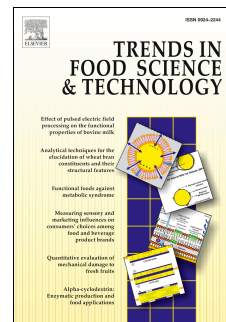


Journal Pre-proof

Seaweeds as promising resource of bioactive compounds: Overview of novel extraction strategies and design of tailored meat products

Beatriz Gullón, Mohammed Gagaoua, Francisco J. Barba, Patricia Gullón, Wangang Zhang, José M. Lorenzo



PII: S0924-2244(19)30968-9

DOI: <https://doi.org/10.1016/j.tifs.2020.03.039>

Reference: TIFS 2808

To appear in: *Trends in Food Science & Technology*

Received Date: 4 November 2019

Revised Date: 24 March 2020

Accepted Date: 27 March 2020

Please cite this article as: Gullón, B., Gagaoua, M., Barba, F.J., Gullón, P., Zhang, W., Lorenzo, José.M., Seaweeds as promising resource of bioactive compounds: Overview of novel extraction strategies and design of tailored meat products, *Trends in Food Science & Technology* (2020), doi: <https://doi.org/10.1016/j.tifs.2020.03.039>.

This is a PDF file of an article that has undergone enhancements after acceptance, such as the addition of a cover page and metadata, and formatting for readability, but it is not yet the definitive version of record. This version will undergo additional copyediting, typesetting and review before it is published in its final form, but we are providing this version to give early visibility of the article. Please note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

© 2020 Published by Elsevier Ltd.

1 **Seaweeds as promising resource of bioactive**
2 **compounds: Overview of novel extraction**
3 **strategies and design of tailored meat products**

4
5 Beatriz Gullón¹, Mohammed Gagaoua², Francisco J Barba³, Patricia Gullón¹,
6 Wangang Zhang⁴ and José M. Lorenzo^{1,*}

7 ¹Centro Tecnológico de la Carne de Galicia, Rúa Galicia Nº 4, Parque Tecnológico de
8 Galicia, San Cibrao das Viñas, 32900 Ourense, Spain

9 ²Food Quality and Sensory Science Department, Teagasc Ashtown Food Research
10 Centre, Ashtown, Dublin 15, Ireland

11 ³Universitat de València, Faculty of Pharmacy, Preventive Medicine and Public Health,
12 Food Science, Toxicology and Forensic Medicine Department, Avda. Vicent Andrés Estellés,
13 s/n, 46100, Burjassot, València, Spain

14 ⁴Key Laboratory of Meat Processing and Quality Control, Ministry of Education China,
15 Jiangsu Collaborative Innovation Center of Meat Production and Processing, Quality and Safety
16 Control, College of Food Science and Technology, Nanjing Agricultural University, Nanjing
17 210095, China

18
19 *Corresponding author: Jose M. Loernzo

20 Email address: jmlorenzo@ceteca.net

21

Abstract

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

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

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

41 **Keywords:** Seaweeds, Bioactive compounds, Novel extraction technologies, Functional

42 meat products, Oxidative stability

Journal Pre-proof

43 **1. Introduction**

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

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

60 Among the different approaches that can be used to solve this public health problem, the
61 reformulation of meat products throught the substitution, removal, reduction, increase and/or

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

79 In this sense, great efforts have been bestowed by different investigation groups to find
80 the better alternatives to incorporate seaweeds or bioactives from seaweeds into different meat

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

95 It is necessary to take into account that to revalorize more efficiently these marine
96 resources and to obtain high quality bioactives with greater yield, the development of new,
97 innovative and efficient extraction processes with remarkable advantages over the conventional
98 technologies is a prerequisite. Until now, the extraction of biologically active molecules from
99 seaweeds has been carried out using conventional techniques which present negative aspects

100 that can affect the bioactive extracts yield and their bioactivities (Kadam, Tiwari, & O'Donnell,
101 2013; Cikoš et al., 2018). However, over the last years, the application of processes more
102 efficient from an environmental and economic point of view based on the green extraction
103 concept has allowed to develop new non-conventional or intensification technologies to recover
104 valuable compounds from marine biomass (Kadam et al., 2013; Cikoš et al., 2018; Wen, Zhang,
105 Sun, Sivagnanam, & Tiwari, 2019). Some of these novel extraction approaches such as
106 microwave assisted extraction (MAE), ultrasound-assisted extraction (UAE), enzyme-assisted
107 extraction (EAE), pressurized liquid extraction (PLE), and supercritical fluid extraction (SFE)
108 among other have been applied to obtain biologically active compounds from different
109 seaweeds (Dang et al., 2017; Becerra et al., 2015; Otero, Quintana, Reglero, Fornari, & García-
110 Risco, 2018). Moreover, the combination of these new extraction approaches would allow to
111 find the optimal processes in terms of short extraction times, reduced temperature, minimizing
112 solvent use and the obtaining of bioactive extracts with properties being better preserved
113 (Kovačević et al., 2018; Kadam et al., 2013).

114 Encouraged by the growing interest in the seaweeds due to their significant potential as a
115 functional ingredient sources, this review encompasses aspects related to the state of art of the
116 current extraction methodologies applied to the algae as well as the application of both the
117 whole algae and their bioactives in meat and meat products. The role of the seaweeds and their
118 biocompounds in meat and meat products as functional ingredients conferring them additional

119 health promoting functions, as conservation agents that allow to keep their technological
120 attributes and as reformulation agents to improve their nutritional properties are also evaluated.
121 The main aspects discussed in this review are highlighted in Figure 2.

122 **2. Main components of seaweeds and their bioactivities**

123 *2.1. Marine algae polysaccharides*

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

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

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

140 2.2. Phenolic compounds

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

156 2.3. Pigments

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

170 *2.4. Fatty acids (FA)*

171 Generally, algae contain a low amount of lipids which does not surpass 5% d.w. (Kendel
172 et al., 2015). In the last years, fatty acid profile of seaweeds has attracted much attention due to
173 their high amounts of polyunsaturated fatty acids (PUFA), such as α -linolenic (ALA, 18:3 n-3),
174 octadecatetraenoic (18:4 n-3), arachidonic (AA, 20:4 n-6), eicosapentaenoic (EPA, 20:5 n-3)
175 and docosahexaenoic (DHA, 22:6 n-3) acids (Kendel et al., 2015). It is well known that this

176 type of acids has important nutritional properties as well as beneficiary effects on human health.
177 For example, PUFA possess anti-tumoural, antiviral and anti-obesity properties, and they are
178 further related with the prevention of cardiovascular diseases (Kendel et al., 2015).

179 *2.5. Proteins, peptides, and amino acids*

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

188 *2.6. Vitamins*

189 Seaweeds are also an important source of vitamins both hydro- and liposoluble, therefore
190 their consumption could improve the vitamin status. Vitamins mainly belonging to the group B
191 (B₁, B₂, B₃, B₆, B₁₂), as well as vitamins A, C, D, E, riboflavin, niacin, pantothenic acid, folic
192 acid and folate derivatives have been identified. For example, the values reported for vitamin C
193 were in a similar range for brown, red and green seaweeds (34.5-1847, 35.3-1610.6, 34.7-1250
194 mg/100 d.w., respectively) (Cherry, O'Hara, Magee, McSorley, & Allsopp, 2019). However, in

195 the case of vitamin B₁₂, the data are more scattered, varying between 16.4-43.1 mg/100 d.w. for
196 brown seaweeds, 96.1-1338 mg/100 d.w. for red seaweeds, and 60-787.5 mg/100 d.w. for green
197 seaweeds (Cherry et al., 2019). Another data that can be highlighted are reported for vitamin B₃
198 founding values in the range 612-900 mg/100 d.w. for brown seaweeds, 95.1-100 mg/100 d.w.
199 for red seaweeds and 4.9-1000 mg/100 d.w. for red seaweeds (Cherry et al., 2019).

200 *2.7. Minerals*

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

209 **3. Extraction techniques of bioactive compounds from marine macroalgae**

210 Considering the variety of phytonutrients that can be recovered from marine biomass, the
211 choice of the most adequate extraction technique is key to maintain the quality of the end
212 compounds as well as for the process to be feasible on an industrial scale. Conventional and
213 intensification extraction techniques have been used for the obtaining of the valuable molecules

214 present in algae (Kadam et al., 2013). Some works about extraction methods of different
215 bioactive compounds from seaweeds, as well as the bioactivities associated with them, are
216 summarised in Table 2.

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

229 *3.1. Ultrasound-assisted extraction (UAE)*

230 Ultrasound-assisted extraction (UAE) has been proposed as a promising green technology
231 for the isolation of several biologically active molecules from seaweeds. Compared to
232 conventional extraction, UAE presents several benefits such as simplicity, lower solvent

233 consumption, reduces the extraction time, and operates at mild temperatures which prevent the
234 degradation of thermolabile compounds. Moreover, equipment costs are lower than the other
235 modern extraction technologies and UAE is suitable for an industrial scale (Kadam et al., 2013).
236 In UAE, there are several operating variables that influence in the extraction yield, such as
237 power, time, temperature, frequency and solvent to solid ratio. In this context, Dang et al.
238 (2017) studied the UAE operational conditions to increase the recovery of phenolics with high
239 antioxidant capacity from brown alga *Hormosira banksii*. According to the authors, temperature
240 was the factor most influencing both the extraction of total phenolics and the antioxidant
241 activity, followed by ultrasonic time and in the last place by the power.

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

248 In order to improve the extraction performance of polysaccharides from marine algae,
249 some studies have proposed the simultaneous combination of sonication and enzymatic
250 treatment (Fidelis et al. 2014; Le Guillard et al., 2016). For example, Fidelis et al. (2014)
251 studied different strategies to isolate bioactive polysaccharides from *Gracilaria birdiae*. The

252 findings of this work revealed that the combination of ultrasounds and proteolytic enzymes was
253 the best strategy to extract sulfated polysaccharides with anticoagulant and antioxidant
254 properties. In another study, Le Guillard et al. (2016) applied simultaneously enzymes and
255 ultrasound to recover carbohydrates from *Grateloupia turuturu* Yamadam. The authors found
256 that the combination of ultrasounds and enzymes allow increasing the extraction yield of water-
257 soluble compounds by 50% in comparison to the treatment using only ultrasound.

258 Recently, UAE has been also reported as an attractive method for the obtaining of
259 pigments from seaweeds. Dang, Bowyer, Van Altena, and Scarlett (2018) reported the use of
260 ultrasounds to extract fucoxanthin from six brown algae. According to their results, UAE using
261 70% ethanol allowed to recover up to 0.197 g/100 dry sample of fucoxanthin from *Padina sp*
262 with a high antioxidant activity. In another study, Fabrowska, Messyasz, Szyling, Walkowiak,
263 and Łęska (2018) compared the extraction efficiency of UAE and classic Soxhlet extraction to
264 isolate chlorophylls and carotenoids from *Ulva flexuosa*. The authors found that UAE led to a
265 higher content of chlorophylls (37.7 µg/mL) and carotenoids (2.2 µg/mL) compared to that
266 obtained using the conventional method (10.9 µg/mL and 1.39 µg/mL, respectively).

