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Abstract

Background: Meat and meat products have been recently perceived by consumers as unhealthy foods. To avoid this drawback, the reformulation is a feasible approach that allows obtaining custom meat-based products that incorporate compounds with certain beneficial properties for health and remove other attributes considered negative. In this framework, the edible seaweeds have been proposed to offer interesting possibilities in the meat sector to develop functional foods as they are an excellent natural source of nutrients and biocompounds with myriad functionalities.

Scope and approach: This review collects aspects related to the recent technologies employed to obtain and isolate biocompounds from seaweeds. The use of whole seaweeds and their bioactive extracts to develop meat foods that confer them health properties while simultaneously reducing components considered unhealthy in meat are reviewed. Furthermore, the prevention of oxidation events was also described.

Key findings and conclusions: Several studies have demonstrated that the incorporation of whole seaweeds and their bioactives to reformulate meat products is an excellent approach to improve certain nutritional aspects considered “bad”. However, there are still some challenges regarding the organoleptic and sensory properties of the resulting products that affect the consumer acceptability. In conclusion, more research is necessary to overcome these gaps allowing put in the market seaweeds -based meat products.

Keywords: Seaweeds, Bioactive compounds, Novel extraction technologies, Functional meat products, Oxidative stability

1. Introduction

In recent years, there is a growing awareness about the diet-health binomio by consumers, so they demand more and more healthy and nutritive foods with functional properties (Granato et al., 2020). However, the lifestyle of industrialised countries has led to an increase in sedentarism and fast food consumption, and therefore, diseases such as cardiovasculars and obesity have become one of the most worrying epidemics of the century XXI. To reverse this current scenario, it is necessary that both the food industry and the countries's governements act jointly.

The meat industry is no stranger to these changes in eating habits and therefore must face the great challenge of offering consumers meat products with functional properties beneficial to health (Nikmaram et al., 2018). In addition, lowering economic losses due to the deterioration of meat products it seemed necessary to identify new alternatives in line with the promotion of health through diet. Although in recent years, meat and processed meat products are not yet longer considered essential in the diet, their incorporation ensures a balanced diet due to their good content in bioavailable nutrients. However, some of their constituents when are consumed in high amounts, may increase the risk of some of the main degenerative and chronic diseases (ischaemic heart disease, cancer, etc.) (Cofrades et al., 2017).

Among the different approaches that can be used to solve this public health problem, the reformulation of meat products throught the substitution, removal, reduction, increase and/or addition of some of their components by other more healthy has gained strength in the last decade (Heck et al., 2017; Roohinejad, 2017; Lorenzo et al., 2016; Cofrades et al., 2017; López-López et al., 2009). These reformulations allow obtaining custom meat-based products with certain beneficial properties for health, *i.e.* functional foods (Cofrades et al., 2017). In this framework, edible seaweeds offer interesting possibilities in the meat sector to develop functional foods (Roohinejad et al., 2017; Moroney, O'Grady, O'Doherty, & Kerry, 2013). These marine macroorganisms are an excellent source of a great variety of biocompounds such as polysaccharides, protein, omega-3 fatty acids, carotenoids, phenolic compounds, vitamins and minerals (Cikoš, Jokić, Šubarić, & Jerković, 2018; Agregán et al., 2017). These phytonutrients are responsible for the several bio-activities and healthy properties attributed to the marine algae, such as antiviral, antibacterial, antioxidant, anti-inflammatory, neuroprotective, antihypertensive, antihyperlipidemic, anticoagulant, prebiotic and anticancer properties (Wang et al., 2017, Ryu et al., 2014; Rodrigues et al., 2015). Accurately, the identification of this large number of active agents has encouraged the interest of researchers and of the food industry to design seaweed-based functional foods that can help maintain the human health, prevent diseases, and reduce the risk of chronic illness (Cofrades et al., 2017; Roohinejad et al., 2017).

In this sense, great efforts have been bestowed by different investigation groups to find the better alternatives to incorporate seaweeds or bioactives from seaweeds into different meat products. For example, Figure 1 displays the number of published articles on bioactive compounds extracted from seaweeds, as well as studies related to their application in meat products since 2005. As it can be observed, the research trend on bioactive compounds recovery from seaweeds has been exponential in the last 15 years while the publications about the application of these compounds in meat foods have remained almost steady. In fact, despite the growing interest in seaweeds or their extracts as a source of biologically active compounds (antioxidants, pigments, peptides, polysaccharides, fatty acids, among others), its application to develop new meat products not only with improved nutritional and technological properties but also with functional properties are still under-exploited. Moreover, in the last decade several projects about the seaweeds have been funded under European agency, highlighting the interest that this marine biomass arouses; these iniciatives propose to explore their potential as promising source of biocompounds with new properties as functional ingredients. Accordingly, the Table 1 summarises the funded projects from 2010 until now in the field of the algae and bioactive compounds.

It is necessary to take into account that to revalorize more efficiently these marine resources and to obtain high quality bioactives with greater yield, the development of new, innovative and efficient extraction processes with remarkable advantages over the conventional technologies is a prerequisite. Until now, the extraction of biologically active molecules from seaweeds has been carried out using conventional techniques which present negative aspects that can affect the bioactive extracts yield and their bioactivities (Kadam, Tiwari, & O'Donnell, 2013; Cikoš et al., 2018). However, over the last years, the application of processes more efficient from an environmental and economic point of view based on the green extraction concept has allowed to develop new non-conventional or intensification technologies to recover valuable compounds from marine biomass (Kadam et al., 2013; Cikoš et al., 2018; Wen, Zhang, Sun, Sivagnanam, & Tiwari, 2019). Some of these novel extraction approaches such as microwave assisted extraction (MAE), ultrasound-assisted extraction (UAE), enzyme-assisted extraction (EAE), pressurized liquid extraction (PLE), and supercritical fluid extraction (SFE) among other have been applied to obtain biologically active compounds from different seaweeds (Dang et al., 2017; Becerra et al., 2015; Otero, Quintana, Reglero, Fornari, & García-Risco, 2018). Moreover, the combination of these new extraction approaches would allow to find the optimal processes in terms of short extraction times, reduced temperature, minimizing solvent use and the obtaining of bioactive extracts with properties being better preserved (Kovačević et al., 2018; Kadam et al., 2013).

Encouraged by the growing interest in the seaweeds due to their significant potential as a functional ingredient sources, this review encompasses aspects related to the state of art of the current extraction methodologies applied to the algae as well as the application of both the whole algae and their bioactives in meat and meat products. The role of the seaweeds and their biocompounds in meat and meat products as functional ingredients conferring them additional health promoting functions, as conservation agents that allow to keep their technological attributes and as reformulation agents to improve their nutritional properties are also evaluated. The main aspects discussed in this review are highlighted in Figure 2.

2. Main components of seaweeds and their bioactivities

2.1. Marine algae polysaccharides

Seaweeds are considered as a good source of polysaccharides, varying in its total content between 4-76% d.w. depending on the species (Kraan, 2012). Carbohydrates are present mostly in the form of sulfated and non-sulfated polysaccharides. The presence of a type of polysaccharide is algae species-specific. For example, brown algae are characterized by presenting alginic acid, laminarin and fucoidan; red algae contain agar, carrageenans, xylans, floridean starch, water-soluble sulphated galactan and porphyran; while green algae are rich in ulvans (Kraan, 2012).

The functional activities of these polysaccharides have been widely described in the literature. For example, isolated fucoidans from three Mediterranean brown seaweeds showed anti-inflammatory and gastroprotective activities (Hadj et al., 2015). Antiinflammatory (Isaka et al., 2015), antihyperlipidemic (Wang et al., 2017), antioxidant (Isaka et al., 2015) and antitumor activities (Liu, Deng, Geng, Wang, & Zhang, 2019) of porphyran have been well explored. Immunostimulatory activity of ulvan has also been confirmed by Berri et al. (2017). A research work conducted by Kadam et al. (2015a) showed that laminarin rich extracts isolated from

Ascophyllum nodosum and *Laminaria hyperborea* exhibited antioxidant and antimicrobial activities.

2.2. Phenolic compounds

Among the bioactive compounds identified in algae, special attention has been paid on phenolic compounds due to their health benefits. These include phenolic acids, tannins, flavonoids, catechins, and phlorotannins. The presence of one type or another of phenolic compound depends on the species of seaweeds. Marine brown algae are characterized by containing mainly phlorotannins, complex polymers made up units of phloroglucinol (1,3,5-trihydroxybenzene), while green and red algae are rich in bromophenols, phenolic acids, and flavonoids (Gómez-Guzmán, Rodríguez-Nogales, Algieri, & Gálvez, 2018). Numerous biological properties have been assigned to algal polyphenols like as antioxidant, anti-inflammatory, antiproliferative, antiviral, antimicrobial, anti-obesity and antidiabetic activities, *inter alia* (Gómez-Guzmán et al., 2018). Ryu et al. (2014) confirmed the anti-inflammatory effect *in vitro* of a polyphenol-rich extract from the red algae. Phlorotannins and bromophenols showed bioactivity to inhibit cancer cells proliferation *in vitro* as well as the growth of tumors *in vivo* (Liu, Hansen, & Lin, 2011). It has also been demonstrated that these compounds possess antidiabetic and antithrombotic properties evaluated *in vitro* (Liu, Kongstad, Wiese, Jager, Staerk, 2016; Liu et al., 2011).

2.3. Pigments

Pigments present in seaweed are divided into three classes: chlorophyll, carotenoid and phycobiliproteins. Chlorophyll is a greenish lipid-soluble pigment which plays a key role in photosynthesis and is commonly found in plants, algae, and cyanobacteria (Aryee, Agyei, & Akanbi, 2018). The main carotenoids present in algae include carotenes, lycopene, fucoxanthin, astaxanthin, zeaxanthin, lutein, neoxanthin and violaxanthin (Aryee et al., 2018). Fucoxanthin is one of the most abundant carotenoids found in edible brown algae and contributes over 10% total production of carotenoids in nature. Phycobiliproteins are a group of water-soluble pigment, distinguishing three classes of molecules with different protein structure: phycocyanins (blue pigment), allophycocyanins (light blue pigment) and phycoerythrins (red pigment), being this latter the most abundant (Aryee et al., 2018). These pigments have important properties as biologically active agents (antioxidant, anti-inflammatory, immune-modulatory, antidiabetic, and antiangiogenic) as well as outstanding sensorial attributes so they are used as nutraceutical ingredients and food colourants (Aryee et al., 2018).

2.4. Fatty acids (FA)

Generally, algae contain a low amount of lipids which does not surpass 5% d.w. (Kendel et al., 2015). In the last years, fatty acid profile of seaweeds has attracted much attention due to their high amounts of polyunsaturated fatty acids (PUFA), such as α-linolenic (ALA, 18:3 n-3), octadecatetraenoic (18:4 n-3), arachidonic (AA, 20:4 n-6), eicosapentaenoic (EPA, 20:5 n-3) and docosahexaenoic (DHA, 22:6 n-3) acids (Kendel et al., 2015). It is well known that this type of acids has important nutritional properties as well as beneficiary effects on human health. For example, PUFA possess anti-tumoural, antiviral and anti-obesity properties, and they are further related with the prevention of cardiovascular diseases (Kendel et al., 2015).

2.5. Proteins, peptides, and amino acids

The protein content in algae ranges from 5% to 47% of d.w. in function of the species, season and environment. Generally, red and green algae have a high protein porcentage compared to brown seaweed (Černá, 2011). Seaweed proteins are a good source of most amino acids, especially glycine, alanine, proline, arginine, glutamic, and aspartic acids (Černá, 2011). From the protein fraction, peptides with a broad spectrum of bioactivities can be obtained. For example, phycobiliproteins of *Palmaria palmata* showed angiotensin-converting enzyme (ACE) inhibitory activity, so they could be used in the prevention of hypertension (Furuta, Miyabe, Yasui, Kinoshita, & Kishimura, 2016).

