fatty acids which are substances of particular interest in animal feeding, because of their antimicrobial and antioxidant properties [15, 41] and the ability of biofortification of animal products [78]. In research [39] the antimicrobial activity of lipid extract of *Gracilariopsis longissima* against aquaculture pathogens was evaluated. The extract contained significant levels of omega-3 fatty acid and showed antibacterial properties and was reccomended as a dietary supplement for fish nourishment. Addition of PUFAs to the animal feed aims in biofortification of animal products with these substances, because they are essential for human [78, 79]. Studies show that feeding animals with omega-3 fatty acid supplement increases the content of these substances in milk, meat [78] and eggs [15, 38].

Carotenoids and phycobiliproteins are the most useful pigments in terms of animal feeding. Carotenoid compounds have been reported to have antimicrobial and antioxidant properties [20, 21, 27, 39]. Moreover, some pigments can accumulate in muscles of salomonids and enhance their color, which makes them more attractive for consumers [15]. Nevertheless, some researches on chlorophylls were done as well. For example, pheophorbide a, chlorophyll-related compound, was found as a major colour constituent in green seaweed pigments having strong antioxidant properties [80].

Polyphenols are reported to have very strong antioxidative properties among many other biological activities [19, 63, 81, 82] like anti-inflamatory or antimutagenic [20]. Studies have shown that polyphenolic compounds extracted from seaweeds are bioavailable for animals from the colon [20]. Polyphenols can be absorbed either directly in the upper digestive tract in unchanged form or in the lower intestine, after modification by present bacteria [83]. Nagayama *et al*. [84] suggested a potential use of phlorotannins extracted from brown algae *Ecklonia kurome* as antibacterial drugs, which could be an alternative for recently banned feed antibiotics. The minor role of polyphenols is to protect plant organism from damages caused by free radicals and other oxidiants [85].

Many of minerals found in seaweed extracts act as macro- and micronutrients (I, Zn, Fe, Cu, Ca, Mg etc.), which importance for health maintenance of animal organism is well documented. Seaweeds contain higher levels of macro- and microelements than any edible terrestrial plants [86]. Therefore, seaweed extracts could be an alternative for currently used mineral supplements.

3.3. Fertilizers

It was shown by different researchers that marine algae are a rich source of many bioactive substances that can positively affect cellular metabolism and beneficially condition the plants [23, 36]. These substances are also present in seaweed extracts. Among them there are many compounds such as polysaccharides (e.g. laminaran and fucoidan), polyphenols [21], phytohormones, carotenoids and minor nutrients [32].

Polymers synthesized by seaweeds play an important role in defending plants against microorganisms [25, 36]. Fucoidan is well known for its antiviral and antibacterial action, while laminaran stimulates genes for producing special proteins that participate in antimicrobial response [31, 36, 59, 87, 88]. Another polysaccharide – alginate, is responsible for activating growth of some symbiotic fungi in rhizosphere [31, 59, 87, 88]. Galactans, carrageenans and agars present in cell wall of red seaweeds [89] are known for anticoagulant and antiviral activity [90] and act as natural chelators, support root elongation and improve moistness of the soil (as hydrocolloids with antioxidant and gelling activity) [36].

Polyphenols, identified in algal extracts, are known for antibacterial activity, which protects plants against diseases [2]. Carotenoids have also been detected in seaweed extracts. They enable plants to protect them from chlorophyll degradation [33]. Sesquiterpenes – plant pheromones, were included among substances found in seaweed extracts [87]. They were shown to reveal antibacterial and antifungal activity [21].

As it was shown, seaweed extracts are also a rich source of macro- and micronutrients (Fe, Mn, Co, Cu) which play many important roles in plants [25]. They are essential for plants life cycle, occurring in metalloproteins active sites. Furthermore, they improve crops quality and increase crop yields [91] because of their influence on soil conditions [92].

Seaweed extracts can act as plant biostimulants improving condition and vitality of plants due to the presence of many bioactive substances important for higher plants [21, 93] and can enhance nutrient uptake from soil [94]. There are many proved advantages of using seaweed extracts as biostimulants of plant growth [32]. They revealed beneficial effect on seed germination and root development [36, 95]. Plant biostimulants are also able to improve crop yields [96]. Currently, seaweed extracts are the components of many commercial products (i.e. Nitrozime, Kelprosoil) applicated as plant growth stimulants [36, 95, 97].