267 UAE has been also investigated for the extraction of protein from marine algae. For
268 example, Fitzgerald et al. (2013) reported the protein isolation from *Palmaria palmata* applying
269 ultrasounds at low temperature. The crude protein obtained was hydrolyzed using papain to
270 obtain bioactive peptides with properties that allow preventing atherosclerosis and high blood

271 pressure. Wang et al. (2015) optimized the conditions of ultrasound-assisted extraction for the
272 recovery of taurine from *Porphyra yezoensis*. The authors found that operating under optimal
273 conditions, ultrasonic process enabled reducing the extraction time by 9 times compared to
274 conventional methods.

275 3.2. Microwave-Assisted Extraction (MAE)

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

282 MAE has been extensively used for the isolation of polysaccharides and polyphenols
283 from macroalgae (Table 2). As in UAE, the efficiency of MAE process depends on several
284 factors (solvent, microwave power, temperature and time, and the solvent-to-solid ratio) that
285 need to be optimized to achieve high extraction yields. For example, Ren et al. (2017) applied
286 Response Surface Methodology (RSM) to study the influence of some extraction parameters
287 (extraction time, microwave power, temperature and solid-to-solvent ratio) on the efficient
288 recovery of polysaccharides from *Sargassum thunbergii*. Under optimized extraction conditions
289 (microwave power 547 W for 23 min at 80 °C, and sample to solvent ratio of 1:27 g/mL), a

290 yield of polysaccharides of 2.84% was obtained. The authors reported that the polysaccharides
291 recovered showed good antioxidant and α -glucosidase inhibitory activities. More recently, Yuan
292 et al. (2018a) also assessed the microwave-assisted hydrothermal technology to extract
293 polysaccharides from *Ulva prolifera*. The results showed that the functional properties and
294 bioactivities of polysaccharides were greatly influenced by the extraction conditions. Thus,
295 polysaccharides extracted at 90 °C or 150 °C using 0.05 M HCl presented the best functional
296 characteristics in terms of water-holding and oil-holding capacity, as well as foaming properties.
297 Polysaccharides that exhibited the highest antioxidant capacity and pancreatic lipase inhibition
298 activity were obtained at 150 °C and 0.1 M HCl.

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

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

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

314 In recent years, several groups have also successfully applied MAE for the recovery of
315 pigments from marine algae. A study conducted by Xiao, Si, Yuan, Xu, & Li (2012) optimized
316 the microwave extraction conditions for the isolation of fucoxanthin from *Undaria pinnatifida*
317 using RSM methodology. Microwave treatment at 60 °C with solid-to-solvent ratio of 1:15
318 (g/mL) for 10 min and using microwave power of 300 W resulted in an optimal fucoxanthin
319 yield of 109.3 mg/100 g dry sample. In another work, Fabrowska et al. (2018) assessed the
320 extraction of chlorophylls and carotenoids from *Ulva flexuosa* using MAE. At 40 °C, a
321 microwave power of 800 W and 60 min of extraction time, the amount of chlorophylls and
322 carotenoids recovered was 37.7 and 2.2 μ g/mL, respectively. Patra, Lee, Kwon, Park, and Baek
323 (2017) have also investigated the use of microwave-assisted hydrodistillation to recover the
324 essential oils from different edible seaweeds finding extracts with strong antioxidant and
325 antibacterial activities.

326 *3.3. Enzyme-Assisted Extraction (EAE)*

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

338 Charoensiddhi, Franco, Su, and Zhang (2014) compared conventional acidic extraction,
339 enzymatic and microwave-assisted enzymatic extraction (MAEE) to recover phlorotannins and
340 antioxidant compounds from *Ecklonia radiata*. The results showed that the employment of
341 MAEE for a short extraction time (5 to 30 min) provided a high-performance recovery of target
342 compounds in comparison to the enzymatic and conventional extraction at 24 h. This greater
343 efficiency of MAEE can be attributed to the synergistic effect of the combination of microwave
344 radiation and the hydrolytic action of enzymes that lead to a greater alteration of the cell wall
345 structure than when both techniques are applied separately (Wen et al., 2019). Enzymatic

346 extraction has also been suggested as an appropriate technology for algae protein recovery. The
347 use of enzymes facilitates the degradation of cell wall polysaccharides, improving the
348 solubilization of the protein fraction (Rodrigues et al., 2015).

349 *3.4. Supercritical Fluid Extraction (SFE)*

350 Supercritical Fluid Extraction (SFE) is widely recognized as an efficient green extraction
351 method that has been used to selectively isolate heat-sensitive biocompounds like pigments and
352 fatty acids from algae (Table 2). Different parameters involved in the SFE process such as
353 pressure, temperature, co-solvents or solvent flow rate have been optimized in order to improve
354 extraction performance and the selectivity of the recovered compounds. For instance, Ospina et
355 al. (2017) evaluated the effects of pressure (10-30 MPa), temperature (40-60 °C), and co-solvent
356 concentration (2-8%) on the extraction efficiency, the recovery of phenols and carotenes as well
357 as on the antioxidant capacity from *Gracilaria mammillaris* using a central composite design.
358 The authors stated that the percentage of co-solvent was the parameter most significant on both
359 extraction yield and phenolic content while the pressure was the parameter that more affected
360 the antioxidant capacity. Similar results were previously reported by Quitain et al. (2013), who
361 also observed an increase on fucoxanthin recovery increasing pressure of SFE process. This
362 trend can be attributed to the fact that by increasing the pressure also increased density and
363 solvating power of SC-CO₂ (Quitain et al., 2013). In another study, Becerra et al. (2015) have
364 successfully employed SFE to recover fucoesterol with antileishmanial activity from *Lessonia*

365 *vadosa*. The best results in terms of yield, solvent consumption, time and purity were achieved
366 using CO₂ at 180 bar and 50 °C with 20 to 30% of cellulose as modifier followed by a
367 purification based on centrifugal partition chromatography.

368 3.5. Pressurized Liquid Extraction (PLE)

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

377 Recently, Otero et al. (2018) evaluated the influence of various solvents (hexane, ethyl
378 acetate, acetone, ethanol and ethanol: water 50:50) and temperatures (80 °C, 120 °C and 160 °C)
379 on lipid recovery from *Fucus vesiculosus* by PLE. The results showed that the highest yields of
380 fatty acids were obtained using ethyl acetate, followed by acetone and ethanol. In addition, the
381 fatty acid profile was also dependent on the solvent used. For example, ethyl acetate favoured
382 the extraction of long-chain fatty acids (oleic acid, arachidonic acid and eicosapentaenoic acid),
383 while the most polar solvents (ethanol and ethanol: water 50:50) allowed the obtaining of

384 extracts with a better ratio ω -6/ ω -3. On the contrary, the authors observed that the temperature
385 didnot affect to lipidic profile. In another study, the extraction of bioactive compounds from
386 *Padina pavonica* was assessed by PLE using ethyl acetate, ethanol, petroleum ether, and water
387 as the extraction solvents at fixed conditions of pressure (150 bar), temperature (60 °C) and time
388 (10 min). Overall, the results suggested that water was the most appropriate solvent for the
389 recovery of extracts with anti-hyaluronidase activity (Fayad et al., 2017).

390 **4. Oxidative processes in meat and meat products**

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

399 Protein oxidation is attributed to a covalent modification of protein caused either directly
400 by reactive species (ROS and RNS) or indirectly by reaction with secondary products of
401 oxidative stress. The progress of protein oxidation can compromise physical and chemical
402 characteristics of proteins like as solubility, hydrophobicity, water-holding capacity, meat

403 tenderness, and gelation functions. Moreover, protein oxidation-induced alterations may decline
404 the bioavailability of amino acid residues and alter the digestibility of proteins, resulting in a
405 worst nutritional profile of meat proteins (Lorenzo et al., 2018). Therefore, the consequences of
406 the alterations from protein oxidation can affect both the technological and sensory properties of
407 meat, which might have effects on human health and safety when the products are consumed.

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

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

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

423 Over the last decades, the meat industry has used antioxidant compounds as strategy to
424 reduce both oxidation processes and inhibit the growth of microorganisms. The incorporation of
425 these compounds in the formulation of meat products increases the shelf life and preserves the
426 quality during their processing and storage (Fernandes et al., 2018; Fernandes et al., 2016;
427 Kumar et al., 2015). These phytochemicals must meet the following specifications: be effective
428 at low percentages (0.001-0.01%), do not affect negatively the organoleptic properties of food
429 products, maintain their function during processing and shelf life, and to do not be toxic to the
430 consumer (Lorenzo et al., 2018). Although there are hundreds of compounds, which are
431 attributed antioxidant properties, only a few are approved for use in food products. The
432 synthetic antioxidants most widely applied to prolong the storage stability of meat and meat
433 products are butylated hydroxy anisole (BHA), butylated hydroxyl toluene (BHT), propyl
434 gallate (PG) and tertiary butyl hydroxy quinone (TBHQ) (Kumar et al., 2015; Lorenzo et al.,
435 2018).

436 On the other hand, the employment of these synthetic compounds has fallen under
437 scrutiny due their toxicity and carcinogenicity in the last decades. In response to the growing
438 concern of consumers about the safety of these synthetic additives, it has led both the meat
439 industry and academic researchers to search novel and naturally occurring compounds that have
440 no harmful effects on human health and can be used safely. In this context, bioactive

441 compounds extracted from natural sources with antioxidant properties, besides preserving the
442 sensory and microbial quality of meat products have functional activities beneficial to human
443 health (Lorenzo et al., 2018; Cofrades et al., 2017; Roohinejad et al., 2017).

444 **6. Role of the seaweeds and their extracts in the prevention of spoilage of meat**

445 **products and of their quality**

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

454 Table 3 includes some studies about the incorporation of seaweeds or seaweed extracts in
455 meat products and their role in the oxidative deterioration, foregrounding the macroalgae
456 species from which the extracts have been obtained, the concentration used of the extract or
457 seaweed, the meat product in which the extract or seaweed has been incorporated and the more
458 noticeable results. Recently, Agregán et al. (2018) investigated the effects of the incorporation
459 of seaweed extracts (e.g. *Ascophyllum Nodosum*, *Fucus Vesiculosus* and *Bifurcaria Bifurcata*)

460 on the oxidative stability of low-fat pork liver patties. In this study, seaweed extracts were
461 incorporated at 500 mg/kg to the patties and compared with those elaborated using a synthetic
462 antioxidant (BHT at 50 mg/Kg) and a control sample during 180 days of storage at 4°C. The
463 authors observed that samples formulated with seaweed extracts showed greater lipid and
464 protein stability, measured in terms of conjugated dienes, TBARS index and carbonyl
465 compounds, as well as an adequate maintenance of the redness (a*) and yellowness (b*)
466 compared to the control experiment. The findings also displayed that the incorporation of
467 seaweed extracts provided a similar protection to those of BHT added to the samples. In
468 addition, the formulated patties with antioxidants did not modify microbial characteristics.

