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Application of seaweeds to develop new food products with enhanced shelf-life, quality and health-related beneficial properties

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ABSTRACT

Edible seaweeds are a good source of antioxidants, dietary fibers, essential amino acids, vitamins, phytochemicals, polyunsaturated fatty acids, and minerals. Many studies have evaluated the gelling, thickening and therapeutic properties of seaweeds when they are used individually. This review gives an overview on the nutritional, textural, sensorial, and health-related properties of food products enriched with seaweeds and seaweed extracts. The effect of seaweed incorporation on properties of meat, fish, bakery, and other food products were highlighted in depth. Moreover, the positive effects of foods enriched with seaweeds and seaweed extracts on different lifestyle diseases such as obesity, dyslipidemia, hypertension, and diabetes were also discussed. The results of the studies demonstrated that the addition of seaweeds, in powder or extract form, can improve the nutritional and textural properties of food products. Additionally, low-fat products with less calories and less saturated fatty acids can be prepared using seaweeds. Moreover, the addition of seaweeds also affected the health properties of food products. The results of these studies demonstrated that the health value, shelf-life and overall quality of foods can be improved through the addition of either seaweeds or seaweed extracts.

1. Introduction

The consumption of marine products has been and is increasingly gaining attention, as people become more aware of the relation between diet and health. Nowadays, many new marine products have been developed and marketed, offering enhanced health benefits and the potential to decrease the risk of diseases. Selling such "functional foods" has significantly increased in Europe and other parts of the world (Annunziata & Vecchio, 2011). Moreover, marine foods and their ingredients such as fish oils, fish proteins, bioactive peptides, seaweeds, macroalgae and microalgae can be added to different food products such as meat, dairy, fish or vegetable-based products to make them more "functional" (Jimenez-Colmenero, 2007).

Among cultivated marine organisms, edible seaweeds or marine macroalgae are one of the richest sources of natural antioxidants and antimicrobials, which are traditionally consumed by humans as food (Gupta & Abu-Ghannam, 2011). Several studies have reported the antioxidant and antimicrobial influence of crude extracts from seaweeds using simple and fast *in vitro* assays (Cox, Abu-Ghannam, & Gupta, 2010; Rajauria, Jaiswal, Abu-Ghannam, & Gupta, 2010). The potential of using seaweed powder and extracts against lipid oxidation in foods and oxidative stress in target tissues has been widely studied. Moreover, the food industry is still the main market for the seaweed hydrocolloids where they are used as texturing agents and stabilizers (Bixler & Porse, 2011). Seaweed polysaccharides are a potential source of soluble and insoluble dietary fibers. These compounds exhibit higher water holding capacity than cellulosic (insoluble) fibers. Soluble dietary fibers demonstrate the ability to increase viscosity, form gels and/or act as emulsifiers (Elleuch et al., 2011).

In addition to the vast range of functional properties such as nutritional, physicochemical and textural properties that seaweeds impart to food products, many studies showed their health benefits either when they are consumed directly or after minor pre-processing as dietary supplements (Mikami & Hosokawa, 2013; Yende, Harle, &

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Chaugule, 2014). For instance, bioactive peptides isolated from fish protein hydrolysates as well as algal fucans, galactans and alginates showed anticoagulant, anticancer, and hypercholesterolemic activities (Lordan, Ross, & Stanton, 2011). On the other hand, evidences showing that these bioactive compounds have a clear health benefit present a dilemma because the effect of the compounds on the human body may be very small and not constant over a period. However, it is believed that seaweeds' bioactive components can significantly increase the health status if they are consumed throughout life as part of the daily diet (Biesalski et al., 2009).

Considering the extensive data that is available on the functional properties of seaweed and seaweed extracts, it will be interesting to review how effective these compounds have been when they are incorporated into several food products (Fig. 1). Thus, the purpose of this review is to highlight the potential applications of seaweed extracts or whole seaweeds as functional ingredients to increase the nutritional, textural, and sensorial properties of food products (e.g. meat, bakery, dairy, and other products). Moreover, the effect of seaweed addition on improving the health-related properties of the food products against different diseases (e.g. obesity, dyslipidemia, hypertension, diabetes) has been also discussed in this review.