2.6. Vitamins

Seaweeds are also an important source of vitamins both hydro- and liposoluble, therefore their consumption could improve the vitamin status. Vitamins mainly belonging to the group B (B_1, B_2, B_3, B_6, B_{12}), as well as vitamins A, C, D, E, riboflavin, niacin, pantothanic acid, folic acid and folate derivatives have been identified. For example, the values reported for vitamin C were in a similar range for brown, red and green seaweeds (34.5-1847, 35.3-1610.6, 34.7-1250 mg/100 d.w., repectively) (Cherry, O'Hara, Magee, McSorley, & Allsopp, 2019). However, in the case of vitamin B_{12}, the data are more scattered, variyng between 16.4-43.1 mg/100 d.w. for brown seaweeds, 96.1-1338 mg/100 d.w. for red seaweeds, and 60-787.5 mg/100 d.w. for green seaweeds (Cherry et al., 2019). Another data that can be highlighted are reported for vitamin B_3 founding values in the range 612-900 mg/100 d.w. for brown seaweeds, 95.1-100 mg/100 d.w. for red seaweeds and 4.9-1000 mg/100 d.w. for red seaweeds (Cherry et al., 2019).

2.7. Minerals

The seaweeds also contain a spread variety of minerals in high percentages ranging between 8-40% (Cofrades et al., 2017; Lorenzo et al., 2017). In general, macroalgae present a significant amount of Na, K, Mg, Fe, Zn, Mn and Cu, among others. Seaweeds are also the most important vegetal source of Ca due to its high content in this mineral. The iodine levels found in this biomass differ from species and range in the interval of 4.3 to 2660 mg/kg (Roohinejad et al., 2017). It is worthwhile to note that the presence of this mineral in high proportions has been reported harmulf for health, so new strategies to reduce its content in seaweeds food products are necessary.

3. Extraction techniques of bioactive compounds from marine macroalgae

Considering the variety of phytonutrients that can be recovered from marine biomass, the choice of the most adequate extraction technique is key to maintain the quality of the end compounds as well as for the process to be feasible on an industrial scale. Conventional and intensification extraction techniques have been used for the obtaining of the valuable molecules present in algae (Kadam et al., 2013). Some works about extraction methods of different bioactive compounds from seaweeds, as well as the bioactivities associated with them, are summarised in Table 2.

Conventional extraction processes are widely used due to low investment cost and simplicity of operation. Nevertheless, these methods present several drawbacks including the use of huge quantities of organic solvents and high extraction temperatures for long periods of time which causes the degradation of thermolabile compounds, as well as low extraction yield of target compounds (Kadam et al., 2013). To solve these inconveniences and respond to the increase demand of natural products from algae, a variety of novel techniques, known as “green", have been developed. Among these innovative technologies, microwave-assisted extraction (MAE), ultrasound-assisted extraction (UAE), enzyme assisted extraction (EAE), pressurized liquid extraction (PLE), and supercritical fluid extraction (SFE) have been identified to use eco-friendlier processing conditions and to improve the extraction efficiency and to preserve the quality of the final compounds (Kadam et al., 2013; Cikoš et al., 2018; Putnik et al., 2018; Putnik et al., 2017).

3.1. Ultrasound-assisted extraction (UAE)

Ultrasound-assisted extraction (UAE) has been proposed as a promising green technology for the isolation of several biologically active molecules from seaweeds. Compared to conventional extraction, UAE presents several benefits such as symplicity, lower solvent consumption, reduces the extraction time, and operates at mild temperatures which prevent the degradation of thermolabile compounds. Moreover, equipment costs are lower than the other modern extraction technologies and UAE is suitable for an industrial scale (Kadam et al., 2013). In UAE, there are several operating variables that influence in the extraction yield, such as power, time, temperature, frequency and solvent to solid ratio. In this context, Dang et al. (2017) studied the UAE operational conditions to increase the recovery of phenolics with high antioxidant capacity from brown alga *Hormosira banksii*. According to the authors, temperature was the factor most influencing both the extraction of total phenolics and the antioxidant activity, followed by ultrasonic time and in the last place by the power.

UAE was also applied for the recovery of biologically active polysaccharides from seaweed. For example, Kadam et al. (2015a) successfully applied UAE to obtain laminarin from two brown algae. The authors found that UAE improved the extraction yield of this polysaccharide in comparison to the conventional liquid-solid extraction. In addition, the results showed that laminaria-rich extracts obtained using ultrasound exhibited better biological activities in terms of antioxidant and antimicrobial activities.

In order to improve the extraction performance of polysaccharides from marine algae, some studies have proposed the simultaneous combination of sonication and enzymatic treatment (Fidelis et al. 2014; Le Guillard et al., 2016). For example, Fidelis et al. (2014) studied different strategies to isolate bioactive polysaccharides from *Gracilaria birdiae*. The findings of this work revealed that the combination of ultrasounds and proteolytic enzymes was the best strategy to extract sulfated polysaccharides with anticoagulant and antioxidant properties. In another study, Le Guillard et al. (2016) applied simultaneously enzymes and ultrasound to recover carbohydrates from *Grateloupia turuturu* Yamadam. The authors found that the combination of ultrasounds and enzymes allow increasing the extraction yield of water-soluble compounds by 50% in comparison to the treatment using only ultrasound.

Recently, UAE has been also reported as an attractive method for the obtaining of pigments from seaweeds. Dang, Bowyer, Van Altena, and Scarlett (2018) reported the use of ultrasounds to extract fucoxanthin from six brown algae. According to their results, UAE using 70% ethanol allowed to recover up to 0.197 g/100 dry sample of fucoxanthin from *Padina sp* with a high antioxidant activity. In another study, Fabrowska, Messyasz, Szyling, Walkowiak, and Łęska (2018) compared the extraction efficiency of UAE and classic Soxhlet extraction to isolate chlorophylls and carotenoids from *Ulva flexuosa*. The authors found that UAE led to a higher content of chlorophylls (37.7 μg/mL) and carotenoids (2.2 μg/mL) compared to that obtained using the conventional method (10.9 μg/mL and 1.39 μg/mL, respectively).

UAE has been also investigated for the extraction of protein from marine algae. For example, Fitzgerald et al. (2013) reported the protein isolation from *Palmaria palmata* applying ultrasounds at low temperature. The crude protein obtained was hydrolyzed using papain to obtain bioactive peptides with properties that allow preventing atherosclerosis and high blood pressure. Wang et al. (2015) optimized the conditions of ultrasound-assisted extraction for the recovery of taurine from *Porphyra yezoensis*. The authors found that operating under optimal conditions, ultrasonic process enabled reducing the extraction time by 9 times compared to conventional methods.

3.2. Microwave-Assisted Extraction (MAE)

Another promising approach to recover phytonutrients from marine algae is the Microwave-Assisted Extraction (MAE). This technique is based on the application of electromagnetic radiation which transfers heat to the system by two processes occuring simultaneously: ionic conduction and dipole rotation. MAE has various advantages compared to the conventional processes since it requires less solvent, energy and time, it allows a better heating distribution control, leading to better extraction efficiency (Kadam et al., 2013).

MAE has been extensively used for the isolation of polysaccharides and polyphenols from macroalgae (Table 2). As in UAE, the efficiency of MAE process depends on several factors (solvent, microwave power, temperature and time, and the solvent-to-solid ratio) that need to be optimized to achieve high extraction yields. For example, Ren et al. (2017) applied Response Surface Methodology (RSM) to study the influence of some extraction parameters (extraction time, microwave power, temperature and solid-to-solvent ratio) on the efficient recovery of polysaccharides from *Sargassum thunbergii*. Under optimized extraction conditions (microwave power 547 W for 23 min at 80 ºC, and sample to solvent ratio of 1:27 g/mL), a yield of polysaccharides of 2.84% was obtained. The authors reported that the polysaccharides recovered showed good antioxidant and α-glucosidase inhibitory activities. More recently, Yuan et al. (2018a) also assessed the microwave-assisted hydrothermal technology to extract polysaccharides from *Ulva prolifera*. The results showed that the functional properties and bioactivities of polysaccharides were greatly influenced by the extraction conditions. Thus, polysaccharides extracted at 90 ºC or 150 ºC using 0.05 M HCl presented the best functional characteristics in terms of water-holding and oil-holding capacity, as well as foaming properties. Polysaccharides that exhibited the highest antioxidant capacity and pancreatic lipase inhibition activity were obtained at 150 °C and 0.1 M HCl.

Regarding the extraction of polyphenols by MAE, the optimization of the extraction conditions particularly, the microwave power, is key to avoid the degradation of these compounds. Li et al. (2012) using microwave radiation as extraction technology studied the influence of different operation variables on the recovery of phenolic compounds from *Caulerpa racemosa* by an orthogonal array design. According to the authors, microwave power had a strong influence on the recovery of phenolic compounds, observing a higher thermal degradation of these compounds at the highest tested power.

In another study, Yuan et al. (2018b) explored the use of MAE for the extraction of phenolics from four brown seaweeds. The results indicated that the use of microwaves was a suitable technology in terms of yield and extraction time compared to conventional processes.

Thus, the recovery of phenolics from *Lessonia trabeculate*, using MAE yielded 74.13 GAE mg/100 g dry seaweed (d.s.) in an extraction time of 15 min, while with conventional extraction and a longer time interval (4 h) only 49.80 GAE mg/100 g d.s. was reached. In addition, MAE extracts exhibited better antioxidant properties and inhibitory activities on α-amylase, α-glucosidase, pancreatic lipase and tyrosinase than conventional extracts.

In recent years, several groups have also successfully applied MAE for the recovery of pigments from marine algae. A study conducted by Xiao, Si, Yuan, Xu, & Li (2012) optimized the microwave extraction conditions for the isolation of fucoxanthin from *Undaria pinnatifida* using RSM methodology. Microwave treatment at 60 ºC with solid-to-solvent ratio of 1:15 (g/mL) for 10 min and using microwave power of 300 W resulted in an optimal fucoxanthin yield of 109.3 mg/100 g dry sample. In another work, Fabrowska et al. (2018) assessed the extraction of chlorophylls and carotenoids from *Ulva flexuosa* using MAE. At 40 ºC, a microwave power of 800 W and 60 min of extraction time, the amount of chlorophylls and carotenoids recovered was 37.7 and 2.2 µg/mL, respectively. Patra, Lee, Kwon, Park, and Baek (2017) have also investigated the use of microwave-assisted hydrodistillation to recover the essential oils from different edible seaweeds finding extracts with strong antioxidant and antibacterial activities.

3.3. Enzyme-Assisted Extraction (EAE)

Another promising and ecofriendly strategy that has aroused special interest in recent years for the isolation of phytochemicals is the Enzyme-Assisted Extraction (EAE). The hydrolytic action of specific enzymes disrupts the integrity of the cell structure favoring the release of the desired bioactive (Kadam et al., 2013; Wen et al., 2019). Several enzyme preparations like Viscozyme, Celluclast, Flavourzyme, Termamyl, Ultraflo, Alcalase, agarase, xylanase, amyloglucosidase, Neutrase, Kojizyme, Protamex, and Alcalase have been commonly used for the extraction of polysaccharides, proteins or phenolics from seaweeds (Rodrigues et al., 2015). Yaich et al. (2017) performed an enzymatic treatment with cellulases and proteases to obtain sulphated polysaccharides with antioxidant properties from *Ulva lactuca*. In addition, the authors also compared EAE with conventional acid-assisted extraction and found that the amount of extracted ulvan was higher when enzymes were used (17.14% *vs.* 13.06%).