469 These same authors also investigated the effectiveness of *Fucus vesiculosus* extracts
470 (FVE) at three different amounts (200, 500 and 1000 mg/kg) on the shelf-life of pork patties
471 during the storage in modified atmosphere at 2 °C for 18 days (Agregán et al., 2019). The
472 evolution of patties elaborated with seaweed extracts was compared with patties without
473 antioxidants and with those formulated with BHT at 200 mg/kg. They observed that the addition
474 of FVE at different concentrations did not alter the lightness value (L*); however, they had a
475 stabilizing effect of the red color (a*), although this protective effect was more pronounced
476 using BHT. After 18 days of storage, the TBARS and carbonyl levels of patties containing 1000
477 mg seaweed extract/kg were lower than those obtained for the control sample. These results can
478 be explained by the high content of phenolic compounds, mainly phlorotannin present in *Fucus*

479 *vesiculosus*. Indeed, these active agents present a strong antioxidant capacity which contributes
480 to delay the formation of degradation products by lipid and protein oxidation. On the other
481 hand, the authors also revealed that the addition of FVE did not negatively affect the sensory
482 attributes of the patties.

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

495 In an effort to delay the lipid oxidation of chicken sausages, Pindi, Mah, Munsu, and Ab
496 Wahab (2017) studied the effect of the incorporation of red seaweed (*Kappaphycus alvarezii*) as
497 an antioxidant ingredient in its formulation. Sausages containing 2%, 4% and 6% seaweed

498 powder were prepared using mechanically deboned chicken meat (MDCM). During the storage
499 period (12 days at 4 °C), the presence of seaweed powder reduced the lightness (L*) and
500 increased the redness (a*) values with respect to the control sample. The addition of algae
501 allowed obtaining MDCM sausages with better physicochemical properties. Furthermore,
502 sausages formulated with seaweed also showed a significant reduction in the TBARS index,
503 evidencing that seaweed acts as an antioxidant agent that reduces the rate of lipid oxidation.

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

516 the fact that during heating, Maillard reaction products can be formed, particularly brown
517 melanoidins, that have a strong antioxidant activity.

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

524 As mentioned above, the pigments present in seaweeds exhibit also important bioactive
525 properties with potential to prevent determined diseases. This has encouraged the food industry
526 to formulate new food enriched with these bioactive compounds. Moreover, these pigments
527 present high antioxidant activity so that they can contribute to overcome the problems linked to
528 the oxidative spoilage in food products rich in fat. In this regard, some reports are available
529 about the incorporation of several pigments from seaweeds in meat products. For example,
530 Sasaki et al. (2008) evaluated the effect of adding fucoxanthin as a source of antioxidants to
531 control lipid oxidation and loss of color in ground chicken breast meat during storage at 4 °C for
532 6 days, before and after cooking. The authors found that the incorporation of fucoxanthin at a
533 concentration of 200 mg/Kg had no effect on lipid peroxidation during the storage of the
534 samples before cooking. Contrary, in the cooked samples, the presence of fucoxanthin

535 decreased TBARS index during chilled storage with a reduction of 58.5% on day 6. Concerning
536 color parameters, fucoxanthin decreased L* and increased a* and b* values in both cooked and
537 fresh samples during chilled storage.

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

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

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

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

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

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

583 The saturated fat has a key role in the organoleptic and technological properties of meat
584 products, contributing to the texture, flavor, juiciness, springiness, chewiness, as well as to
585 improve the water-holding capacity, stabilizing emulsions and cooking yield of these products
586 (Barbut, Wood, & Marangoni, 2016). For these reasons, fat reduction in meat products is not
587 easy as it results in undesirable modifications of sensory and technological properties of those
588 products with the consequent risk of rejection by consumers (Atashkar, Hojjatoleslami, &
589 Sedaghat Boroujeni, 2018). To overcome these drawbacks, the meat industry has faced a new
590 challenge producing low-saturated fat meat products with quality characteristics similar to
591 traditional products. One of the strategies used for the formulation of these products involves

592 the substitution of fat by non-meat ingredients (Brewer et al., 2012). In this regard, several fat
593 replacers have been evaluated for the development of low-fat meat products including proteins
594 (whey, collagen, legume proteins), carbohydrates-based hydrocolloids (alginate, carrageenans,
595 xanthan gum, locust bean gum, starches and pectins) and vegetable (canola, olive, linseed,
596 sunflower) or marine (algae and fish) oils (Barbut et al., 2016; Brewer, 2012).

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

610 and they have been added successfully as fat replacement ingredients to various meat products,
611 hence improving the overall quality (Brewer, 2012).

612 Table 5 collects some studies about the effects of the incorporation of seaweeds or their
613 isolated compounds in the development of low-fat meat products. The effects of the adding of *L.*
614 *japonica* powder in the elaboration of reduced-fat pork patties were investigated by Choi et al.
615 (2012). The authors reported that the patties formulated with different seaweed powder content
616 (1%, 3% and 5%) and a 10% fat content exhibited lower cooking loss, lower reduction in
617 diameter and lower thickness. Moreover, the reformulation (using 1% and 3% *L. japonica*
618 powder) improved textural properties (springiness, hardness, gumminess, and chewiness);
619 however, the color was negatively affected due to the brown dark coloration of seaweed extract.

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

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

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

643 A similar study was carried out by Kumar, Sharma and Kumar (2007) who evaluated the
644 incorporation of different concentrations of sodium alginate (0.1, 0.2 and 0.3%) as fat replacer
645 in low-fat ground pork patties. In comparison to the control formulation (20% fat), reformulated
646 patties showed an increase of cooking yield, moisture and fat retention dependent of the alginate
647 concentration used. In addition, the authors also reported a decrease of 49.78 and 43.22% in the

648 total lipid and cholesterol content. Overall, low-fat patties (<10%) formulated with sodium
649 alginate maintained sensory, microbiological and textural characteristics similar to control with
650 20% fat during storage at 4 °C for 21 days in aerobic conditions and for 35 days in anaerobic
651 conditions. Poyato, Astiasar, Barriuso, Ansorena, (2015) also developed an emulsion based on
652 carrageenan as fat replacer in burger patties. The authors found that the total pork back fat
653 substitution by the gelled emulsion led a reduction of 41, 47 and 62% of the content of total fat,
654 cholesterol and saturated fat, respectively, also observing an increment of 74.5% of the
655 unsaturated fatty acids.

656 In an attempt to improve the nutritional quality of chicken nuggets, a study by Sharma,
657 Mendiratta and Sharma (2011) incorporated carrageenan as fat replacer in the formulation of
658 low-fat chicken nuggets. Four formulations were tested including 5% fat and three different
659 doses of carrageenan (0.3%, 0.6% and 0.9%) and as control chicken nugget with 15% added fat.
660 The presence of carrageenan improved significantly cooking yield, fat and water retention in the
661 low-fat products as compared to control batch. In this study, the 0.6% carrageenan incorporation
662 resulted in a reduction of total lipid and cholesterol levels of 43.14 and 45.22%, respectively.
663 The sensorial acceptance of formulated chicken nuggets with 0.6% carrageenan was comparable
664 to high-fat control. Based on the results obtained, the authors concluded that it was feasible to
665 obtain low-fat chicken nuggets with sensory attributes and technological characteristics similar
666 to conventional products. Nayak & Pathak (2016) also demonstrated that the carrageenan can be

667 used successfully as a fat replacer in processed meat products. In this study, the authors assessed
668 the quality of low-fat chevon patties reformulated with carrageenan (0.3%, 0.6% and 0.9%). The
669 modified patties presented a higher retention of water, fat, emulsion stability and cooking yield.
670 In addition, the general acceptability scores were higher for those hamburgers to which 0.6%
671 carrageenan was added compared to the high-fat control lot.

672 **8. Final remarks**

673 Seaweeds have attracted great interest in the last decades because of their significant
674 potential as excellent biocompounds source with noticeable nutritional, technological and
675 functional values. The adequate selection of the extraction technologies is overriding in the
676 recovery of bioactives from seaweeds. The studies mentioned in the present review evidenced
677 the importance of use of seaweeds and/or seaweed extracts into meat products as a suitable
678 reformulation strategy enhancing their shelf-life, nutritional, textural, organoleptic, sensorial
679 and health-promoting properties. Usually, this reformulation seeks the substitution of some
680 components present in meat products perceived as harmful by consumers by other with healthy
681 attributes. Although it has been demonstrated the effectiveness of the use of these macroalgae
682 and their biocompounds to modify fat profile and to prevent oxidative deterioration of meat
683 products, there are still some challenges regarding the organoleptic and sensorial properties of
684 the resulting products that affect consumer acceptability. For this reason, optimizing the
685 formulation of meat products based on seaweeds and their bioactive extracts is necessary since

686 the effects depend on the seaweed species and the amount used. In this regard, systematized
687 information about the amounts of seaweeds and bioactive extracts from algae used to
688 reformulate meat products can not be provided because these quantities depend on the sought
689 technological, nutritional, functional effects or the sensory attributes as well as on the type of
690 algae, the way in which the algae is incorporated (whole or extract) and the final product
691 wanted. The research in this field must advance towards the elucidation of the interaction
692 between the meat products and the seaweeds and their bioactives as well as their
693 biodisponibility once these products are ingested.

694 **Acknowledgements**

695 Thanks to GAIN (Axencia Galega de Innovación) for supporting this review (grant
696 number IN607A2019/01). Jose M. Lorenzo is member of the HealthyMeat network, funded by
697 CYTED (ref. 119RT0568). B. Gullón would like to express their gratitude to the Spanish
698 Ministry of Economy and Competitiveness for financial support (Grant reference RYC2018-
699 026177-I).

700 **References**

701 Agregán, R., Barba, F. J., Gavahian, M., Franco, D., Khaneghah, A. M., Carballo J. et al.
702 (2019). *Fucus vesiculosus* extracts as natural antioxidants for improvement of physicochemical
703 properties and shelf life of pork patties formulated with oleogels. *Journal of the Science of Food*
704 *and Agricultural*, 99, 4561-4570.
705 Agregán, R., Franco, D., Carballo, J., Tomasevic, I., Barba, F. J., Gómez, B. et al. (2018).
706 Shelf life study of healthy pork liver pâté with added seaweed extracts from *Ascophyllum*
707 *nodosum*, *Fucus vesiculosus* and *Bifurcaria bifurcata*. *Food Research International*, 112, 400-
708 411.