2. Chemical composition of seaweeds

Although the detailed chemical composition of seaweeds is not well known, these marine plants have been reported to be a good source of micro- and macronutrients (Gupta & Abu-Ghannam, 2011; Kadam & Prabhasankar, 2010). Seaweeds are a rich source of micronutrient compounds such as vitamins (e.g. vitamin A, B_1, B_2, B_3, B_6, B_{12}, C, D, E, pantothenic acid and folic acid) (Kolb, Vallorani, Milanovic, & Stocchi, 2004; Ferraces-Casais, Lage-Yusty, de Quirós, & López-Hernández, 2012), sterols (Lopes et al., 2011; Lopes, Sousa, Valentao, & Andrade, 2013), and minerals (e.g. calcium, magnesium, potassium, iodine, sodium, phosphorus, nickel, chromium, selenium, iron, zinc, manganese, copper, lead, cadmium, mercury and arsenic) (Kolb, Vallorani, Milanovic, & Stocchi, 2004; Ferraces-Casais, Lage-Yusty, de Quirós, & López-Hernández, 2012; Ladra-Ramos, Domínguez-González, Moreda-Piñeiro, Bermejo-Barrera, & Bermejo-Barrera, 2005; García-Casal, Pereira, Leets, Ramírez, & Quiroga, 2007; Marsham, Scott, & Tobin, 2007; Moreda-Piñeiro et al., 2007; Patarra, Paiva, Neto, Lima, & Baptista, 2011; Peña-Rodríguez, Mawhinney, Ricque-Marie, & Cruz-Suárez, 2011). Moreover, seaweeds are known to be one of the best natural sources of iodine (Nagataki 2008; Zimmermann 2008;