Charoensiddhi, Franco, Su, and Zhang (2014) compared conventional acidic extraction, enzymatic and microwave-assisted enzymatic extraction (MAEE) to recover phlorotannins and antioxidant compounds from *Ecklonia radiata*. The results showed that the employment of MAEE for a short extraction time (5 to 30 min) provided a high-performance recovery of target compounds in comparison to the enzymatic and conventional extraction at 24 h. This greater efficiency of MAEE can be attributed to the synergistic effect of the combination of microwave radiation and the hydrolytic action of enzymes that lead to a greater alteration of the cell wall structure than when both techniques are applied separately (Wen et al., 2019). Enzymatic extraction has also been suggested as an appropriate technology for algae protein recovery. The use of enzymes facilitates the degradation of cell wall polysaccharides, improving the solubilization of the protein fraction (Rodrigues et al., 2015).

3.4. Supercritical Fluid Extraction (SFE)

Supercritical Fluid Extraction (SFE) is widely recognized as an efficient green extraction method that has been used to selectively isolate heat-sensitive biocompounds like pigments and fatty acids from algae (Table 2). Different parameters involved in the SFE process such as pressure, temperature, co-solvents or solvent flow rate have been optimized in order to improve extraction performance and the selectivity of the recovered compounds. For instance, Ospina et al. (2017) evaluated the effects of pressure (10-30 MPa), temperature (40-60 ºC), and co-solvent concentration (2-8%) on the extraction efficiency, the recovery of phenols and carotenes as well as on the antioxidant capacity from *Gracilaria mammillaris* using a central composite design. The authors stated that the percentage of co-solvent was the parameter most significant on both extraction yield and phenolic content while the pressure was the parameter that more affected the antioxidant capacity. Similar results were previously reported by Quitain et al. (2013), who also observed an increase on fucoxanthin recovery increasing pressure of SFE process. This trend can be attributed to the fact that by increasing the pressure also increased density and solvating power of SC-CO_2 (Quitain et al., 2013). In another study, Becerra et al. (2015) have successfully employed SFE to recover fucosterol with antileishmanial activity from *Lessonia* *vadosa*. The best results in terms of yield, solvent consumption, time and purity were achieved using CO_2 at 180 bar and 50 ºC with 20 to 30% of cellulose as modifier followed by a purification based on centrifugal partition chromatography.

3.5. Pressurized Liquid Extraction (PLE)

Pressurized Liquid Extraction (PLE), also called accelerated solvent extraction, has been recognized as a promising technology for the extraction of a wide range of biologically active compounds from different natural sources. The PLE applies high temperatures (up to 200 ºC) and pressures (up to 200 bar) using low solvent volumes, which favours rapid extraction of the desired compounds (Kadam et al., 2013). Some examples of the application of this technique for the recovery of valuable compounds from marine biomass are presented in Table 2. For example, Plaza et al. (2010) reported that PLE was a suitable technique to produce extracts with antioxidant and antimicrobial activities from *Himanthalia elongata*.

Recently, Otero et al. (2018) evaluated the influence of various solvents (hexane, ethyl acetate, acetone, ethanol and ethanol: water 50:50) and temperatures (80 ºC, 120 ºC and 160 ºC) on lipid recovery from *Fucus vesiculosus* by PLE. The results showed that the highest yields of fatty acids were obtained using ethyl acetate, followed by acetone and ethanol. In addition, the fatty acid profile was also dependent on the solvent used. For example, ethyl acetate favoured the extraction of long-chain fatty acids (oleic acid, arachidonic acid and eicosapentaenoic acid), while the most polar solvents (ethanol and ethanol: water 50:50) allowed the obtaining of extracts with a better ratio ω-6/ω-3. On the contrary, the authors observed that the temperature didnot affect to lipidic profile. In another study, the extraction of bioactive compounds from *Padina pavonica* was assessed by PLE using ethyl acetate, ethanol, petroleum ether, and water as the extraction solvents at fixed conditions of pressure (150 bar), temperature (60 ºC) and time (10 min). Overall, the results suggested that water was the most appropiate solvent for the recovery of extracts with anti-hyaluronidase activity (Fayad et al., 2017).

4. Oxidative processes in meat and meat products

Oxidative processes involve the degradation of lipids, proteins and pigments due to the generation of free radicals (Dominguez et al., 2019). Lipid oxidation is a complex process of chain reactions called auto-oxidation that occurrs in three successive stages: initiation, propagation, and termination. In the termination stage, hydroperoxides radicals react with each other to form stable or non-reactive final compounds such as aldehydes, ketones, alkanes and other hydrocarbons (Dominguez et al., 2019). All these compounds are known to affect the sensory characteristics of meat, being responsible for off-flavor and rancid odor (Kumar, Yadav, Ahmad, & Narsaiah, 2015).

Protein oxidation is attributed to a covalent modification of protein caused either directly by reactive species (ROS and RNS) or indirectly by reaction with secondary products of oxidative stress. The progress of protein oxidation can compromise physical and chemical characteristics of proteins like as solubility, hydrophobicity, water-holding capacity, meat tenderness, and gelation functions. Moreover, protein oxidation-induced alterations may decline the bioavailability of amino acid residues and alter the digestibility of proteins, resulting in a worst nutritional profile of meat proteins (Lorenzo et al., 2018). Therefore, the consequences of the alterations from protein oxidation can affect both the technological and sensory properties of meat, which might have effects on human health and safety when the products are consumed.

Special attention deserves the color of meat and meat products since it is one of the main sensorial attribute that contributes to the perception of their quality and is directly related to consumer's purchase decision (Gómez & Lorenzo, 2012). The fresh meat owes its characteristic color to the heme protein myoglobin. The oxidative state of iron ion present in this molecule influences the form in which can be found, i.e., deoxymyoglobin, oxymyoglobin and metmyoglobin, and therefore, the different coloration to the meat (Lorenzo et al., 2018).

Despite the avances in the food science and technology, the effects of lipid and protein oxidation on meat and meat products are not completely clear. This problematic has boosted an intense research to find solutions that allow decreasing or preventing these alterations in those products throught the use of natural additives that on the one hand can reduce the incidence of such reactions and on the other hand conferring functional properties to the meat products (Dominguez et al., 2018; Pateiro et al., 2018). This approach will contribute to decrease the economic losses in the meat sector. In this sense, the incorporation of seaweeds or their extracts into meat and meat products can be a suitable alternative to avoid the described problematic.

5. Use of bioactive compounds to preserve the quality of meat products

Over the last decades, the meat industry has used antioxidant compounds as strategy to reduce both oxidation processes and inhibit the growth of microorganisms. The incorporation of these compounds in the formulation of meat products increases the shelf life and preserves the quality during their processing and storage (Fernandes et al., 2018; Fernandes et al., 2016; Kumar et al., 2015). These phytochemicals must meet the following specifications: be effective at low percentages (0.001-0.01%), do not affect negatively the organoleptic properties of food products, maintain their function during processing and shelf life, and to do not be toxic to the consumer (Lorenzo et al., 2018). Although there are hundreds of compounds, which are attributed antioxidant properties, only a few are approved for use in food products. The synthetic antioxidants most widely applied to prolong the storage stability of meat and meat products are butylated hydroxy anisole (BHA), butylated hydroxyl toluene (BHT), propyl gallate (PG) and tertiary butyl hydroxy quinine (TBHQ) (Kumar et al., 2015; Lorenzo et al., 2018).

On the other hand, the employment of these synthetic compounds has fallen under scrutiny due their toxicity and carcinogenicity in the last decades. In response to the growing concern of consumers about the safety of these synthetic additives, it has led both the meat industry and academic researchers to search novel and naturally occurring compounds that have no harmful effects on human health and can be used safely. In this context, bioactive compounds extracted from natural sources with antioxidant properties, besides preserving the sensory and microbial quality of meat products have functional activities beneficial to human health (Lorenzo et al., 2018; Cofrades et al., 2017; Roohinejad et al., 2017).

6. Role of the seaweeds and their extracts in the prevention of spoilage of meat products and of their quality

Seaweeds are an excellent source of valuable active compounds with antioxidant and antimicrobial activities. As mentioned previously, the main phytochemicals responsible for these beneficial properties include phenolics, carotenoids pigments, phlorotannins and sulphated polysaccharides to name a few. The potential of using seaweeds and their extracts in meat products to delay both oxidation reactions and microbial growth has been widely studied (Roohinejad et al., 2017). Besides of its important role as natural preservatives, the inclusion of algae or its isolated compounds in meat products can be an interesting strategy for consumers in order to increase the content of bioactive agents with health benefits in their daily diet.

Table 3 includes some studies about the incorporation of seaweeds or seaweed extracts in meat products and their role in the oxidative deterioration, foregrounding the macroalgae species from which the extracts have been obtained, the concentration used of the extract or seaweed, the meat product in which the extract or seaweed has been incorporated and the more noticeable results. Recently, Agregán et al. (2018) investigated the effects of the incorporation of seaweed extracts (e.g. *Ascophyllum Nodosum*, *Fucus Vesiculosus* and *Bifurcaria Bifurcata*) on the oxidative stability of low-fat pork liver patties. In this study, seaweed extracts were incorporated at 500 mg/kg to the patties and compared with those elaborated using a synthetic antioxidant (BHT at 50 mg/Kg) and a control sample during 180 days of storage at 4ºC. The authors observed that samples formulated with seaweed extracts showed greater lipid and protein stability, measured in terms of conjugated dienes, TBARS index and carbonyl compounds, as well as an adequate maintenance of the redness (a*) and yellowness (b*) compared to the control experiment. The findings also displayed that the incorporation of seaweed extracts provided a similar protection to those of BHT added to the samples. In addition, the formulated patties with antioxidants did not modify microbial characteristics.

These same authors also investigated the effectiveness of *Fucus vesiculosus* extracts (FVE) at three different amounts (200, 500 and 1000 mg/kg) on the shelf-life of pork patties during the storage in modified atmosphere at 2 ºC for 18 days (Agregán et al., 2019). The evolution of patties elaborated with seaweed extracts was compared with patties without antioxidants and with those formulated with BHT at 200 mg/kg. They observed that the addition of FVE at different concentrations did not alter the lightness value (L*); however, they had a stabilizing effect of the red color (a*), although this protective effect was more pronounced using BHT. After 18 days of storage, the TBARS and carbonyl levels of patties containing 1000 mg seaweed extract/kg were lower than those obtained for the control sample. These results can be explained by the high content of phenolic compounds, mainly phlorotannin present in *Fucus* *vesiculosus*. Indeed, these active agents present a strong antioxidant capacity which contributes to delay the formation of degradation products by lipid and protein oxidation. On the other hand, the authors also revealed that the addition of FVE did not negatively affect the sensory attributes of the patties.

Another study by Cox & Abu-Ghannam (2013) assessed the effects of the addition of *Himanthalia elongata* seaweed (Sea Spaghetti) at different concentrations (10-40%) on the lipid oxidation, microbial growth and sensory properties of cooked beef patties during a period of refrigeration of 30 days. All seaweed-fortified patties exhibited significantly lower TBARS levels (38-45%) in comparison to the control formulation. The authors justified this increased lipid stability due to the phenolic compounds with high DDPH activity presents in the Sea Spaghetti seaweed as well as by the reduction in meat content in these samples, resulting in a lower fat content, thus reducing potential oxidation. The results also confirmed that the seaweed extract exerted a strong protective effect against microbial deterioration, since at the end of the storage period no microbial growth was detected. Regarding sensory quality, the authors reported that patties formulated with seaweeds had good acceptance in terms of aroma, appearance, texture and taste.