- 709 Agregán, R., Munekata, P. E., Franco, D., Dominguez, R., Carballo, J., & Lorenzo, J. M.
710 (2017). Phenolic compounds from three brown seaweed species using LC-DAD–ESI-MS/MS.
711 *Food Research International*, 99, 979-985.
- 712 Alejandro, M., Passarini, D., Astiasarán, I., & Ansorena, D. (2017). The effect of low-fat
713 beef patties formulated with a low-energy fat analogue enriched in long-chain polyunsaturated
714 fatty acids on lipid oxidation and sensory attributes. *Meat Science*, 134, 7-13.
- 715 Aryee, A. N., Agyei, D., & Akanbi, T. O. (2018). Recovery and utilization of seaweed
716 pigments in food processing. *Current Opinion in Food Science*, 19, 113-119.
- 717 Atashkar, M., Hojjatoleslami, M., & Sedaghat Boroujeni, L. (2018). The influence of fat
718 substitution with κ - carrageenan, konjac, and tragacanth on the textural properties of low - fat
719 sausage. *Food Science & Nutrition*, 6, 1015-1022.
- 720 Barbut, S., Wood, J., & Marangoni, A. (2016). Potential use of organogels to replace
721 animal fat in comminuted meat products. *Meat Science*, 122, 155-162.
- 722 Beaulieu, L., Sirois, M., & Tamigneaux, É. (2016). Evaluation of the *in vitro* biological
723 activity of protein hydrolysates of the edible red alga, *Palmaria palmata* (dulse) harvested from
724 the Gaspé coast and cultivated in tanks. *Journal of Applied Phycology*, 28, 3101-3115.
- 725 Becerra, M., Boutefnouchet, S., Córdoba, O., Vitorino, G. P., Brehu, L., Lamour, I., ... &
726 Kritsanida, M. (2015). Antileishmanial activity of fucosterol recovered from *Lessonia vadosa*
727 Searles (Lessoniaceae) by SFE, PSE and CPC. *Phytochemistry Letters*, 11, 418-423.
- 728 Berri, M., Olivier, M., Holbert, S., Dupont, J., Demais, H., Le Goff, M. et al., (2017).
729 Ulvan from *Ulva armoricana* (Chlorophyta) activates the PI3K/Akt signalling pathway *via*
730 TLR4 to induce intestinal cytokine production. *Algal Research*, 28, 39-47.
- 731 Brewer, M. S. (2012). Reducing the fat content in ground beef without sacrificing quality:
732 A review. *Meat Science*, 91, 385-395.
- 733 Carballo, D. E., Caro, I., Andrés, S., Giráldez, F. J., & Mateo, J. (2018). Assessment of
734 the antioxidant effect of astaxanthin in fresh, frozen and cooked lamb patties. *Food Research*
735 *International*, 111, 342-350.
- 736 Catarino, M. D., Silva, A. M. S., Mateus, N., & Cardoso, S. M. (2019). Optimization of
737 phlorotannins extraction from *Fucus vesiculosus* and evaluation of their potential to prevent
738 metabolic disorders. *Marine Drugs*, 17, 162.
- 739 Černá, M. (2011). Seaweed proteins and amino acids as nutraceuticals. *Advances in Food*
740 *and Nutrition and Research*, 64, 297-312.
- 741 Charoensiddhi, S., Franco, Ch., Su, P., & Zhang, W. (2014). Improved antioxidant
742 activities of brown seaweed *Ecklonia radiata* extracts prepared by microwave-assisted
743 enzymatic extraction. *Journal of Applied Phycology*, 27, 2049-2058.
- 744 Cherry, P., O'Hara, C., Magee, P. J., McSorley, E. M., & Allsopp, P. J. (2019). Risks and
745 benefits of consuming edible seaweeds. *Nutrition Reviews*, 77, 307-329.

- 746 Choi, Y. S., Choi, J. H., Han, D. J., Kim, H. Y., Kim, H. W., Lee, M. A. et al. (2012).
747 Effects of *Laminaria japonica* on the physico-chemical and sensory characteristics of reduced-
748 fat pork patties. *Meat Science*, *91*, 1-7.
- 749 Cikoš, A.-M., Jokić, S. Šubarić, D., & Jerković, I. (2018). Overview on the Application
750 of Modern Methods for the Extraction of Bioactive Compounds from Marine Macroalgae.
751 *Marine Drugs*, *16*, 348-368.
- 752 Cofrades, S., Benedí, J., Garcimartin, A., Sánchez-Muniz, F. J., & Jimenez-Colmenero, F.
753 (2017). A comprehensive approach to formulation of seaweed-enriched meat products: From
754 technological development to assessment of healthy properties. *Food Research International*,
755 *99*, 1084-1094.
- 756 Cofrades, S., López-López, I., Solas, M., Bravo, L., & Jiménez-Colmenero, F. (2008).
757 Influence of different types and proportions of added edible seaweeds on characteristics of low-
758 salt gel/emulsion meat systems. *Meat Science*, *79*, 767-776.
- 759 Cox, S., & Abu - Ghannam, N. (2013). Enhancement of the phytochemical and fibre
760 content of beef patties with *Himanthalia elongata* seaweed. *International Journal of Food*
761 *Science and Technology*, *48*, 2239-2249.
- 762 Dang, T. T., Bowyer, M. C., Van Altena, I. A., & Scarlett, C. J. (2018). Comparison of
763 chemical profile and antioxidant properties of the brown algae. *International Journal of Food*
764 *Science and Technology*, *53*, 174-181.
- 765 Dang, T. T., Van Vuong, Q., Schreider, M. J., Bowyer, M. C., Van Altena, I. A., &
766 Scarlett, C. J. (2017). Optimisation of ultrasound-assisted extraction conditions for phenolic
767 content and antioxidant activities of the alga *Hormosira banksii* using response surface
768 methodology. *Journal of Applied Phycology*, *29*, 3161-3173.
- 769 Domínguez, R., Pateiro, M., Gagaoua, M., Barba, F. J., Zhang, W., & Lorenzo, J. M.
770 (2019). A Comprehensive Review on Lipid Oxidation in Meat and Meat Products. *Antioxidants*,
771 *8*(10), 429.
- 772 Domínguez, R., Barba, F. J., Gómez, B., Putnik, P., Kovačević, D. B., Pateiro, M., ... &
773 Lorenzo, J. M. (2018). Active packaging films with natural antioxidants to be used in meat
774 industry: A review. *Food Research International*, *113*, 93-101.
- 775 Eo, H., Jeon, Y., Lee, M., & Lim, Y. (2015). Brown alga *Ecklonia cava* polyphenol
776 extract ameliorates hepatic lipogenesis, oxidative oxidative stress, and inflammation by
777 activation of AMPK and SIRT1 in high-fat diet-induced obese mice. *Journal of Agricultural*
778 *and Food Chemistry*, *63*, 349-359.
- 779 Ermakova, S., Men'shova, R., Vishchuk, O., Kim, S.-M., Um, B.-H., Isakov, V., et al.
780 (2013). Water-soluble polysaccharides from the brown alga *Eisenia bicyclis*: Structural
781 characteristics and antitumor activity. *Algal Research*, *2*, 51-58.
- 782 Fabrowska, J., Messyas, B., Szyling, J., Walkowiak, J., & Łęska, B. (2018). Isolation of
783 chlorophylls and carotenoids from freshwater algae using different extraction methods.
784 *Phycological Research*, *66*, 52-57.

- 785 Fayad, S., Nehmé, R., Tannoury, M., Lesellier, E., Pichon, Ch., & Morin, P. (2017).
786 Macroalga *Padina pavonica* water extracts obtained by pressurized liquid extraction and
787 microwave-assisted extraction inhibit hyaluronidase activity as shown by capillary
788 electrophoresis. *Journal of Chromatography A*, 1497, 19-27.
- 789 Fernández-Martín, F., López-López, I., Cofrades, S., & Colmenero, F. J. (2009).
790 Influence of adding *Sea Spaghetti* seaweed and replacing the animal fat with olive oil or a
791 konjac gel on pork meat batter gelation. Potential protein/alginate association. *Meat Science*, 83,
792 209-217.
- 793 Fernandes, R. D. P. P., Trindade, M. A., Lorenzo, J. M., & De Melo, M. P. (2018).
794 Assessment of the stability of sheep sausages with the addition of different concentrations of
795 *Origanum vulgare* extract during storage. *Meat Science*, 137, 244-257.
- 796 Fernandes, R. D. P. P., Trindade, M. A., Lorenzo, J. M., Munekata, P. E. S., & De Melo,
797 M. P. (2016). Effects of oregano extract on oxidative, microbiological and sensory stability of
798 sheep burgers packed in modified atmosphere. *Food Control*, 63, 65-75.
- 799 Fidelis, G. P., Camara, R. B. Queiroz, M. F., Santos Pereira Costa M. S., Santos, P. C.,
800 Rocha H. A. et al. (2014). Proteolysis, NaOH and ultrasound-enhanced extraction of
801 anticoagulant and antioxidant sulfated polysaccharides from the edible seaweed, *Gracilaria*
802 *birdiae*. *Molecules*, 19, 18511-18526.
- 803 Fitzgerald, C., Gallagher, E., O'Connor, P., Prieto, J., Mora-Soler, L., Greal, M. et al.
804 (2013). Development of a seaweed derived platelet activating factor acetylhydrolase (PAF-AH)
805 inhibitory hydrolysate, synthesis of inhibitory peptides and assessment of their toxicity using the
806 *Zebrafish larvae* assay. *Peptides*, 50, 119-124.
- 807 Furuta, T., Miyabe, Y., Yasui, H., Kinoshita, Y., & Kishimura, H. (2016). Angiotensin I
808 converting enzyme inhibitory peptides derived from phycobiliproteins of Dulse *Palmaria*
809 *palmata*. *Marine Drugs*, 14, 32-42.
- 810 Ganesan, A. R., Shanmugam, M., & Bhat, R. (2019). Quality enhancement of chicken
811 sausage by semi-refined carrageenan. *Journal of Food Processing and Preservation*, 43, 13988.
- 812 Gómez-Guzmán, M., Rodríguez-Nogales, A., Algeri, F., & Gálvez, J. (2018). Potential
813 role of seaweed polyphenols in cardiovascular-associated disorders. *Marine Drugs*, 16, 250-
814 271.
- 815 Gómez, M., & Lorenzo, J. M. (2012). Effect of packaging conditions on shelf-life of fresh
816 foal meat. *Meat Science*, 91(4), 513-520.
- 817 Granato, D., Barba, F. J., Kovačević, D. B., Lorenzo, J. M., Cruz, A. G., & Putnik, P.
818 (2020). Functional Foods: Product Development, Technological Trends, Efficacy Testing, and
819 Safety. *Annual Review of Food Science and Technology*, 11. [https://doi.org/10.1146/annurev-](https://doi.org/10.1146/annurev-food-032519-051708)
820 [food-032519-051708](https://doi.org/10.1146/annurev-food-032519-051708)
- 821 Hadj, A. H., Lajili, S., Ben, S. R., Le, C. D., Bouraoui, A., & Majdoub, H. (2015).
822 Physico-chemical characterization and pharmacological evaluation of sulfated polysaccharides