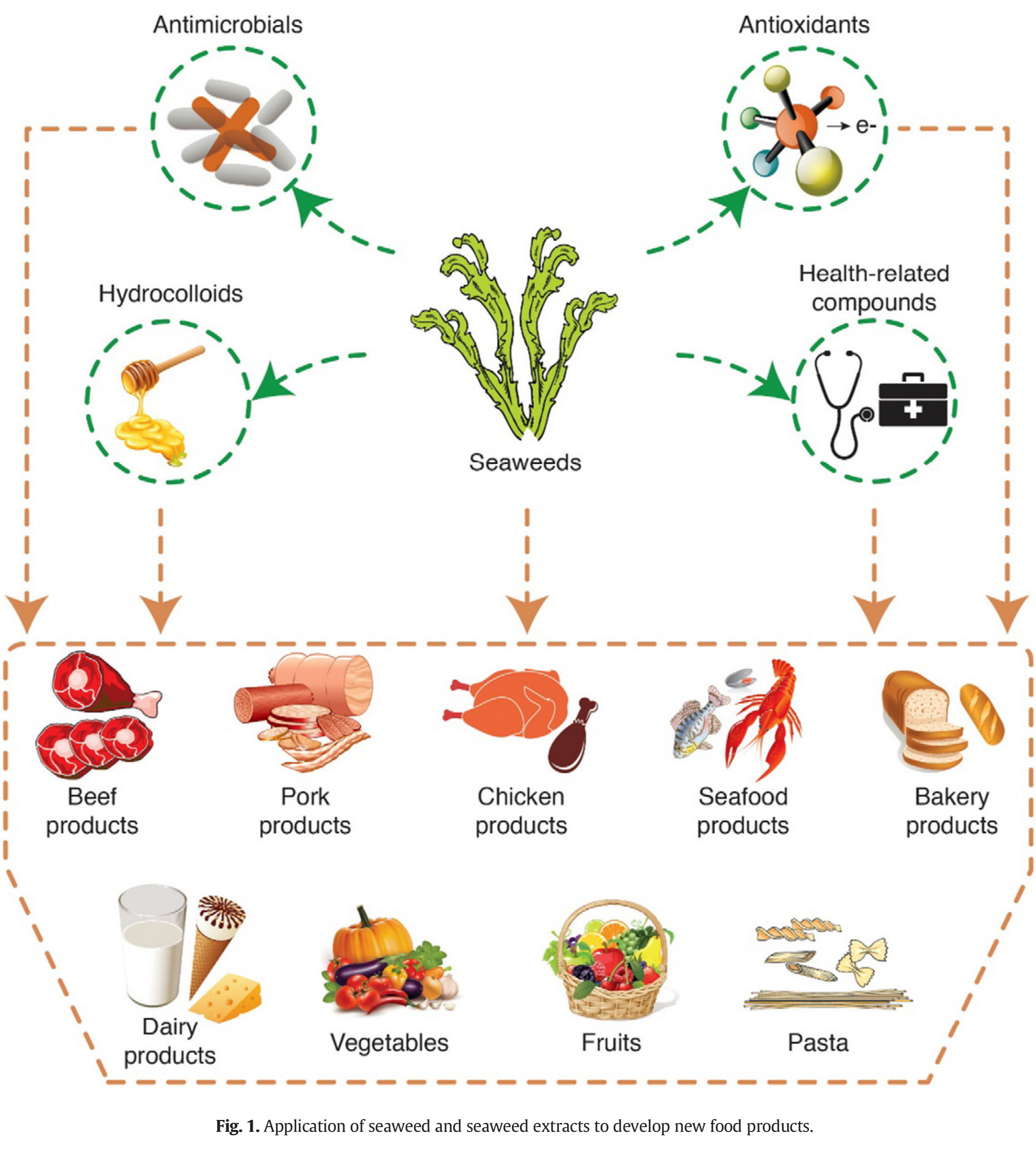

Fig. 1. Application of seaweed and seaweed extracts to develop new food products.

Mišurcová, Machů, & Orsavová, 2011; Romaris-Hortas et al., 2011). Their iodine levels differ from species to species but seaweeds have been identified to contain levels between 4.3 and 2660 mg/kg (Lee, Lewis, Buss, Holcombe, & Lawrance, 1994).

In addition to micronutrients, seaweeds are a rich source of macronutrient compounds including proteins and amino acids (essential and non-essential amino acids), carbohydrates, fibers, and fats (Dawczynski, Schubert, & Jahreis, 2007; Marsham, Scott, & Tobin, 2007; Gressler et al., 2011; Patarra, Paiva, Neto, Lima, & Baptista, 2011; Peña-Rodríguez, Mawhinney, Ricque-Marie, & Cruz-Suárez, 2011). Among the macronutrient compounds, seaweed polysaccharides have been reported to have different biological activities and can improve the structure and strength of food products (Balboa, Conde, Moure, Falqué, & Domínguez, 2013). The main sulphated polysaccharides found in seaweeds include fucoidan and laminaran in brown seaweeds, carrageenan in red seaweeds, and ulvan in green seaweeds (Costa et al., 2010).

Recently, different conventional (e.g. solvents, enzymes, etc.) and innovative technologies (e.g. ultrasounds, pulsed electric fields, etc.) have been used to isolate macro- and micro-nutrient compounds such as sulphated polysaccharides (Rodrigues et al., 2015; Trifan et al., 2015), polyphenols (Sánchez-Camargo et al., 2016), carotenoid pigments (Kanda, Kamo, Machmudah, Wahyudiono, & Goto, 2014), and sterols (Kavita, Singh, & Jha, 2014) from seaweeds. Many of these bioactive compounds have been reported to possess different biological activities and are useful in human and animal healthcare.

3. Antioxidant potential of seaweeds

Over the last years, the natural sources of antioxidant extracts from seaweeds have been progressively studied and well-developed in many countries. Previous studies reported a high correlation between the total phenolic content and the antioxidant activity (Chew, Lim, Omar, & Khoo, 2008; Rajauria, Jaiswal, Abu-Ghannam, & Gupta, 2010; Wang, Jonsdottir, & Ólafsdóttir, 2009). Seaweed phlorotannins have been suggested to scavenge free radicals, namely, superoxide, peroxyl and nitric radicals, and chelate ferrous ions (Kuda, Tsunekawa, Hishi, & Araki, 2005; Wang, Jonsdottir, & Ólafsdóttir, 2009; Chew, Lim, Omar, & Khoo, 2008; Valentão et al., 2010). It was previously reported that, compared to catechin, α-tocopherol and ascorbic acid, phlorotannins isolated from *Eisenia bicyclis* ((Kjellman) Setchell), *Ecklonia cava*, and *Ecklonia kurome* (Okamura) had higher (around 2–10 times) antioxidant activities (Shibata, Ishimaru, Kawaguchi, Yoshikawa, & Hama, 2008). Ferreres et al. (2012) evaluated the antioxidant activity and the hyaluronidase (HAase) inhibitory capacity of purified phlorotannin extracts obtained from four different brown seaweeds. A correlation between the extracts' activity and their chemical composition was found. The species had higher molecular weight phlorotannins (e.g. *Fucus spiralis* (Linnaeus)), and provided the strongest lipid peroxidation inhibitory activity and HAase inhibitory capacity. Regarding superoxide radical scavenging, *Cystoseira nodicaulis* ((Withering) M. Roberts) was the most efficient species, followed by *F. spiralis*.