In an effort to delay the lipid oxidation of chicken sausages, Pindi, Mah, Munsu, and Ab Wahab (2017) studied the effect of the incorporation of red seaweed (*Kappaphycus alvarezii*) as an antioxidant ingredient in its formulation. Sausages containing 2%, 4% and 6% seaweed powder were prepared using mechanically deboned chicken meat (MDCM). During the storage period (12 days at 4 ºC), the presence of seaweed powder reduced the lightness (L*) and increased the redness (a*) values with respect to the control sample. The addition of algae allowed obtaining MDCM sausages with better physicochemical properties. Furthermore, sausages formulated with seaweed also showed a significant reduction in the TBARS index, evidencing that seaweed acts as an antioxidant agent that reduces the rate of lipid oxidation.

Despite the important bioactivities associated with seaweed polysaccharides, there are few studies about the anti-oxidative potential of these compounds in meat products. To the best of our knowledge, only two works have been performed by the group of Moroney and co-workers who investigated the impact of the addition of polysaccharides from seaweeds on oxidative deterioration of meat products. In 2013, they studied the effect of the fortification with algae extract with laminarin and fucoidan at different amounts (0.01%, 0.1% and 0.5%) on the shelf-life and quality of fresh and cooked minced pork patties (Moroney et al., 2013). Polysaccharide addition decreased the surface redness (a* values) of fresh patties in a dose-dependent manner. Curiously, in these fresh products the presence of polysaccharides at a dose of 0.5% favored the lipid oxidation. On the contrary, at the end of the storage period (14 days), cooked pork patties fortified with the seaweed polysaccharides at the same dose showed an important reduction of lipid oxidation, in comparison to control batch. This can be explained by the fact that during heating, Maillard reaction products can be formed, particularly brown melanoidins, that have a strong antioxidant activity.

In a later study, these authors evaluated the anti-oxidative potential of fucoidan, laminarin and a mixture of both on fresh and cooked pork homogenates (Moroney, O'Grady, Lordan, Stanton, & Kerry, 2015). They observed that fucoidan significantly reduced lipid oxidation reactions; however, laminarin did not improve oxidative stability in fresh pork. This outcome may be related to the higher free radical scavenging activity of fucoidan, attributed to the presence of anionic sulphate groups in its composition.

As mentioned above, the pigments present in seaweeds exhibit also important bioactive properties with potential to prevent determined diseases. This has encouraged the food industry to formulate new food enriched with these bioactive compounds. Moreover, these pigments present high antioxidant activity so that they can contribute to overcome the problems linked to the oxidative spoilage in food products rich in fat. In this regard, some reports are available about the incorporation of several pigments from seaweeds in meat products. For example, Sasaki et al. (2008) evaluated the effect of adding fucoxhantin as a source of antioxidants to control lipid oxidation and loss of color in ground chicken breast meat during storage at 4 ºC for 6 days, before and after cooking. The authors found that the incorporation of fucoxanthin at a concentration of 200 mg/Kg had no effect on lipid peroxidation during the storage of the samples before cooking. Contrary, in the cooked samples, the presence of fucoxanthin decreased TBARS index during chilled storage with a reduction of 58.5% on day 6. Concerning color parameters, fucoxanthin decreased L* and increased a* and b* values in both cooked and fresh samples during chilled storage.

More recently, Carballo, Caro, Andrés, Giráldez and Mateo (2018) evaluated the potential of astaxanthin at different amounts (20, 40, 60 and 80 mg/kg) on oxidative stability of raw and cooked lamb patties in different storage conditions. The TBARS values and amount of volatile compounds released along the storage were used as indicators of lipid oxidation. In comparison to the control formulation, patties with astaxanthin reduced TBARS levels in a dose-dependent manner. The TBARS values for both raw and cooked patties were similar, suggesting that astaxanthin has high thermal stability. Moreover, the cooked patties formulated with astaxanthin extract presented lower total sum of volatiles than those from the control batch (21.56 *vs.* 30.1 ng equivalent of hexanal per mL of headspace). The results allowed concluding that the addition of 80 mg/Kg of astaxanthin had greater efficacy in preventing lipid oxidation than the addition of sodium metabisulphite (450 mg/Kg) and sodium ascorbate (500 mg/Kg).

Sellimi et al. (2017) investigated the addition of various concentrations (0.01-0.04%) of a lyophilized aqueous extract from *Cystoseira barbata* seaweed for the quality improvement of reduced nitrites meat sausage. After 5 days of refrigerated storage, in samples formulated with extracts and with 80 ppm of sodium nitrites, all doses tested reduced approximately 36% of the TBARS values compared to the positive control (150 ppm of sodium nitrites and 0.045%

vitamin C). The authors attributed this protection against lipid oxidation during refrigerated storage to the presence in the aqueous extract of phenolic compounds, fatty acids and sterols. In addition, the incorporation of any amount of *Cystoseira barbata* aqueous extract on turkey meat sausages allowed maintaining the red color during the refrigerated storage period.

Another strategy to prevent lipid peroxidation events in meat products is based on the addition of seaweed oils. Besides improving stability and/or shelf-life extension, seaweed oils are excellent sources of omega-3 fatty acids, mainly DHA and EPA, to which important bioactive properties are attributed. Therefore, the fortification with these compounds may be a possible alternative to develop functional meat products improving their nutritional value. In this field, Alejandre, Passarini, Astiasarán, and Ansorena (2017) evaluated the impact of the incorporation of seaweed oil on the lipid oxidation and the sensory attributes of beef patties. According to their results, the addition of 1% of algae oil contributed to the reduction of approximately 80% and 84% of TBARS values for raw and cooked patties respectively, in comparison to the control formulation. In fact, the presence of algae oil led to values of this index (0.14 mg/kg) below the acceptable sensory limit for rancid flavor (1 mg/kg). Interestingly, the analysis of the lipid composition revealed a notable reduction of omega-6/omega-3 ratio in the modified products in relation to the control patties (7.3 *vs.* 16). In addition, the authors reported that the sensory evaluation of these products was positive suggesting a good acceptance by consumers of these functional meat products.

7. Seaweeds and compounds from seaweeds as replacers of fat in meat products

In the last decade, an alarming increase of the consumption of certain meat products with high content in fat such as patties, sausages, frankfurters, or patties has been observed in certain population groups like children, youth people and people with low purchasing power increasing the incidence of the diseases associated with these processed foods in these population groups. In order to prevent these diseases, the World Health Organization recommends that the daily intake of fat not exceed 30% of the total of calories of diet restricting saturated fats below 10% of that total. These recommendations, together with the growing interest of consumers for healthier products, have encouraged the meat industry to develop novel low-fat meat products that are more in compliance with nutritional guidelines.

The saturated fat has a key role in the organoleptic and technological properties of meat products, contributing to the texture, flavor, juiciness, springiness, chewiness, as well as to improve the water-holding capacity, stabilizing emulsions and cooking yield of these products (Barbut, Wood, & Marangoni, 2016). For these reasons, fat reduction in meat products is not easy as it results in undesirable modifications of sensory and technological properties of those products with the consequent risk of rejection by consumers (Atashkar, Hojjatoleslamy, & Sedaghat Boroujeni, 2018). To overcome these drawbacks, the meat industry has faced a new challenge producing low-saturated fat meat products with quality characteristics similar to traditional products. One of the strategies used for the formulation of these products involves the substitution of fat by non-meat ingredients (Brewer et al., 2012). In this regard, several fat replacers have been evaluated for the deveploment of low-fat meat products including proteins (whey, collagen, legume proteins), carbohydrates-based hydrocolloids (alginate, carrageenans, xanthan gum, locust bean gum, starches and pectins) and vegetable (canola, olive, linseed, sunflower) or marine (algae and fish) oils (Barbut et al., 2016; Brewer, 2012).

In function of the type of fat replacer used different attributes of the meat products can be modified and therefore the final product will be different. For example, protein-based fat replacers have been applied successfully in meat product industry since they have important technological properties including thickener and gelling as well as water-binding capacity (Brewer, 2012). The use of vegetable or marine oils as fat substitutes in meat products is especially interesting as it improves the lipid profile of these products, in terms of decreasing the content of saturated fatty acids and increasing the level of polyunsaturated fatty acids resulting in healthier meat products (Alejandre et al., 2017; Barbut et al., 2016). Moreover, the addition of these oils may also be effective to prevent lipid oxidation and increase final product stability (Alejandre et al., 2017). Carbohydrates-based hydrocolloids are routinely used in the elaboration of low fat processed meat products due to their unique characteristics to improve the texture, chewiness, springiness, mouthfeel, and taste (Ganesan, Shanmugam, & Bhat, 2019). Some of these hydrocolloids like alginate and carrageenans are extracted from edible seaweeds and they have been added successfully as fat replacement ingredients to various meat products, hence improving the overall quality (Brewer, 2012).

Table 5 collects some studies about the effects of the incorporation of seaweeds or their isolated compounds in the development of low-fat meat products. The effects of the adding of *L. japonica* powder in the elaboration of reduced-fat pork patties were investigated by Choi et al. (2012). The authors reported that the patties formulated with different seaweed powder content (1%, 3% and 5%) and a 10% fat content exhibited lower cooking loss, lower reduction in diameter and lower thickness. Moreover, the reformulation (using 1% and 3% L. japonica powder) improved textural properties (springiness, hardness, gumminess, and chewiness); however, the color was negatively affected due to the brown dark coloration of seaweed extract.

Fernández-Martín, López-López, Cofrades and Colmenero (2009) assessed the effect of the fortification with *Himanthalia elongata* in low-fat pork meat batter in several technological aspects observing that it was effective for increasing water and fat retention capacity, as well as the improvement of hardness and elastic modulus. According to López-López, Cofrades and Jiménez-Colmenero (2009), the addition of 5% *H. elongata* to low-fat frankfurters fortified with n-3 PUFA improved the water-and fat holding capacities, increased the hardness and chewiness and reduced lightness (L*) and redness (a*) values. However, the sensory evaluation indicated that the reformulated frankfurters with seaweeds presented less acceptability by the consumers compared to the control.

In addition to the use of the whole seaweeds, other studies have evaluated the incorporation of specific compounds extracted from them to replace the fat in meat and meat products. For example, Atashkar et al. (2018) studied the effect of the addition of κ-carrageenan at four different levels (0.0, 0.5, 1.0, and 1.5%) on texture characteristics of sausages formulated with 70% fat reduction and stored at 4 ºC during 30 days. The findings demonstrated that the partial fat substitution with κ-carrageenan, in a concentration-dependent manner, resulted in a reduction of hardness and chewiness and a partial increase of springiness and gumminess.

Alejandre et al. (2017) evaluated the effectiveness of the incorporation of a gel formulated with algae oil (1%) and carrageenan (3%) as a total fat substitute in beef patties. Reformulated patties showed 2.62% fat, which resulted in a 70% reduction as compared to the control (9%). With respect to the lipid profile, modified patties presented a 69% decrease of saturated fat as well as of the omega-6/omega-3 ratio. The algae oil addition also contributed to the enhancement of the lipid profile in terms of docosahexaenoic and eicosapentaenoic fatty acids content, resulting in an increase of 55% in modified patties as compared to the control.