- 823 from three species of Mediterranean brown algae of the genus *Cystoseira*. *DARU Journal of*
824 *Pharmaceutical Sciences*, 23, 1-8.
- 825 He, J., Xu, Y., Chen H., & Sun, P. (2016). Extraction, Structural Characterization, and
826 Potential Antioxidant Activity of the Polysaccharides from Four Seaweeds. *International*
827 *Journal of Molecular Sciences*, 17, 1988-2005.
- 828 Heck, R. T., Vendruscolo, R. G., de Araújo Etchepare, M., Cichoski, A. J., de Menezes,
829 C. R., Barin, J. S., ... & Campagnol, P. C. B. (2017). Is it possible to produce a low-fat burger
830 with a healthy n-6/n-3 PUFA ratio without affecting the technological and sensory
831 properties?. *Meat Science*, 130, 16-25.
- 832 Imbs, T. I., Skriptsova, A. V., & Zvyagintseva, T. N. (2015). Antioxidant activity of
833 fucose-containing sulfated polysaccharides obtained from *Fucus evanescens* by different
834 extraction methods. *Journal of Applied Phycology*, 27, 545-553.
- 835 Isaka, S., Cho, K., Nakazono, S., Abu, R., Ueno, M., Kim, D. et al. (2015).
836 Antioxidant and anti-inflammatory activities of porphyrin isolated from discolored nori
837 (*Porphyra yezoensis*). *International Journal of Biological Macromolecules*, 74, 68-75.
- 838 Kadam, S. U., Álvarez, C., Tiwari, B. K., & O'Donnell, C. P. (2017). Extraction and
839 characterization of protein from Irish brown seaweed *Ascophyllum nodosum*. *Food Research*
840 *International*, 99, 1021-1027.
- 841 Kadam, S. U., O'Donnell, C. P., Rai, D. K., Hossain, M. B., Burgess, C. M., Walsh, D. et
842 al. (2015). Laminarin from Irish Brown Seaweeds *Ascophyllum nodosum* and *Laminaria*
843 *hyperborea*: Ultrasound Assisted Extraction, Characterization and Bioactivity *Marine Drugs*,
844 13, 4270-4280.
- 845 Kadam, S. U., Tiwari, B. K., & O'Donnell, C. P. (2013). Application of novel extraction
846 technologies for extraction of bioactives from marine algae. *Journal of Agricultural and Food*
847 *Chemistry*, 61, 4667-4675.
- 848 Kadam, S. U., Tiwari, B. K., Smyth, T. J., & O'Donnell, C. P. (2015). Optimization of
849 ultrasound assisted extraction of bioactive components from brown seaweed *Ascophyllum*
850 *nodosum* using response Surface methodology. *Ultrasonics Sonochemistry*, 23, 308-316.
- 851 Kanda, H., Kamo, Y., Machmudah, S., Wahyudiono, & Goto, M. (2014). Extraction of
852 fucoxanthin from raw macroalgae excluding drying and cell wall Disruption by liquefied
853 dimethyl ether. *Marine Drugs*, 12, 2383-2396.
- 854 Kendel, M., Wielgosz-Collin, G., Bertrand, S., Roussakis, C., Bourgougnon, N., &
855 Bedoux, G. (2015). Lipid composition, fatty acids and sterols in the seaweeds *Ulva armoricana*,
856 and *Solieria chordalis* from Brittany (France): An analysis from nutritional, chemotaxonomic,
857 and antiproliferative activity perspectives. *Marine Drugs*, 13, 5606-5628.
- 858 Kovačević, D. B., Maras, M., Barba, F. J., Granato, D., Roohinejad, S., Mallikarjunan,
859 K., ... & Putnik, P. (2018). Innovative technologies for the recovery of phytochemicals from
860 *Stevia rebaudiana* Bertoni leaves: A review. *Food Chemistry*, 268, 513-521.

- 861 Kraan, S. (2012). Algal Polysaccharides, Novel Applications and Outlook. In
862 Carbohydrates-Comprehensive Studies on Glycobiology and Glycotechnology; InTech: Rijeka,
863 Croatia, Chapter 22, pp. 489-524.
- 864 Kumar, M., Sharma B. D., & Kumar, R. R. (2007). Evaluation of sodium alginate as a fat
865 replacer on processing and shelf-life of low-fat ground pork patties. *Asian-Australasian Journal*
866 *of Animal Sciences*, 20, 588-597.
- 867 Kumar, Y., Yadav, D. N., Ahmad, T., & Narsaiah, K. (2015). Recent trends in the use of
868 natural antioxidants for meat and meat products. *Comprehensive Reviews in Food Science and*
869 *Food Safety*, 14, 796–812.
- 870 Le Guillard, C., Bergé, J. P., Donnay-Moreno, C., Bruzac, S., Ragon, J. Y., & Baron, R.
871 (2016). Soft liquefaction of the red seaweed *Grateloupia turuturu* Yamada by ultrasound-
872 assisted enzymatic hydrolysis process. *Journal of Applied Phycology*, 28, 2575-2585.
- 873 Li, Z., Wang, B. Zhang, Q., Qu, Y., Xu, H., & Li, G. (2012). Preparation and antioxidant
874 property of extract and semipurified fractions of *Caulerpa racemosa*. *Journal of Applied*
875 *Phycology*, 24, 1527-1536.
- 876 Liu, B., Kongstad, K. T., Wiese, S., Jager, A. K., & Staerk, D. (2016). Edible seaweed as
877 future functional food: Identification of alpha-glucosidase inhibitors by combined use of high-
878 resolution alpha-glucosidase inhibition profiling and HPLC-HRMS-SPE-NMR. *Food*
879 *Chemistry*, 203, 16-22.
- 880 Liu, M., Hansen, P. E., & Lin, X. (2011). Bromophenols in marine algae and their
881 bioactivities. *Marine Drugs*, 9, 1273-1292.
- 882 Liu, Y. J., Deng, Z., Geng, L., Wang, J., & Zhang, Q. (2019). *In vitro* evaluation of the
883 neuroprotective effect of oligo-porphyrin from *Porphyra yezoensis* in PC12 cells. *Journal of*
884 *Applied Phycology*, 31, 2559-2571.
- 885 López-López, I., Cofrades, S., Ruiz-Capillas, C., & Jiménez-Colmenero, F. (2009).
886 Design and nutritional properties of potential functional frankfurters based on lipid formulation,
887 added seaweed and low salt content. *Meat Science*, 83(2), 255-262.
- 888 Lorenzo, J. M., Munekata, P. E. S., Sant'Ana, A. S., Carvalho, R. B., Barba, F. J., Toldrá,
889 F. et al. (2018). Main characteristics of peanut skin and its role for the preservation of meat
890 products. *Trends in Food Science & Technology*, 77, 1-10.
- 891 Lorenzo, J., Agregán, R., Munekata, P., Franco, D., Carballo, J., Şahin, S., ... & Barba, F.
892 (2017). Proximate composition and nutritional value of three macroalgae: *Ascophyllum*
893 *nodosum*, *Fucus vesiculosus* and *Bifurcaria bifurcata*. *Marine Drugs*, 15(11), 360.
- 894 Lorenzo, J. M., Munekata, P. E. S., Pateiro, M., Campagnol, P. C. B., & Domínguez, R.
895 (2016). Healthy Spanish salchichón enriched with encapsulated n– 3 long chain fatty acids in
896 konjac glucomannan matrix. *Food Research International*, 89, 289-295.
- 897 Lu, J., Feng, X., Han, Y., & Xue, Ch. (2014). Optimization of subcritical fluid extraction
898 of carotenoids and chlorophyll a from *Laminaria japonica* Aresch by response Surface
899 methodology. *Journal of the Science of Food and Agriculture*, 94, 139-145.

- 900 Men'shova, R. V., Lepeshkin, F. D., Ermakova, S. P., Pokrovskii, O. I., & Zvyagintseva,
901 T. N. (2013). Effect of pretreatment conditions of brown algae by supercritical fluids on yield
902 and structural characteristics of fucoidans. *Chemistry of Natural Compounds*, *48*, 923-926.
- 903 Mittal, R., Tavanandi, H. A., Mantri, V. A., & Raghavarao, K. S. M. S. (2017).
904 Ultrasound assisted methods for enhanced extraction of phycobiliproteins from marine macro-
905 algae, *Gelidium pusillum* (Rhodophyta). *Ultrasonics Sonochemistry*, *38*, 92-103.
- 906 Moroney, N. C., O'Grady, M. N., Lordan, S., Stanton, C., & Kerry, J. P. (2015). Seaweed
907 polysaccharides (Laminarin and Fucoidan) as functional ingredients in pork meat: An
908 evaluation of anti-oxidative potential, thermal stability and bioaccessibility. *Marine Drugs*, *13*,
909 2447-2464.
- 910 Moroney, N., O'Grady, M., O'Doherty, J., & Kerry, J. (2013). Effect of a brown seaweed
911 (*Laminaria digitata*) extract containing laminarin and fucoidan on the quality and shelf-life of
912 fresh and cooked minced pork patties. *Meat Science*, *94*, 304-311.
- 913 Nayak, N. K., & Pathak, V. (2016). Development and quality assessment of carrageenan
914 incorporated low fat chevon patties. *Journal of Food Science and Technology*, *53*, 3477-3484.
- 915 Nikmaram, N., Budaraju, S., Barba, F. J., Lorenzo, J. M., Cox, R. B., Mallikarjunan, K.,
916 & Roohinejad, S. (2018). Application of plant extracts to improve the shelf-life, nutritional and
917 health-related properties of ready-to-eat meat products. *Meat Science*, *145*, 245-255.
- 918 Ospina, M., Castro-Vargas, H. I., & Parada-Alfonso, F. (2017). Antioxidant capacity of
919 Colombian seaweeds: 1. Extracts obtained from *Gracilaria mammillaris* by means of
920 supercritical fluid extraction. *Journal of Supercritical Fluids*, *128*, 314-322.
- 921 Otero, P., Quintana, S. E., Reglero, G., Fornari, T., & García-Risco, M. R. (2018).
922 Pressurized Liquid Extraction (PLE) as an innovative green technology for the effective
923 enrichment of Galician algae extracts with high quality fatty acids and antimicrobial and
924 antioxidant properties. *Marine Drugs*, *16*, 156-170.
- 925 Pateiro, M., Barba, F. J., Domínguez, R., Sant'Ana, A. S., Khaneghah, A. M., Gavahian,
926 M., ... & Lorenzo, J. M. (2018). Essential oils as natural additives to prevent oxidation reactions
927 in meat and meat products: A review. *Food Research International*, *113*, 156-166.
- 928 Patra, J. K., Lee, S. W., Kwon, Y. S., Park, J. G., & Baek, K. H. (2017). Chemical
929 characterization and antioxidant potential of volatile oil from an edible seaweed *Porphyra*
930 *tenera* (Kjellman, 1897). *Chemistry Central Journal*, *11*, 34-44.
- 931 Pindi, W., Mah, H. W., Munsu, E., & Ab Wahab, N. (2017). Effects of addition of
932 *Kappaphycus alvarezii* on physicochemical properties and lipid oxidation of mechanically
933 deboned chicken meat (MDCM) sausages. *British Food Journal*, *119*, 2229-2239.
- 934 Plaza, M., Santoyo, S., Jaime, L., Garcia-Blairsy Reina, G., Herrero, M., Señorans, F. J.
935 et al. (2010). Screening for bioactive compounds from algae. *Journal of Pharmaceutical and*
936 *Biomedical Analysis*, *51*, 450-455.
- 937 Poyato, C., Astiasarán, I., Barriuso, B., & Ansorena, D. (2015). A new polyunsaturated
938 gelled emulsion as replacer of pork back-fat in burger patties: Effect on lipid composition,