4. CONCLUSIONS AND FUTURE REMARKS

The paper reviewed the latest developments in the research on algal extracts as valuable components of pharmaceuticals, feeds and fertilizers (Fig **1**). The utilitarian properties of biologically active compounds and their beneficial effects on humans, animals and plants were presented.

Nowadays, annually ca. 15 mln Mg of products from seaweeds is manufactured. Only a small part is processed into extracts – 250 000 Mg of seaweed extracts is currently produced. However, a dynamic increase is observed, because algal extract as compared with fresh or dry biomass of algae, is a resource that can be more easily used in the production process.

Presently, algal extracts are found in products commercially available on the market. They are used as the components of cosmetics since are the source of anti-aging, anti-wrinkle, whitening and skin hydrating compounds. This is the function of fucoxanthin, phlorotannins and polysaccharides (alginate, fucoidan). The role of algal extracts in products for animals is the presence of antimicrobial compounds that reduce the growth of pathogenic microorganisms in gastrointestinal tracts and the presence of compounds that stimulate the growth of beneficial microflora (lactic acid bacteria). The latter is the role of polysaccharides. There are also many products for plants. These products are not fertilizers, but plant growth stimulants. Since algal extracts are used in very high dilutions, their role is not to supply plant growth nutrients. The mechanism of their action is to support the growth of plants by supply of biologically active compounds that stimulate the growth of plants: plant growth hormones (increased efficiency of photosynthesis and consequently higher crop yield, protection from biotic (pathogenic organisms) and abiotic stress (salinity, drought, low temperatures), stimulation of growth of beneficial symbiotic microflora in the rhizosphere.

Currently, the main problem of the extracts manufacture is to elaborate an efficient solvent-free method using mild process conditions to prevent the biologically active compounds from degradation. Recently, the first papers appeared

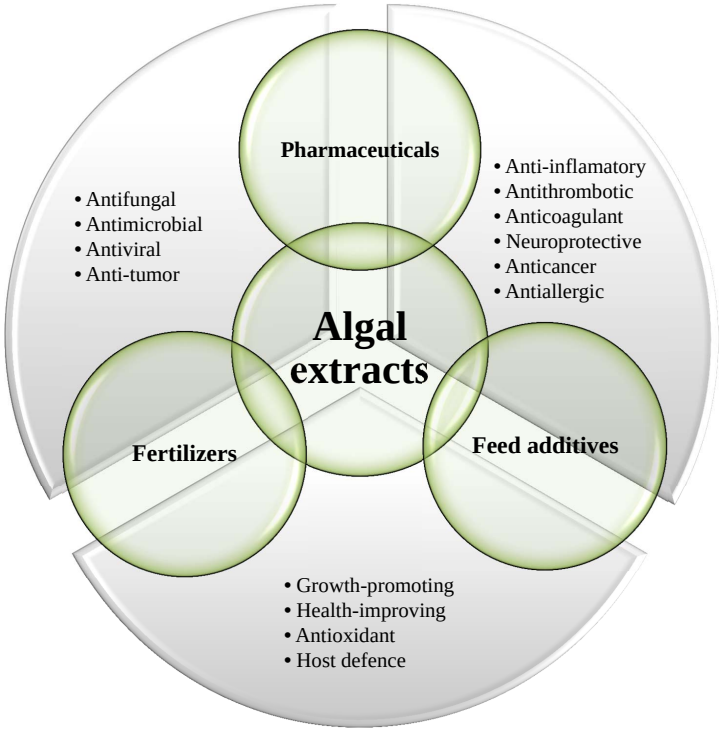

Fig. (1). Activities of algal extracts and their application.

that describe the possibility of production of algal extracts by supercritical extraction with CO_2, with the variants of using co-solvents – water vapor or ethyl alcohol. It would be then possible to manufacture algal extracts, the composition of which would be particularly designed for a given application: for pharmaceuticals, feeds or fertilizers.

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CONFLICT OF INTEREST

The author(s) confirm that this article content has no conflicts of interest.

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