A similar study was carried out by Kumar, Sharma and Kumar (2007) who evaluated the incorporation of different concentrations of sodium alginate (0.1, 0.2 and 0.3%) as fat replacer in low-fat ground pork patties. In comparison to the control formulation (20% fat), reformulated patties showed an increase of cooking yield, moisture and fat retention dependent of the alginate concentration used. In addition, the authors also reported a decrease of 49.78 and 43.22% in the total lipid and cholesterol content. Overall, low-fat patties (<10%) formulated with sodium alginate maintained sensory, microbiological and textural characteristics similar to control with 20% fat during storage at 4 ºC for 21 days in aerobic conditions and for 35 days in anaerobic conditions. Poyato, Astiasar, Barriuso, Ansorena, (2015) also developed an emulsion based on carrageenan as fat replacer in burger patties. The authors found that the total pork back fat substitution by the gelled emulsion led a reduction of 41, 47 and 62% of the content of total fat, cholesterol and saturated fat, respectively, also observing an increment of 74.5% of the unsaturated fatty acids.

In an attempt to improve the nutritional quality of chicken nuggets, a study by Sharma, Mendiratta and Sharma (2011) incorporated carrageenan as fat replacer in the formulation of low-fat chicken nuggets. Four formulations were tested including 5% fat and three different doses of carrageenan (0.3%, 0.6% and 0.9%) and as control chicken nugget with 15% added fat. The presence of carrageenan improved significantly cooking yield, fat and water retention in the low-fat products as compared to control batch. In this study, the 0.6% carrageenan incorporation resulted in a reduction of total lipid and cholesterol levels of 43.14 and 45.22%, respectively. The sensorial acceptance of formulated chicken nuggets with 0.6% carrageenan was comparable to high-fat control. Based on the results obtained, the authors concluded that it was feasible to obtain low-fat chicken nuggets with sensory attributes and technological characteristics similar to conventional products. Nayak & Pathak (2016) also demonstrated that the carrageenan can be used successfully as a fat replacer in processed meat products. In this study, the authors assessed the quality of low-fat chevon patties reformulated with carrageenan (0.3%, 0.6% and 0.9%). The modified patties presented a higher retention of water, fat, emulsion stability and cooking yield. In addition, the general acceptability scores were higher for those hamburgers to which 0.6% carrageenan was added compared to the high-fat control lot.

8. Final remarks

Seaweeds have attracted great interest in the last decades because of their significant potential as excellent biocompounds source with noticeable nutritional, technological and functional values. The adequate selection of the extraction technologies is overriding in the recovery of bioactives from seaweeds. The studies mentioned in the present review evidenced the importance of use of seaweeds and/or seaweed extracts into meat products as a suitable reformulation strategy enhancing their shelf-life, nutritional, textural, organoleptic, sensorial and health-promoting properties. Usually, this reformulation seeks the substitution of some components present in meat products perceived as harmful by consumers by other with healthy attributes. Although it has been demonstrated the effectiveness of the use of these macroalgae and their biocompounds to modify fat profile and to prevent oxidative deterioration of meat products, there are still some challenges regarding the organoleptic and sensorial properties of the resulting products that affect consumer acceptability. For this reason, optimizing the formulation of meat products based on seaweeds and their bioactive extracts is necessary since the effects depend on the seaweed species and the amount used. In this regard, systemathized information about the amounts of seaweeds and bioactive extracts from algae used to reformulate meat products can not be provided because these quantities depend on the seeked technological, nutritional, functional effects or the sensory attributes as well as on the type of algae, the way in which the algae is incorporated (whole or extract) and the final product wanted. The research in this field must advance towards the elucidation of the interaction between the meat products and the seaweeds and their bioactives as well as their biodisponibility once these products are ingested.

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Figure captions

Figure 1. Research tendencies in "bioactive compounds from seaweeds” and "meat products with seaweeds" from 2005 until the current date. Source Scopus (search made on September 17, 2019)

Figure 2. Overall view of the extraction technologies and applications of seaweeds and their bioactives in meat products

Table 1. EU-Funded Research Projects on algae (from 2010 until the current date)

Project	Objetive
Novel cultivation technologies of unique microalgae strains for high quality of fucoxanthin-based products (ALGAHEALTH)	Isolation, development and culture of new and proprietary microalgae strains of Isochrysis species to produce more fucoxanthin
Hydrocolloids as functional food ingredients for gut health (HYFFI)	Production of low molecular weight polysaccharides (LMWP) from alginate- and agar-bearing seaweeds for food and pharmaceutical applications
Boost BLUE economy through market uptake an innovative seaweed bioextract for IODINE fortification (BLUE IODINE)	Production by a cost-effective way new high-quality seaweed iodine products
Boost BLUE economy through market uptake an innovative seaweed bioextract for IODINE fortification II (BLUE IODINE II)	Production by a cost-effective way of new high quality iodine products from seaweed and to resolve the iodine deficiency in 3 main target groups (children, pregnant and breastfeeding women and elderly)
The Application of Edible Seaweed for Taste Enhancement and Salt Replacement (TASTE)	Development of flavour ingredients from edible seaweeds (Ascophyllum nodosum, Saccharina latissima, and Fucus vesiculosus) with potential to replace sodium in food products
Seaweed derived anti-inflammatory agents and antioxidants (SWAFAX)	Obtaining of bioactive compounds from seaweeds for food and pharmaceutical application
Launching first large-scale organic seaweed-to-food cultivation and processing in EU (SEABEST)	Production of low-cost high-volume organic seaweed in Europe food grade certified and ready for use as an ingredient on its own or in a multitude of products
Alginor`s Ocean Refining Total utilizing technology (AORTA)	Study of innovative AORTA technology for sustainable utilization of seaweeds
Alginor's Ocean Refining Total utilisation Application (AORTA 2)	Development and commercialisation of high-quality products from the seaweed Laminaria hyperborea (Lh) through a revolutionary technology – AORTA
GENetic diversity exploitation for Innovative macro-ALGal biorefinery (GENIALG)	Increase of the production and sustainable exploitation of two high-yielding species of the EU seaweed biomass: the brown alga Saccharina latissima and the green algae Ulva spp. and to obtain high-value added products on the market
Value Omega 3 and Astaxanthin products from SeaAlgae (VOPSA2.0)	Production of omega-3 and astaxanthin at scale-up and demonstration of their effectiveness through their inclusion in nutraceuticals and in new ecological products for the treatment of 3 skin diseases: acne, atopic skin and aging skin
Cascading Marine Macroalgal Biorefinery (MACRO CASCADE)	Creation of a seaweed processing platform to obtain a diversity of added-value products for industries within food, feed, cosmetics, pharmaceutical and fine chemical
Convenience Food Enriched with Marine based Raw Materials (ENRICHMAR)	Increase of the value of convenience food by supplementation of functional ingredients from marine seaweeds and by-products from fish processing
Single-step disentanglement and fractionation of microalgal high-value products through acoustophoresis (ALGCOUSTICS)	Development of a simple extraction process based on the use of acoustophoresis to obtain multiple bioactive compounds from microalgae
Fucoxanthin production from microalgae Isochrysis galbana - a solution to solve the global obesity (FUCOPRO)	Production of commercial fucoxanthin from Isochrysis microalgae and apply it in weight loss products
Exploring Marine Resources for Bioactive Compounds: From Discovery to Sustainable Production and Industrial Applications (MAREX)	Study of marine sources to isolate bioactive compounds
The Marine Functional Foods Research Initiative (NutraMara)	Development of functional food based on the incorporation of bioactive compounds with marine origin
Boosting scientific excellence and innovation capacity in biorefineries based on marine	Creation of a European network of internationally-leading stakeholders within the marine biotechnology

resources (BLUEandGREEN)	sector
Production of phycocyanin from the spirulina arthrospira sp. Revisiting the sourcing, extraction and co-valorization of the whole algae in the frame of an industrial biorefinery concept (SpiralG)	Building of a demonstration plant with a progressive production capacity of 10MT of phycocyanin per year
Algae for a biomass applied to the production of added value compounds (ABACUS)	Obtaining of targeted ingredients (terpenes and carotenoids) for cosmetic and nutraceutical applications
Innovative cost-effective technology for maximizing aquatic biomass-based molecules for food, feed and cosmetic applications (BIOSEA)	Development of innovative, competitive and cost-effective processes for the cultivation of Spirulina platensis, Isochrysis galbana, Ulva intestinalis and Saccharina latissima to extract high value active principles at low cost to be used in food, feed and cosmetic/personal care
The Value Chain from Microalgae to PUFA (PUFACHAIN)	Obtaining of highly purified omega-3 fatty acids (EPA and DHA) from microalgae
Development of Microalgae-based novel high added-value products for the Cosmetic and Aquaculture industry (ALGAE4A-B)	Exploration of the microalgae diversity as a source of high-added-value biomolecules for aquaculture and cosmetics.
Sustainable production of biologically active molecules of marine based origin (BAMMBO)	To provide innovative solutions for culturing marine organisms in order to produce high yields of value-added products
The first microalgae platform for the production of anticancer biopharmaceuticals (MABIOS)	Production of paclitaxel from microalgae
Slimming MIcroaLgae Extract : Development of a new highly effective microalgae-based slimming ingredient for nutraceutical applications (SMILE)	Development of a microalgae-based natural marine ingredient with benefits on weight management and metabolism issues
LutEin Algae Feasibility (LEAF)	Development of a method of lutein production from algae
Microalgae As a Green source for Nutritional Ingredients for Food/Feed and Ingredients for Cosmetics by cost-Effective New Technologies (MAGNIFICENT)	Transformation of microalgae biomass into valuable ingredients for food, aquafeed and cosmetics application

1 **Table 2.** Technologies used for the extraction of different bioactive compounds from seaweeds, as well as the bioactivities associated with them

Solvent extraction					
Bioactive compounds	**Macroalgae species**	**Extraction conditions**	**Yield**	**Bioactivity**	**Reference**
Sulphated polysaccharide	*Sphaerococcus coronopifolius* and *Boergeseniella thuyoides*	Distilled water at 80 °C for 4 h with magnetic stirring and a solid -to- solvent ratio of 1:75 (g/mL)	*S. coronopifolius*: 25.5 g/100 g d.s. *B. thuyoides*: 17.8 g/100 g d.s.	Antiviral activity	Bouhlal et al. (2011)
Porphyran	*Porphyra yezoensis*	Distilled water at 95 ºC with constant stirring for 1.5 h and a solid-to solvent ratio of 1:133 (g/mL)	20.6 g/100 g d.s.	Antioxidant and anti-inflammatory	Isaka et al. (2015)
Porphyran	*Porphyra haitanensis*	Alga was firstly treated with diluted formaldehyde solution, and then extracted with hot water	Not specified	Antihyperlipidemic and antioxidant	Wang et al. (2017)
Fucoidan	*Cystoseira sedoides*, *Cystoseira compressa* and *Cystoseira crinita*	Depigmented seaweeds were treated with 2% aqueous solution of $CaCl_2$ for 3 h	*C. sedoides*: 3.3 g/100 g d.s. *C. compressa*: 3.7 g/100 g d.s. *C. crinita*: 2.8 g/100 g d.s.	Anti-radical, anti-inflammatory and gastroprotective activities	Hadj et al. (2015)
Sulfated polysaccharides	*Fucus evanescens*	0.1 M HCl (pH 2–3) at 60 °C for 3 h.	9 g/100 g d.s.	Antioxidant	Imbs et al. (2015)
Laminarin and fucoidan	*Eisenia bicyclis*	0.1 M HCl for 2 h at 60 °C (two twice) using a solid-to-solvent ratio of 1:12.5 (g/mL)	1.6 g/100 g d.s.	Antitumor activity	Ermakova et al. (2013)
Ulvan	*Ulva armoricana*	Not reported	20.5 g/100 g d.s.	Immunostimulatory activity	Berri et al. (2017)
Polyphenols	*Hormosira banksii*	70% ethanol at 30 °C for 12 h using a shaking water bath and a solid-to-solvent ratio of 1:50 (g/mL)	1.6 g GAE/100 g d.s.	Antioxidant	Dang et al. (2017)
Polyphenols	*Callophyllis japonica*	Methanol at solid-to-solvent ratio of 1:10 (g/mL)	Not specified	Anti-inflammatory effect	Ryu et al. (2014)
Polysaccharides	*Sargassum muticum*, *Osmundea pinnatifida*, and *Codium tomentosum*	Water at 50 °C for 24 h in a shaking water bath using a solid-to-solvent ratio of 1:25 (g/mL),	*C. tomentosum*: 45 g/100 g d.s. *O. pinnatifida*: 50 g/100 g d.s. *S. muticum*: 23 g/100 g d.s.	Antioxidant, prebiotic, antidiabetic	Rodrigues et al. (2015)
Dieckol-rich polyphenols	*Ecklonia cava*	Seaweed powder was extracted with 70% ethanol at room temperature under stirring. The extract was purified with ethyl acetate.	28.20 g/100 g d.s.	Antiobesity, antioxidant and anti-inflammatory	Eo et al. (2015)
Phlorotannins	*Fucus vesiculosus*	Mechanical stirring using 67% acetone as solvent, at 25 ºC for 3 h and solid-to-solvent ratio of 1:70(g/mL)	0.292 of phloroglucinol equivalents/100 g d.s.	Antidiabetic and anti-obesity	Catarino et al. (2019)