- 939 oxidative stability and sensory acceptability. *LWT - Food Science and Technology*, 62, 1069-
940 1075.
- 941 Putnik, P., Lorenzo, J. M., Barba, F. J., Roohinejad, S., Režek Jambrak, A., Granato, D.,
942 ... & Bursać Kovačević, D. (2018). Novel food processing and extraction technologies of high-
943 added value compounds from plant materials. *Foods*, 7(7), 106.
- 944 Putnik, P., Bursać Kovačević, D., Režek Jambrak, A., Barba, F. J., Cravotto, G., Binello,
945 A., ... & Shpigelman, A. (2017). Innovative “green” and novel strategies for the extraction of
946 bioactive added value compounds from citrus wastes—A review. *Molecules*, 22(5), 680.
- 947 Quitain, A. T., Kai, T., Sasaki, M., & Goto, M. (2013). Supercritical carbon dioxide
948 extraction of fucoxanthin from *Undaria pinnatifida*. *Journal of Agricultural and Food*
949 *Chemistry*, 61, 5792-5797.
- 950 Rodrigues, D., Sousa, S., Silva, A., Amorim, M., Pereira, L., Rocha-Santos, T. A. P. et al.
951 (2015). Impact of enzyme- and ultrasound-assisted extraction methods on biological properties
952 of red, brown and green seaweeds from the central west coast of Portugal. *Journal of*
953 *Agricultural and Food Chemistry*, 63, 3177-3188.
- 954 Roohinejad, S., Koubaa, M., Barba, F. J., Saljoughian, S., Amid, M., & Greiner, R.
955 (2017). Application of seaweeds to develop new food products with enhanced shelf-life, quality
956 and health-related beneficial properties. *Food Research International*, 99, 1066-1083.
- 957 Ryu, B., Choi, I. W., Qian, Z. J., Heo, S. J., Kang, D. H., Oh, C., et al. (2014).
958 Antiinflammatory effect of polyphenol-rich extract from the red alga *Callophyllis japonica* in
959 lipopolysaccharide-induced RAW 264.7 macrophages. *Algae*, 29, 343-353.
- 960 Sasaki, K., Ishihara, K., Oyamada, C., Sato, A., Fukushi, A., Arakane, T., et al. (2008).
961 Effects of fucoxanthin addition to ground chicken breast meat on lipid and colour stability
962 during chilled storage, before and after cooking. *Asian-Australasian Journal of Animal*
963 *Sciences*, 21, 1067-1072.
- 964 Sellimi, S., Benslimam, A., Ksouda, G., Montero, V. B., Hajji, M., & Nasri, M. (2017).
965 Safer and healthier reduced nitrites turkey meat sausages using lyophilized *Cystoseira barbata*
966 seaweed extract. *Journal of Complementary and Integrative Medicine*, 15, 1-14.
- 967 Sharma, K., Mendiratta, S. K., & Sharma, B. D. (2011). Physico-chemical, sensory and
968 lipid profile of low-fat chicken nuggets incorporated with carrageenan as fat replacer.
969 *International Journal of Meat Science*, 1, 70-76.
- 970 Terme, N., Boulho, R., Kucma, J. P., Bourgougnon, N., & Bedoux, G. (2018). Radical
971 scavenging activity of lipids from seaweeds isolated by solid-liquid extraction and supercritical
972 fluids. *Oilseeds & fats Crops and Lipids*, 25, D505.
- 973 Unnikrishnan, P. S., Suthindhiran, K., & Jayasri, M. A. (2015). Antidiabetic potential of
974 marine algae by inhibiting key metabolic enzymes. *Frontiers in Life Science*, 8(2), 148-159.
- 975 Wang, F., Guo, X. Y., Zhang, D. N., Wu, Y., Wu, T., & Chen, Z. G. (2015). Ultrasound-
976 assisted extraction and purification of taurine from the red algae *Porphyra yezoensis*.
977 *Ultrasonics Sonochemistry*, 24, 36-42.

- 978 Wang, X., Li, W., Xiao, L., Liu, C., Qi, H., & Zhang, Z. (2017). *In vivo*
979 antihyperlipidemic and antioxidant activity of porphyran in hyperlipidemic mice. *Carbohydrate*
980 *Polymers*, *174*, 417-420.
- 981 Wen, L., Zhang, Z., Sun, D.-W., Sivagnanam, S. P., & Tiwari, B. K. (2019). Combination
982 of emerging technologies for the extraction of bioactive compounds. *Critical Reviews in Food*
983 *Science and Nutrition*, *16*, 1-16.
- 984 Xiao, X., Si, X., Yuan, Z., Xu, X., & Li, G. (2012). Isolation of fucoxanthin from edible
985 Brown algae by microwave-assisted extraction coupled with high-speed countercurrent
986 chromatography. *Journal of Separation Science*, *35*, 2313-2317.
- 987 Yaich, H., Ben Amira, A., Abbes, F., Bouaziz, M., Besbes, S., Richel, A., et al. (2017).
988 Effect of extraction procedures on structural, thermal and antioxidant properties of ulvan from
989 *Ulva lactuca* collected in Monastir coast. *International Journal of Biological Macromolecules*,
990 *105*, 1430-1439.
- 991 Yuan, Y., Xu, X., Jing, C., Zou, P., Zhang, C., & Li, Y. (2018a). Microwave assisted
992 hydrothermal extraction of polysaccharides from *Ulva prolifera*: Functional properties and
993 bioactivities. *Carbohydrate Polymers*, *181*, 902-910.
- 994 Yuan, Y., Zhang, J., Fan, J., Clark, J., Shen, P., Li, Y., et al. (2018b). Microwave assisted
995 extraction of phenolic compounds from four economic brown macroalgae species and
996 evaluation of their antioxidant activities and inhibitory effects on α -amylase, α -glucosidase,
997 pancreatic lipase and tyrosinase. *Food Research International*, *113*, 288-297.
- 998 Zhang, R., Yuen, A. K. L., Magnusson, M., Wright, J. T., de Nys, R., Masters, A. F., et
999 al. (2018). A comparative assessment of the activity and structure of phlorotannins from the
1000 brown seaweed *Carpophyllum flexuosum*. *Algal Research*, *29*, 130-141.
1001
1002

1003 **Figure captions**

1004 **Figure 1.** Research tendencies in "bioactive compounds from seaweeds" and "meat
1005 products with seaweeds" from 2005 until the current date. Source Scopus (search made on
1006 September 17, 2019)

1007 **Figure 2.** Overall view of the extraction technologies and applications of seaweeds and
1008 their bioactives in meat products

1009

Journal Pre-proof

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

2

Project	Objective
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 algininate- 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 (<i>Ascophyllum nodosum</i> , <i>Saccharina latissima</i> , and <i>Fucus vesiculosus</i>) 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 <i>Laminaria hyperborea</i> (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 <i>Saccharina latissima</i> and the green algae <i>Ulva</i> 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 <i>Isochrysis galbana</i> - a solution to solve the global obesity (FUCOPRO)	Production of commercial fucoxanthin from <i>Isochrysis</i> 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

3

4

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	<i>Sphaerococcus coronopifolius</i> and <i>Boergeseniella thuyoides</i>	Distilled water at 80 °C for 4 h with magnetic stirring and a solid-to-solvent ratio of 1:75 (g/mL)	<i>S. coronopifolius</i> : 25.5 g/100 g d.s. <i>B. thuyoides</i> : 17.8 g/100 g d.s.	Antiviral activity	Bouhlal et al. (2011)
Porphyran	<i>Porphyra yezoensis</i>	Distilled water at 95 °C 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	<i>Porphyra haitanensis</i>	Alga was firstly treated with diluted formaldehyde solution, and then extracted with hot water	Not specified	Antihyperlipidemic and antioxidant	Wang et al. (2017)
Fucoidan	<i>Cystoseira sedoides</i> , <i>Cystoseira compressa</i> and <i>Cystoseira crinita</i>	Depigmented seaweeds were treated with 2% aqueous solution of CaCl ₂ for 3 h	<i>C. sedoides</i> : 3.3 g/100 g d.s. <i>C. compressa</i> : 3.7 g/100 g d.s. <i>C. crinita</i> : 2.8 g/100 g d.s.	Anti-radical, anti-inflammatory and gastroprotective activities	Hadj et al. (2015)
Sulfated polysaccharides	<i>Fucus evanescens</i>	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	<i>Eisenia bicyclis</i>	0.1 M HCl for 2 h at 60 °C (two times) 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	<i>Ulva armoricana</i>	Not reported	20.5 g/100 g d.s.	Immunostimulatory activity	Berri et al. (2017)
Polyphenols	<i>Hormosira banksii</i>	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	<i>Callophyllis japonica</i>	Methanol at solid-to-solvent ratio of 1:10 (g/mL)	Not specified	Anti-inflammatory effect	Ryu et al. (2014)
Polysaccharides	<i>Sargassum muticum</i> , <i>Osmundea pinnatifida</i> , and <i>Codium tomentosum</i>	Water at 50 °C for 24 h in a shaking water bath using a solid-to-solvent ratio of 1:25 (g/mL),	<i>C. tomentosum</i> : 45 g/100 g d.s. <i>O. pinnatifida</i> : 50 g/100 g d.s. <i>S. muticum</i> : 23 g/100 g d.s.	Antioxidant, prebiotic, antidiabetic	Rodrigues et al. (2015)
Dieckol-rich polyphenols	<i>Ecklonia cava</i>	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	<i>Fucus vesiculosus</i>	Mechanical stirring using 67% acetone as solvent, at 25 °C 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	<i>Gelidium pusillum</i>	Serial extraction in 5 cycles using 0.1 M phosphate buffer as solvent (pH 6.8), for 1 hour at 4 °C (with intermittent stirring)	0.331 g/100 g d.s.	Not determined	Mittal et al. (2017)
Sulphated polysaccharide	<i>Ulva lactuca</i>	pH 2 at 80 °C, 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	and <i>Cladophora glomerata</i> , <i>Cladophora rivularis</i> and <i>Ulva flexuosa</i>	70% ethanol, for 60 min and solid-to-solvent ratio of 1:25 (g/mL)	<i>C. glomerata</i> : 6.5 µg of chlorophylls/mL extract and 1.7 µg of carotenoids/mL extract <i>C. rivularis</i> : 5 µg of chlorophylls/mL extract and 0.9 µg of carotenoids/mL extract <i>U. flexuosa</i> : 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	<i>Fucus evanescens</i>	Water, 150 W for 15 min at 23 °C	4.64 g/100 g d.s.	Anticancer activity	Hmelkov et al. (2017)
Laminarin	<i>Ascophyllum nodosum</i> and <i>Laminaria hyperborea</i>	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 .	<i>A. nodosum</i> : 5.82 g/100 g d.s. <i>L. hyperborea</i> : 6.24 g/100 g d.s.	Antioxidant and antimicrobial activities	Kadam et al. (2015a)
Phenolics, fucose and uronic aci	<i>Ascophyllum nodosum</i>	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	and <i>Sargassum vestitum</i> , <i>Sargassum linearifolium</i> , <i>Phyllospora comosa</i> , <i>Padina</i> sp., <i>Hormosira banksii</i> and <i>Sargassum podocanthum</i>	70% ethanol, 150 W for 60 min, at 30 °C	<i>S. vestitum</i> : 14.2 g GAE/100 g DS and 0.165 g FX/100 g d.s. <i>S. linearifolium</i> : 4.71 g GAE/100 g d.s. and 0.176 g FX/100 g d.s. <i>P. comosa</i> : 6.77 g GAE/100 g d.s. and	Antioxidant	Dang et al. (2018)