Phycobiliproteins	*Gelidium pusillum*	Serial extraction in 5 cycles using 0.1 M phosphate buffer as solvent (pH 6.8), for 1 hour at 4 ºC (with intermittent stirring)	0.331 g/100 g d.s.	Not determined	Mittal et al. (2017)
Sulphated polysaccharide	*Ulva lactuca*	pH 2 at 80 ºC, for 1 h with agitation and solid-to-solvent ratio of 1:16.66 (g/mL)	13.06 g/100 g d.s.	Antioxidant	Yaich et al. (2017)
Chlorophylls and carotenoids	*Cladophora glomerata*, *Cladophora rivularis* and *Ulva flexuosa*	70% ethanol, for 60 min and solid-to-solvent ratio of 1:25 (g/mL)	*C. glomerata*: 6.5 µg of chlorophylls/mL extract and 1.7 µg of carotenoids/mL extract *C. rivularis*: 5 µg of chlorophylls/mL extract and 0.9 µg of carotenoids/mL extract *U. flexuosa*: 10.9 µg of chlorophylls/mL extract and 1.3 µg of carotenoids/mL extract	Not determined	Fabrowska et al. (2018)

Ultrasound assisted extraction (UAE)

Bioactive compounds	**Macroalgae species**	**Extraction conditions**	**Yield**	**Bioactivity**	**Reference**
Fucoidan	*Fucus evanescens*	Water, 150 W for 15 min at 23 ºC	4.64 g/100 g d.s.	Anticancer activity	Hmelkov et al. (2017)
Laminarin	*Ascophyllum nodosum* and *Laminaria hyperborea*	0.1 M hydrochloric acid. Ultrasound treatment was applied for 15 min at an amplitude level of 60% which corresponds to an ultrasonic intensity of 35.61 W cm^{-2}.	*A. nodosum*: 5.82 g/100 g d.s. *L. hyperborea*: 6.24 g/100 g d.s.	Antioxidant and antimicrobial activities	Kadam et al. (2015a)
Phenolics, fucose and uronic aci	*Ascophyllum nodosum*	0.03 M of HCl, 750 W, for 25 min at an amplitude level of 114 µm which corresponds to an ultrasonic intensity of 75.78 W cm^{-2} and solid-to-solvent ratio of 1:10 (g/mL)	Phenolics: 14.31 g GAE/100 g d.s. Fucose: 8.71 g/100 g DS Uronic acid: 12.85 g/100 g d.s.	Not determined	Kadam et al. (2015b)
Polyphenols and Fucoxanthin	*Sargassum vestitum*, *Sargassum linearifolium*, *Phyllospora comosa*, *Padina* sp., *Hormosira banksii* and *Sargassum podocanthum*	70% ethanol, 150 W for 60 min, at 30 °C	*S. vestitum*: 14.2 g GAE/100 g DS and 0.165 g FX/100 g d.s. *S. linearifolium*: 4.71 g GAE/100 g d.s. and 0.176 g FX/100 g d.s. *P. comosa*: 6.77 g GAE/100 g d.s. and	Antioxidant	Dang et al. (2018)

			0.028 g FX/100 g d.s. *Padina* sp.: 12.46 g GAE/100 g d.s. and 0.197 g FX/100 g d.s. *H. banksii*: 15.88 g GAE/100 g d.s. and 0.061 g FX/100 g d.s. *S. podocanthum*: 4.81 g GAE/100 g d.s. and 0.146 g FX/100 g d.s.		
Pholyphenols	*Hormosira banksii*	70% ethanol, 150 W, at 30 ºC for 60 min and solid-to-solvent ratio of 1:50 (g/mL)	2.31 g GAE/100 g d.s.	Antioxidant	Dang et al. (2017)
Chlorophylls and carotenoids	*Cladophora glomerata*, *Cladophora rivularis* and *Ulva flexuosa*	70% ethanol, 800 W, at 40 ºC for 60 min and solid-to-solvent ratio of 1:25 (g/mL)	*C. glomerata*: 15.9 µg of chlorophylls/mL extract and 0.5 µg of carotenoids/mL extract *C. rivularis*: 5.1 µg of chlorophylls/mL extract and 0.6 µg of carotenoids/mL extract *U. flexuosa*: 37.7 µg of chlorophylls/mL extract and 2.2 µg of carotenoids/mL extract	Not determined	Fabrowska et al. (2018)
Extracts containing sulfated polysaccharides, phenolic compounds and protein	*Sargassum muticum*, *Osmundea pinnatifida*, and *Codium tomentosum*	400 W, water at 50 ºC for 60 min and solid-to-solvent ratio of 1:25 (g/mL)	*C. tomentosum*: 48.6 g/100 g d.s. *O. pinnatifida*: 49.1 g/100 g d.s. *S. muticum*: 24 g/100 d.s.	Antioxidant, antidiabetic, and prebiotic activities	Rodrigues et al. (2015)
Phycobiliproteins (R-phycoerythrin, R-PE and R-phycocyanin, R-PC)	*Gelidium pusillum*	41.97 W, phosphate buffer (0.1 M, pH 6.8) at 30 ºC for 10 min and solid-to-solvent ratio of 1:10 (g/mL)	0.009 g/100 g d.s.	Not determined	Mittal et al. (2017)
Protein	*Ascophyllum nodosum*	750 W and frequency of 20 kHz, 0.1 M NaOH buffer for 10 min and solid-to-solvent ratio of 1:15 (g/mL)	57 g/100 g d.s.	Not determined	Kadam et al. (2017)
Peptides	*Palmaria palmata*	Extraction protein was performed with sonication for 1 h at 4 ºC and solid-to-solvent ratio of 1:10 (g/mL) Enzymatic hydrolysis of protein was performed using papain at 60 ºC, pH 6, for 24 h and solid-to-solvent ratio of 1:66.66 (g/mL)	Not specified	Prevention of atherosclerosis and high blood pressure	Fitzgerald et al. (2013)

Taurine	*Porphyra yezoensis*	300 W at 40.5 ºC for 38.3 min and solid-to-solvent ratio of 1:20 (g/mL)	1.3 g/100 g d.s.	Not determined	Wang et al. (2015)
Sulfated polysaccharides	*Gracilaria birdiae*	First stage of sonication: 60 W, 0.1 M of NaOH at 60 ºC for 30 min. Second stage of enzymatic digestion: pH of 8, at 60 ºC for 12 h	8.26 g/100 g d.s.	Antioxidant and anticoagulant	Fidelis et al. (2014)
Carbohydrates	Grateloupia turuturu	Power of 400 W, 1% enzymatic cocktail, at 40 ºC for 6 h and solid-to-solvent ratio of 1:4 (g/mL)	43.9 g/100 g d.s.	Not determined	Le Guillard et al. (2016)

Microwave assisted extraction (MAE)

Bioactive compounds	**Macroalgae species**	**Extraction conditions**	**Yield**	**Bioactivity**	**Reference**
Polysaccharides	*Sargassum thunbergii*	547 W, water as solvent at 80 ºC for 23 min and solid-to-solvent ratio of 1:27 (g/mL)	2.84 g/100 g d.s.	Antioxidant and hypoglycemic	Ren et al. (2017)
Sulfated polysaccharide	Ulva prolifera	500 W, 0.1 M HCl at 150 ºC for 15 min and solid-to-solvent ratio of 1:20 (g/mL)	6.09 g/100 g d.s.	Antioxidant and anti-hyperlipidemic	Yuan et al. (2018a)
Phenolic compound	*Ascophyllum nodosum*, *Laminaria japonica*, *Lessonia trabeculate* and *Lessonia nigrecens*	Frequency of 2.45 GHz, 70% methanol at 110 ºC for 15 min and solid-to-solvent ratio of 1:10 (g/mL)	*A. nodosum*: 12.46 g/100 g d.s. *L. japonica*: 20.93 g/100 g d.s. *L. trabeculate*: 5.22 g/100 g d.s. *L. nigrecens*: 9.28 g/100 g d.s.	Antioxidant, anti-hyperglycemic, anti-obesity and anti-tyrosinase	Yuan et al. (2018b)
Pholyphenols	*Caulerpa racemosa*	200 W, 60% ethanol at 50 ºC for 40 min and solid-to-solvent ratio of 1:40 (g/mL)	67.89 mg/100 g d.s.	Antioxidant	Li et al. (2012)
Chlorophylls	*Cladophora glomerata*, *Cladophora rivularis* and *Ulva flexuosa*	800 W, 70% ethanol, at 40 ºC for 60 min and solid-to-solvent ratio of 1:25 (g/mL)	*C. glomerata*: 26.8 µg/mL extract *C. rivularis*: 8.5 µg/mL extract and *U. flexuosa*: 34.1 µg/mL extract	Not determined	Fabrowska et al. (2018)
Carotenoids	*Cladophora glomerata*, *Cladophora rivularis* and *Ulva flexuosa*	800 W, 70% ethanol, at 40 ºC for 60 min and solid-to-solvent ratio of 1:25 (g/mL)	*C. glomerata*: 3 µg/mL extract *C. rivularis*: 1 µg/mL extract *U. flexuosa*: 2.1 µg/mL extract	Not determined	Fabrowska et al. (2018)
Fucoxanthin	*Undaria pinnatifida*	300 W, ethanol at 60 ºC for 10 min and solid-to-solvent ratio of 1:15 (g/mL)	109.3 mg/ 100 g d.s.	Not determined	Xiao et al. (2012)
Phlorotannins	*Carpophyllum flexuosum*,	Water at 160 ºC for 3 min and solid-to-solvent ratio of	*C. flexuosum*: 15.8 g/100	Antioxidant	Zhang et al. (2018)

	Carpophyllum plumosum and *Ecklonia radiata*	1:30 (g/mL)	g d.s. *C. plumosum*: 9.2 g/100 g d.s. *E. radiata*: 2 g/100 g DS		
Sulfated polysaccharides	*Sarcodia ceylonensis*, *Ulva lactuca* L., and *Durvillaea antarctica*	500 W, water at 70 ºC for 51 min, and a ratio of solid-to-solvent ratio of 1:51 (g/mL).	*S. ceylonensis*: 12.49 g/100 g d.s. *U. lactuca* L.: 11.09 g/100 g d.s. D. *antarctica*: 14.21 g/100 g d.s.	Antioxidant	He et al. (2016)
Not specified	*Padina pavonica*	1000 W, water at 60 ºC for 2 min	Not specified	Anti-hyaluronidase	Fayad et al. (2017)
Essential oil	*Enteromorpha linza*, *Porphyra tenera*	40 W, for 4 h, using water as solvent and solid-to-solvent ratio of 1:10 (g/mL)	Not specified	Antioxidant	Patra et al. (2015) and Patra et al. (2017)

Enzyme-Assisted Extraction (EAE)

Bioactive compounds	**Macroalgae species**	**Extraction conditions**	**Yield**	**Bioactivity**	**Reference**
Extracts containing sulfated polysaccharides, phenolic compounds and protein	*Sargassum muticum*, *Osmundea pinnatifida*, and *Codium tomentosum*	Cellulase, Viscozyme, Flavourzyme and Alcalase were assessed. Water at the optimum pH of each enzyme (4.5-8), at 50 ºC for 24 h and solid-to-solvent ratio of 1:25 (g/mL)	*C. tomentosum*: 60 g/100 g d.b. for Cellulase and 62 g/100 g d.b. for Viscozyme *O. pinnatifida*: 54 g/100 g d.b. for cellulase and 55 g/100 g d.s. for Flavourzyme *S. muticum*: 31.3 g/100 g d.s. for Cellulase	Antioxidant, antidiabetic, and prebiotic activities	Rodrigues et al. (2015)
Protein hydrolysates	*Palmaria palmata*	Extraction was performed with Tris – HCl buffer (20mM, pH 8) under stirring for 24 h. The supernatants were treated with 80 % ammonium sulfate for protein precipitation. The sample was ultrafiltered using a 10 kDa cut-off membrane. The protein fraction >10 kDa was hydrolyzed using chymotrypsin for 24 h at 30 °C.	12.50 g/100 g d.s.	Antihypertensive and antioxidant	Beaulieu et al. (2016)
Extracts containing polysacharides and amino acid	*Ulva armoricana*	Different enzymes were evaluated: (C4) exo-β-1,3(4)-glucanase, (P1) neutral endo-protease and (P2) mix of neutral and alkaline endo-proteases. Water at pH of 6.2, at 50 ºC for 3 h and a solid-to-solvent ratio of 1:23 (g/mL)	C4: 70.7 g/100 g d.s. P1: 76.7 g/100 g d.s. P2. 88.4 g/100 g d.s.	Antioxidant and antiviral	Hardouin et al., (2016)
Sulphated	*Ulva lactuca*	Sequential extraction using a cellulase followed by a	17.14 g/100 g d.s.	Antioxidant	Yaich et al. (2017)

polysaccharide		protease at 50 °C for 2 h and solid-to-solvent ratio of 1:12.5 (g/mL)			
Phlorotannin	*Ecklonia radiata*	Two extraction strategies: (1) enzymatic extraction using Viscozyme + Celluclast at 50 ºC for 24 h and (2) microwave-assisted enzymatic extraction at 50 ºC for 3 h using the same enzymes. In both experiments the solid-to-solvent ratio was 1:100 (g/mL)	55 g/100 g d.s.	Antioxidant	Charoensiddhi et al. (2014)
Supercritical fluid extraction (SFE)					
Bioactive compounds	**Macroalgae species**	**Extraction conditions**	**Yield**	**Bioactivity**	**Reference**
Fucoxanthin and xanthophyll	*Fucus serratus* and *Laminaria digitata*	$SCCO_2$ using ethanol as co-solvent, at 50 °C for 60 min and 300 atm	1.6 g/100 g d.s.	Not determined	Heffernan et al. (2016)
Fucoxanthin	*Undaria pinnatifida*	$SCCO_2$ at 40 °C for 180 min and 40 MPa	38.5 mg fucoxanthin/g extract	Not determined	Quitain et al. (2013)
Pholyphenols and carotenes	*Gracilaria mammillaris*	$SCCO_2$ using 8% ethanol as co-solvent at 60 °C for 240 min and 30 MPa	3.791 mg GAE/g d.s. 2.214 mg carotenes/g d.s.	Antioxidant	Ospina et al. (2017)
Fucosterol	*Lessonia vadosa*	$SCCO_2$ using ethanol as co-solvent at 50 °C and 180 bar	0.15 g/100 g d.s.	Antileishmanial	Becerra et al. (2015)
Carotenoids and chlorophyll a	*Laminaria japonica* Aresch	SFE was performed using 4.73% of ethanol-modified subcritical 1,1,1,2-tetrafluoroethane (R134a) as cosolvent, at 51 ºC and 17 MPa	carotenoids: 0.0239 g/100 g d.s. chlorophyll: 0.2326 g/100 g d.s.	Not determined	Lu et al. (2014)
Fucoxanthin	*Undaria pinnatifida*	$SCCO_2$ using 3.23% ethanol as co-solvent at 60 °C for 180 min and 40 MPa	0.099 g fucoxanthin/100 g d.s.	Not determined	Kanda et al. (2014)
Lipids	*Solieria chordalis* and *Sargassum muticum*	Three strategies studied: $SCCO_2$ at 45 ºC and 290 bar, $SCCO_2$ with 2% or 8% of ethanol as co-solvent	Not specified	Free radical scavenging	Terme et al. (2018)
Fucoidan	*Saccharina japonica*, and *Sargassum oligocystum*	$SCCO_2$ using 5% ethanol as co-solvent at 60 ºC, 550 bar and mass ratio of spent fluid to loaded raw material of 30:1	*S. japonica*: 1.35 g/100 g d.s. *S. oligocystum*: 0.57g/100 g d.s.	Not determined	Men'shova et al. (2013)
Not specified	*Padina pavonica*	$SCCO_2$ using 20% ethanol-water as co-solvent (16/4) at 30 ºC for 30 min and 15MPa	Not specified	Anti-hyaluronidase	Fayad et al. (2017)
Oil containing fatty acids, phenolic compounds and fucoxanthin	*Saccharina japonica* and *Sargassum horneri*	$SCCO_2$ with ethanol as co-solvent at 45 °C for 120 min and 250 bar	*S. japonica*: 1.09 g/100 g d.s. S. *horneri*: 1.41 g/100 g d.s.	Antioxidant, antimicrobial, and antihypertension	Sivagnanam et al. (2015)
Pressurized Liquid Extraction (PLE)					

Bioactive compounds	Macroalgae species	Extraction conditions	Yield	Bioactivity	Reference
Palmitic, arachidonic, stearidonic, γ linolenic, oleic, and eicosapentaenoic acids	*Fucus vesiculosus*	80 ºC, 120 ºC and 160 ºC, for 10 min, 100 bar, solid-to-solvent ratio of 1:20 (g/mL). Different solvents were evaluated: ethyl acetate, acetone, ethanol, hexane and ethanol:water 50:50.	Ethyl acetate: 0.693 g total FA/g extract Acetone: 0.596 g total FA/g extract Ethanol: 0.554 g total FA/g extract hexane: 0.426 g total FA/g extract ethanol:water 50:50: 0.156 g total FA/g extract	Antioxidant and antibacterial	Otero et al. (2018)
Phenols	*Ascophyllum nodosum*, *Pelvetia canaliculata*, *Fucus spiralis* and *Ulva intestinalis*	80% ethanol, at 100 ºC for 20 min and pressure of 1000 psi	*A. nodosum*: 66.26 µg PE/mg *P. canaliculata*: 40.07 µg PE/mg *F. spiralis*: 124.30 µg PE/mg *U. intestinalis*: 20.95 µg PE/mg	Antioxidant activities	Tierney et al. (2013)
Volatiles, fatty acids, and carotenoids (antioxidant extract)	*Himanthalia elongata*	Ethanol at 200 ºC for 20 min	36.91 g/100 g DS	Antimicrobial and antioxidant	Plaza et al. (2010)
Fucosterol	*Lessonia vadosa*	Ethyl acetate, at 60 ºC for 80 min and a pressure of 100 bar and a solid-to-solvent ratio of 1:16.5 (g/mL)	0.33 g/100 g DS	Antileishmanial	Becerra et al. (2014)
Not specified	*Padina pavonica*	Water, at 60 ºC for 2 min with 2 extraction cycles and a pressure of 150 bar	Not specified	Anti-hyaluronidase	Fayad et al. (2017)

Table 3. Effects of seaweeds and seaweed extracts on the oxidative deterioration incorporation in meat products

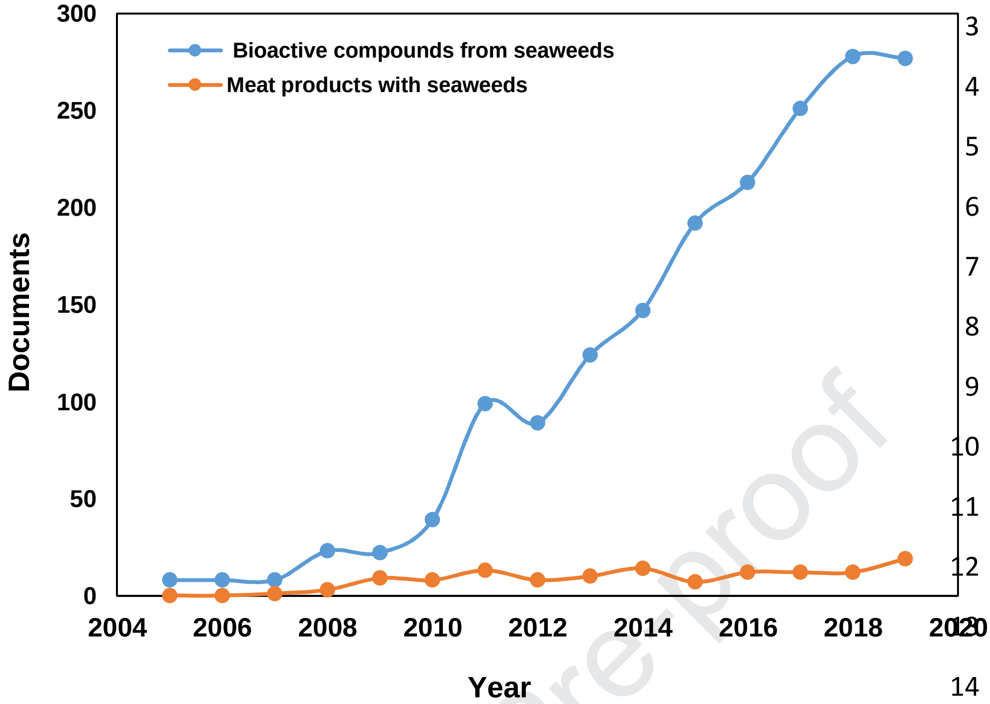
Meat product	Seaweed and form of incorporation	Dose used	Storage conditions	Main results	References
Pork liver pâté	Seaweed aqueous extracts from *Ascophyllum nodosum*, *Fucus vesiculosus* and *Bifurcaria bifurcata*	500 mg/kg	4 ºC for 180 days	Greater lipid and protein stability due to the reduction of conjugated dienes, TBARs index and carbonyl compounds	Agregán et al. (2018)
Pork patties	*Fucus vesiculosus* extracts	250, 500, 1000 mg/kg	2 ºC under light in modified atmosphere (80% O_2 and 20% CO_2) for 18 days	Color preservation and reduced both TBARs and carbonyl values during storage Good acceptation of pork patties, especially those formulated with 500 mg/Kg of seaweed extract Color, surface discoloration and odor attributtes did not improve	Agregán et al. (2019)
Cooked beef patties	*Himanthalia elongata* powder (Sea Spaguetti)	10, 20, 30, 40%	4 °C for 30 days	Inhibition of lipid oxidation and lower microbiological counts	Cox & Abu-Ghannam, (2013)
Pork meat batter	*Himanthalia elongata* podwer	3.4%	Stored at 2 ºC for 12-24 h, followed by heat processing at 70 ºC for 30 min	Prevented thermal denaturation of protein fraction	Fernández-Martín et al. (2009)
Fresh and cooked minced pork patties	Extracts containing laminarin and fucoidan from *Laminaria digitata*	0.01%, 0.1% and 0.5%	Modified atmosphere (80% O_2:20% CO_2 for fresh product and 70% N_2:30% CO_2 for cooked product) at 4 ºC for 14 days	In fresh patties: reduced the surface redness and exercised a high lipid pro-oxidant activity In cooked patties: decreased lipid oxidation	Moroney et al. (2013)
Fresh and cooked pork	Extracts containing laminarin and fucoidan from *Laminaria digitata*	3 and 6 mg/mL	4 ºC	Fucoidan reduced lipid oxidation reactions	Moroney et al. (2015)
Fresh, frozen and cooked lamb patties	Commercial astaxanthin powder	20, 40, 60 and 80 mg/Kg	(1) raw patties were refrigerated at 4 ºC for 11 days; (2) frozen patties were stored at −18 °C for 90 days; (3) cooked patties after of heat treatment were refrigerated at 4 ºC for 4 days	Reduced TBARs values, resulting a protective effect against lipid degradation Cooked patties with astaxanthin extract presented less content of volatile compounds	Carballo et al. (2018)
Cured turkey meat sausages	Fucoxanthin from *Cystoseira barbata*	0.01, 0.02 and 0.04%	4 ºC for 15 days	43% reduction TBARs value and increased the redness and yellowness values compared to the control formulation	Sellimi et al. (2017)
Ground Chicken Breast Meat	Fucoxanthin extracts from *Undaria pinnatifida*	200 mg/kg	Chilled storage for 6 days of samples prepared in fresh or cooked	Delay lipid oxidation in cooked samples Improved redness in both fresh and cooked samples	Sasaki et al. (2008)
Mechanically deboned chicken meat sausages	*Kappaphycus alvarezii* podwer	0, 2, 4 and 6%	4 ºC for 12 days	Reduced TBARs values Decreased the lightness and increased the redness values	Pindi et al. (2017)