Phenolics	<i>Hormosira banksii</i>	70% ethanol, 150 W, at 30 °C for 60 min and solid-to-solvent ratio of 1:50 (g/mL)	0.028 g FX/100 g d.s. <i>Padina</i> sp.: 12.46 g GAE/100 g d.s. and 0.197 g FX/100 g d.s. <i>H. banksii</i> : 15.88 g GAE/100 g d.s. and 0.061 g FX/100 g d.s. <i>S. podocanthum</i> : 4.81 g GAE/100 g d.s. and 0.146 g FX/100 g d.s. 2.31 g GAE/100 g d.s.	Antioxidant	Dang et al. (2017)
Chlorophylls and carotenoids	and <i>Cladophora glomerata</i> , <i>Cladophora rivularis</i> and <i>Ulva flexuosa</i>	70% ethanol, 800 W, at 40 °C for 60 min and solid-to-solvent ratio of 1:25 (g/mL)	<i>C. glomerata</i> : 15.9 µg of chlorophylls/mL extract and 0.5 µg of carotenoids/mL extract <i>C. rivularis</i> : 5.1 µg of chlorophylls/mL extract and 0.6 µg of carotenoids/mL extract <i>U. flexuosa</i> : 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	<i>Sargassum muticum</i> , <i>Osmundea pinnatifida</i> , and <i>Codium tomentosum</i>	400 W, water at 50 °C for 60 min and solid-to-solvent ratio of 1:25 (g/mL)	<i>C. tomentosum</i> : 48.6 g/100 g d.s. <i>O. pinnatifida</i> : 49.1 g/100 g d.s. <i>S. muticum</i> : 24 g/100 d.s.	Antioxidant, antidiabetic, and prebiotic activities	Rodrigues et al. (2015)
Phycobiliproteins (R-phycoerythrin, R-PE and R-phycoyanin, R-PC) Protein	<i>Gelidium pusillum</i> <i>Ascophyllum nodosum</i>	41.97 W, phosphate buffer (0.1 M, pH 6.8) at 30 °C for 10 min and solid-to-solvent ratio of 1:10 (g/mL) 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)	0.009 g/100 g d.s. 57 g/100 g d.s.	Not determined Not determined	Mittal et al. (2017) Kadam et al. (2017)
Peptides	<i>Palmaria palmata</i>	Extraction protein was performed with sonication for 1 h at 4 °C and solid-to-solvent ratio of 1:10 (g/mL) Enzymatic hydrolysis of protein was performed using papain at 60 °C, 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	<i>Porphyra yezoensis</i>	300 W at 40.5 °C 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	<i>Gracilaria birdiae</i>	First stage of sonication: 60 W, 0.1 M of NaOH at 60 °C for 30 min. Second stage of enzymatic digestion: pH of 8, at 60 °C for 12 h	8.26 g/100 g d.s.	Antioxidant and anticoagulant	Fidelis et al. (2014)
Carbohydrates	<i>Grateloupia turuturu</i>	Power of 400 W, 1% enzymatic cocktail, at 40 °C 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	<i>Sargassum thunbergii</i>	547 W, water as solvent at 80 °C 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	<i>Ulva prolifera</i>	500 W, 0.1 M HCl at 150 °C 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	<i>Ascophyllum nodosum</i> , <i>Laminaria japonica</i> , <i>Lessonia trabeculate</i> and <i>Lessonia nigrecens</i>	Frequency of 2.45 GHz, 70% methanol at 110 °C for 15 min and solid-to-solvent ratio of 1:10 (g/mL)	<i>A. nodosum</i> : 12.46 g/100 g d.s. <i>L. japonica</i> : 20.93 g/100 g d.s. <i>L. trabeculate</i> : 5.22 g/100 g d.s. <i>L. nigrecens</i> : 9.28 g/100 g d.s.	Antioxidant, anti-hyperglycemic, anti-obesity and anti-tyrosinase	Yuan et al. (2018b)
Phenylphenols	<i>Caulerpa racemosa</i>	200 W, 60% ethanol at 50 °C 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	<i>Cladophora glomerata</i> , <i>Cladophora rivularis</i> and <i>Ulva flexuosa</i>	800 W, 70% ethanol, at 40 °C for 60 min and solid-to-solvent ratio of 1:25 (g/mL)	<i>C. glomerata</i> : 26.8 µg/mL extract <i>C. rivularis</i> : 8.5 µg/mL extract and <i>U. flexuosa</i> : 34.1 µg/mL extract	Not determined	Fabrowska et al. (2018)
Carotenoids	<i>Cladophora glomerata</i> , <i>Cladophora rivularis</i> and <i>Ulva flexuosa</i>	800 W, 70% ethanol, at 40 °C for 60 min and solid-to-solvent ratio of 1:25 (g/mL)	<i>C. glomerata</i> : 3 µg/mL extract <i>C. rivularis</i> : 1 µg/mL extract <i>U. flexuosa</i> : 2.1 µg/mL extract	Not determined	Fabrowska et al. (2018)
Fucoxanthin	<i>Undaria pinnatifida</i>	300 W, ethanol at 60 °C 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	<i>Carpophyllum flexuosum</i> ,	Water at 160 °C for 3 min and solid-to-solvent ratio of	<i>C. flexuosum</i> : 15.8 g/100	Antioxidant	Zhang et al. (2018)

	<i>Carpophyllum plumosum</i> and <i>Ecklonia radiata</i>	1:30 (g/mL)		g d.s. <i>C. plumosum</i> : 9.2 g/100 g d.s. <i>E. radiata</i> : 2 g/100 g DS		
Sulfated polysaccharides	<i>Sarcodia ceylonensis</i> , <i>Ulva lactuca</i> L., and <i>Durvillaea antarctica</i>	500 W, water at 70 °C for 51 min, and a ratio of solid-to-solvent ratio of 1:51 (g/mL).		<i>S. ceylonensis</i> : 12.49 g/100 g d.s. <i>U. lactuca</i> L.: 11.09 g/100 g d.s. <i>D. antarctica</i> : 14.21 g/100 g d.s.	Antioxidant	He et al. (2016)
Not specified Essential oil	<i>Padina pavonica</i> <i>Enteromorpha linza</i> , <i>Porphyra tenera</i>	1000 W, water at 60 °C for 2 min 40 W, for 4 h, using water as solvent and solid-to-solvent ratio of 1:10 (g/mL)		Not specified Not specified	Anti-hyaluronidase Antioxidant	Fayad et al. (2017) 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	<i>Sargassum muticum</i> , <i>Osmundea pinnatifida</i> , and <i>Codium tomentosum</i>	Cellulase, Viscozyme, Flavourzyme and Alcalase were assessed. Water at the optimum pH of each enzyme (4.5-8), at 50 °C for 24 h and solid-to-solvent ratio of 1:25 (g/mL)	<i>C. tomentosum</i> : 60 g/100 g d.b. for Cellulase and 62 g/100 g d.b. for Viscozyme <i>O. pinnatifida</i> : 54 g/100 g d.b. for cellulase and 55 g/100 g d.s. for Flavourzyme <i>S. muticum</i> : 31.3 g/100 g d.s. for Cellulase	Antioxidant, antidiabetic, and prebiotic activities	Rodrigues et al. (2015)
Protein hydrolysates	<i>Palmaria palmata</i>	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 polysaccharides and amino acid	<i>Ulva armoricana</i>	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 °C 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 antiviral	Hardouin et al., (2016)
Sulphated	<i>Ulva lactuca</i>	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	<i>Ecklonia radiata</i>	Two extraction strategies: (1) enzymatic extraction using Viscozyme + Celluclast at 50 °C for 24 h and (2) microwave-assisted enzymatic extraction at 50 °C 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	<i>Fucus serratus</i> and <i>Laminaria digitata</i>	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	<i>Undaria pinnatifida</i>	SCCO ₂ at 40 °C for 180 min and 40 MPa	38.5 mg fucoxanthin/g extract	Not determined	Quitain et al. (2013)
Pholyphenols carotenes	<i>Gracilaria mammillaris</i>	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	<i>Lessonia vadosa</i>	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 chlorophyll a	and <i>Laminaria japonica</i> Aresch	SFE was performed using 4.73% of ethanol-modified subcritical 1,1,1,2-tetrafluoroethane (R134a) as cosolvent, at 51 °C 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	<i>Undaria pinnatifida</i>	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	<i>Solieria chordalis</i> and <i>Sargassum muticum</i>	Three strategies studied: SCCO ₂ at 45 °C and 290 bar, SCCO ₂ with 2% or 8% of ethanol as co-solvent	Not specified	Free radical scavenging	Terme et al. (2018)
Fucoidan	<i>Saccharina japonica</i> , and <i>Sargassum oligocystum</i>	SCCO ₂ using 5% ethanol as co-solvent at 60 °C, 550 bar and mass ratio of spent fluid to loaded raw material of 30:1	<i>S. japonica</i> : 1.35 g/100 g d.s. <i>S. oligocystum</i> : 0.57g/100 g d.s.	Not determined	Men'shova et al. (2013)
Not specified	<i>Padina pavonica</i>	SCCO ₂ using 20% ethanol-water as co-solvent (16/4) at 30 °C for 30 min and 15MPa	Not specified	Anti-hyaluronidase	Fayad et al. (2017)
Oil containing fatty acids, phenolic compounds and fucoxanthin	<i>Saccharina japonica</i> and <i>Sargassum horneri</i>	SCCO ₂ with ethanol as co-solvent at 45 °C for 120 min and 250 bar	<i>S. japonica</i> : 1.09 g/100 g d.s. <i>S. horneri</i> : 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	<i>Fucus vesiculosus</i>	80 °C, 120 °C and 160 °C, 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	<i>Ascophyllum nodosum</i> , <i>Pelvetia canaliculata</i> , <i>Fucus spiralis</i> and <i>Ulva intestinalis</i>	80% ethanol, at 100 °C for 20 min and pressure of 1000 psi	<i>A. nodosum</i> : 66.26 μ g PE/mg <i>P. canaliculata</i> : 40.07 μ g PE/mg <i>F. spiralis</i> : 124.30 μ g PE/mg <i>U. intestinalis</i> : 20.95 μ g PE/mg	Antioxidant activities	Tierney et al. (2013)
Volatiles, fatty acids, and carotenoids (antioxidant extract)	<i>Himantalia elongata</i>	Ethanol at 200 °C for 20 min	36.91 g/100 g DS	Antimicrobial and antioxidant	Plaza et al. (2010)
Fucoesterol	<i>Lessonia vadosa</i>	Ethyl acetate, at 60 °C 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	<i>Padina pavonica</i>	Water, at 60 °C for 2 min with 2 extraction cycles and a pressure of 150 bar	Not specified	Anti-hyaluronidase	Fayad et al. (2017)