Table 4. Effects of seaweeds and seaweed extracts on low-salt reformulated meat products

Meat product	Seaweed and form of incorporation	Dose used	Storage conditions	Main results	References
Sausages	AlgySalt® (commercial powder of seaweed extract)	2%	Storage at 4 ºC during 15 days	Decreases cooking loss Increases hardness	Triki et al. (2017)
Poultry steaks	Sea Spaghetti powder	3%	Storage at 2 ºC during 6 days	Decreases cooking losses Increase in purge loss and biogenic amines formation Greater microbial growth	Cofrades et al. (2011)
Frankfurters	Powder of sea tangle, sea mustard, hijiki, and glasswort powder	1%	Not indicated	Sea tangle and with sea mustard presented a decrease in moisture content, salinity, cooking loss, lightness, redness, hardness, gumminess, and chewiness	Choi et al. (2015)
Meat emulsion model	Powder of Sea Spaghetti, Wakame and Nori	5.6%	Not indicated	75% reduction of NaCl Increases content in n-3 polyunsaturated fatty acids Decreases the n-6/n-3 PUFA ratio Increase in K, Ca, Mg and Mn content	López-López et al. (2009a)
Beef patties	Wakame	3%	Storage at -18 ºC for 152 days	Decreases thawing and cooking losses Softer texture Increases mineral content	López-López et al. (2010)
Pork gel/emulsion systems	Sea Spaghetti, Wakame and Nori	2.5 and 5%	Not indicated	75% reduction of NaCl Increases the water and fat retention capacity Increases hardness and chewiness of cooked products Decreases springiness and cohesivenes	Cofrades et al. (2008)

Table 5. Effects of seaweeds and seaweed extracts on low-fat reformulated meat products

Meat product	Seaweed and form of incorporation	Dose used	Storage conditions	Main results	References
Sausage	κ-carrageenan	0.0, 0.5, 1.0, and 1.5%	Storage at 4 ºC during 30 days	Fat reduction of 70%, reduction of hardness and chewiness and an increase of springiness and gumminess	Atashkar et al. (2018)
Beef patties	Algae oil and carrageenan	1% (algae oil) and 3% (carrageenan)	Vacuum storage at 4 ºC during 31 days	Fat reduction of 70%, increased EPA+ DHA content reduced saturated fat and omega-6/omega-3 ratio	Alejandre et al. (2017)
Ground Pork Patties	Sodium Alginate	0.1, 0.2 and 0.3%	Refrigerated storage at 4°C in aerobic conditions for 21 days and in vacuum conditions for 35 days	Increase of cooking yield, moisture and fat retention reduction in the total lipid (49.78%) and cholesterol content (43.22%)	Kumar et al. (2007)
Pork patties	*Laminaria japonica* powder	1, 3 and 5%	Not specified	Increase of moisture, ash, carbohydrate content, yellowness, and springiness values decreased protein and fat contents, energy value, hardness, gumminess, chewiness, cooking loss, reduction in diameter, reduction in thickness, lightness and redness	Choi et al. (2012)
Chicken Nuggets	Carrageenan	0.3, 0.6 and 0.9%	Not specified	Increased cooking yield and moisture percentage The incorporation of 0.6% carrageenan results in a reduction of 43.14% of total lipids and of 45.22% of cholesterol content. In this condition, the sensory acceptance was comparable to control	Sharma et al. (2011)
Chevon patties	Carrageenan	0.3, 0.6 and 0.9%	Storage at 4 ºC	Increases retention of water, fat, emulsion stability and cooking yield high overall acceptability scores by adding 0.6% carrageenan	Nayak & Pathak, (2016)
Pork meat batter	*Himanthalia elongata* podwer (Sea Spaguetti)	3.4%	Stored at 2 ºC for 12-24 h, followed by heat processing at 70 ºC for 30 min	Increases water and fat retention capacity, hardness and elastic modulus	Fernández-Martín et al. (2009)
Frankfurters	*Himanthalia elongata*	5%	Storage at 2 ºC for 41 days	Improves water and fat binding capacity Reduces lightness and redness Increases the hardness and chewiness	López-López et al. (2009)
Beef patties	Wakame podwer	3%	Storage at -18 ºC for 152 days	Less thawing and cooking losses Softer texture	López-López et al. (2010)
Burger patties	Gelled emulsion containing carrageenan and sunflower oil	25, 50, 75 and 100%	Storage at -20 ºC	Total fat reduction of 41% Increase of 74.5% of the unsaturated fatty acids	Poyato et al. (2015)


Bioactive compounds from seaweeds
Meat products with seaweeds
Documents
0
50
100
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2016
2018
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Year

Figure 1

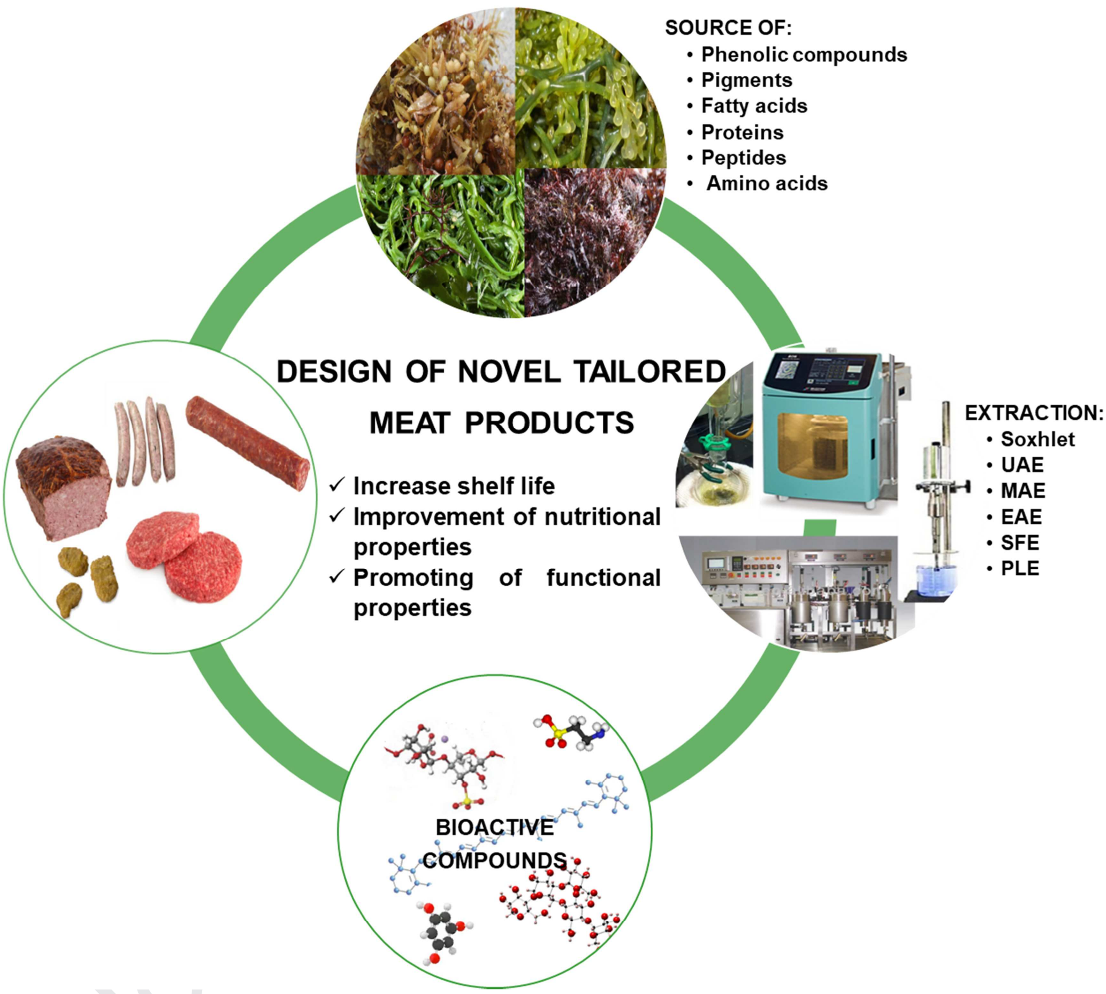
SOURCE OF:
• Phenolic compounds
• Pigments
• Fatty acids
• Proteins
• Peptides
• Amino acids
DESIGN OF NOVEL TAILORED MEAT PRODUCTS
✓ Increase shelf life
✓ Improvement of nutritional properties
✓ Promoting of functional properties
EXTRACTION:
• Soxhlet
• UAE
• MAE
• EAE
• SFE
• PLE
BIOACTIVE COMPOUNDS

Figure 2

Highlights

► Technologies for the extraction of bioactive compounds from seaweeds are reviewed

► Bioactive compounds from seaweeds are suitable to use in the meat industry

► Preservation of the overall quality of meat products using seaweeds and their extracts

► Design of functional meat products based on seaweeds and their extracts

► Reformulation of meat products with seaweeds enhances their healthy attributes