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

2

Meat product	Seaweed and form of incorporation	Dose used	Storage conditions	Main results	References
Pork liver pâté	Seaweed aqueous extracts from <i>Ascophyllum nodosum</i> , <i>Fucus vesiculosus</i> and <i>Bifurcaria bifurcata</i>	500 mg/kg	4 °C 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	<i>Fucus vesiculosus</i> extracts	250, 500, 1000 mg/kg	2 °C 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 acceptance of pork patties, especially those formulated with 500 mg/Kg of seaweed extract Color, surface discoloration and odor attributes did not improve	Agregán et al. (2019)
Cooked beef patties	<i>Himanthalia elongata</i> 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	<i>Himanthalia elongata</i> powder	3.4%	Stored at 2 °C for 12-24 h, followed by heat processing at 70 °C 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 <i>Laminaria digitata</i>	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 °C 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 <i>Laminaria digitata</i>	3 and 6 mg/mL	4 °C	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 °C 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 °C 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	Fucoanthin from <i>Cystoseira barbata</i>	0.01, 0.02 and 0.04%	4 °C 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	Fucoanthin extracts from <i>Undaria pinnatifida</i>	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	<i>Kappaphycus alvarezii</i> powder	0, 2, 4 and 6%	4 °C for 12 days	Reduced TBARs values Decreased the lightness and increased the redness values	Pindi et al. (2017)

1 **Table 4.** Effects of seaweeds and seaweed extracts on low-salt reformulated meat products
2

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 °C during 15 days	Decreases cooking loss Increases hardness Decreases cooking losses	Triki et al. (2017)
Poultry steaks	Sea Spaghetti powder	3%	Storage at 2 °C during 6 days	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 75% reduction of NaCl	Choi et al. (2015)
Meat emulsion model	Powder of Sea Spaghetti, Wakame and Nori	5.6%	Not indicated	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 °C for 152 days	Decreases thawing and cooking losses Softer texture Increases mineral content 75% reduction of NaCl	López-López et al. (2010)
Pork gel/emulsion systems	Sea Spaghetti, Wakame and Nori	2.5 and 5%	Not indicated	Increases the water and fat retention capacity Increases hardness and chewiness of cooked products Decreases springiness and cohesiveness	Cofrades et al. (2008)

3

1 **Table 5.** Effects of seaweeds and seaweed extracts on low-fat reformulated meat products
2

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 °C 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 °C 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	<i>Laminaria japonica</i> 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 °C	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	<i>Himanthalia elongata</i> powder (Sea Spaguetti)	3.4%	Stored at 2 °C for 12-24 h, followed by heat processing at 70 °C for 30 min	Increases water and fat retention capacity, hardness and elastic modulus	Fernández-Martín et al. (2009)
Frankfurters	<i>Himanthalia elongata</i>	5%	Storage at 2 °C for 41 days	Improves water and fat binding capacity Reduces lightness and redness	López-López et al. (2009)
Beef patties	Wakame powder	3%	Storage at -18 °C for 152 days	Increases the hardness and chewiness 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 °C	Total fat reduction of 41% Increase of 74.5% of the unsaturated fatty acids	Poyato et al. (2015)

1

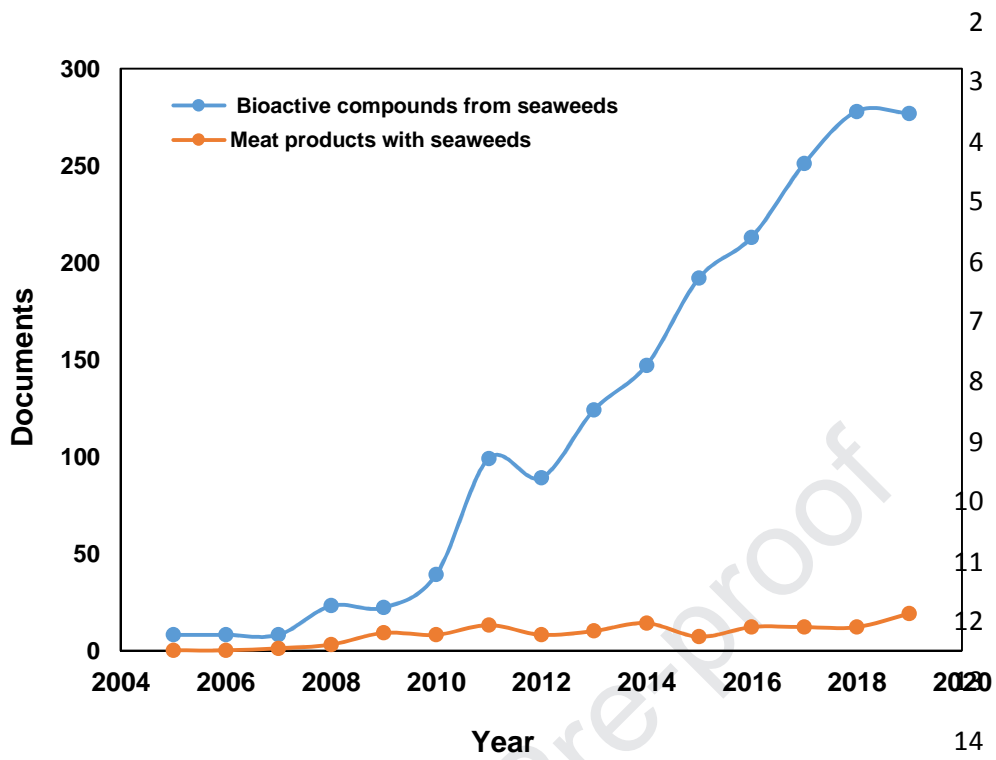


Figure 1

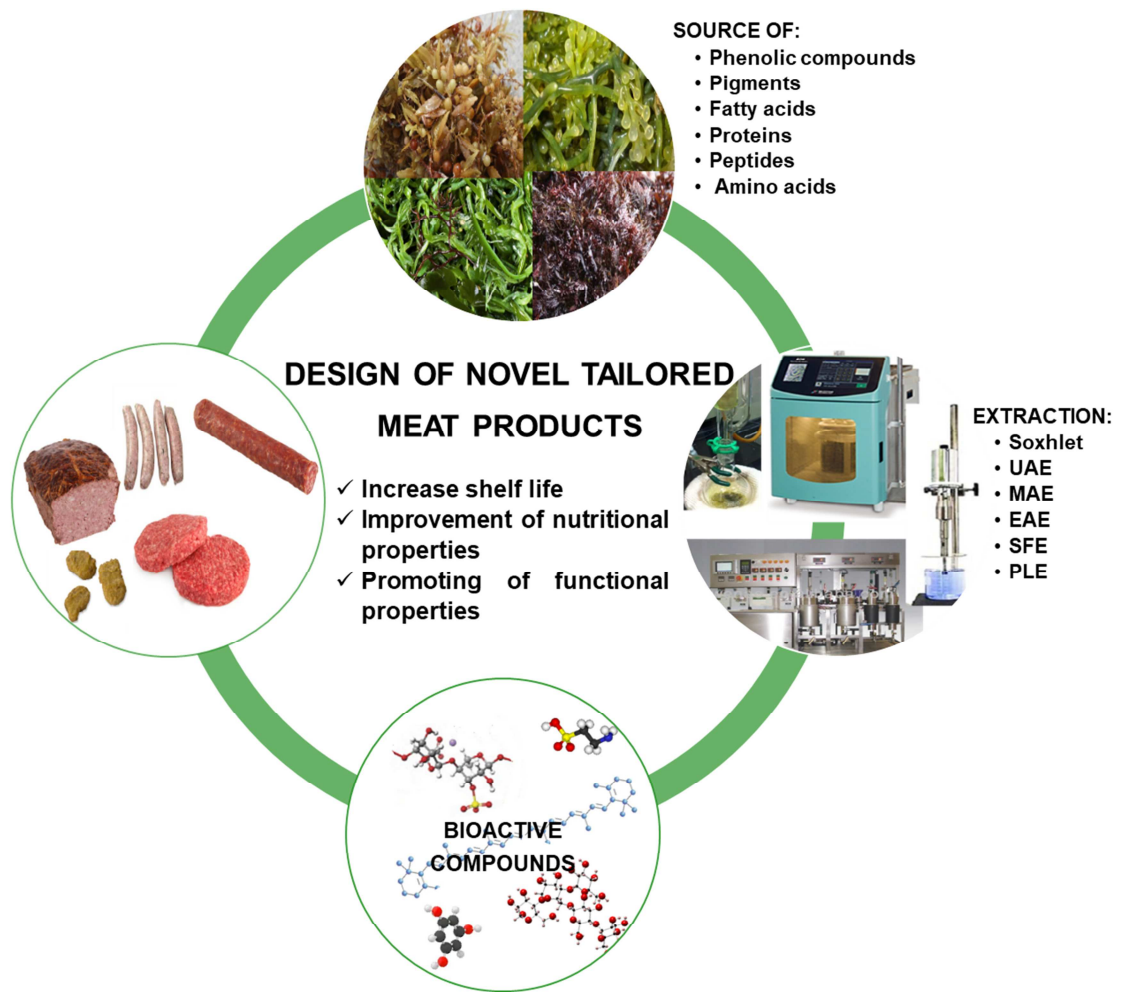
15

16

17

18

19



20

21

22

23

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

Journal Pre-proof