In another study, the ethanol extracts of *Sargassum siliquastrum* ((Mertens ex Turner) C. Agardh) exhibited a 95% scavenging effect of DPPH free radicals at 0.5 mg/ml or greater (Cho et al., 2007). It was reported that, among the thirteen algae species investigated, *Taonia atomaria* ((Woodward) J. Agardh) extracts had the best radical scavenging activity (Nahas et al., 2007). A water extract of *Scytosiphon lomentaria* ((Lyngbye) Link) revealed strong antioxidant activity in linoleic acid peroxidation assay (around 22 mg catechin equivalents/g dry sample) (Kuda, Tsunekawa, Hishi, & Araki, 2005).

In a study reported by Chew, Lim, Omar, & Khoo (2008), the antioxidant activities of three different seaweed varieties (*Padina antillarum* ((Kützing) Piccone), *Caulerpa racemosa* ((Forsskål) J. Agardh) and *Kappaphycus alvarezzi* ((Doty) Doty ex P.C. Silva)) were assessed using several *in vitro* methods (e.g. 2,2-diphenyl-1-picrylhydrazyl (DPPH), ferric reducing antioxidant power (FRAP), ferrous ion chelating (FIC), and β-carotene bleaching (BCB)). The antioxidant activity of these seaweeds measured using BCB assay were found to be equally high. It was suggested that these seaweeds can be used as food preservatives to prevent spoilage. Similarly, it was found that natural antioxidant extracts derived from marine sources such as seaweeds may have the potential to be used in the food and pharmaceutical industries (O'Sullivan et al., 2011). Another study was conducted by Souza et al. (2012) in order to isolate polysaccharides from *Gracilaria birdiae* (Gracilariales, Rhodophyta) using aqueous extraction at 90 °C and to evaluate their antioxidant activity by DPPH free-radical scavenging assay. It was found that the seaweed polysaccharide extract had a significant antioxidant activity. The presence of sulphate groups in seaweed polysaccharides was suggested to play an important role in enhancing the antioxidant activities (Qi et al., 2005; Wang, Jonsdottir, & Ólafsdóttir, 2009).

Recently, the bioactive compounds present in ethanolic extracts from 18 macroalgae of the Portuguese coast were evaluated using gas chromatography–mass spectrometry (GC–MS) (Andrade et al., 2013). A principal component analysis (PCA) was used to evaluate the correlation between the algae chemical composition and the biological activity. Phaeophyta was found to be the most promising group of microalgae and displayed better results against enzymes and free radicals due its higher content in biologically active compounds such as phloroglucinol, mannitol, fatty acids, and fucosterol. Yangthong, Hutadilok-Towatana, & Phromkunthong (2009) collected the aqueous extracts of four marine seaweeds (*C. racemosa* var. *macrophysa*, *Gracilaria tenuistipitata* (C.F. Chang & B.M. Xia) var. *tenuistipitata*, *Sargassum* sp., and *Ulva lactuca* (Linnaeus)) from the coastal regions in Southern Thailand. The antioxidant activities were evaluated using DPPH, hydroxyl radical ($OH^{\bullet -}$) and superoxide anion ($O_2^{\bullet -}$) scavenging assays. *Sargassum* sp. was found to have the highest total phenolic compounds and also displayed the strongest DPPH and $OH^{\bullet -}$ inhibitory activities compared to the autoclaving method. The present findings suggested that these seaweed hot-water extracts can be potentially used as a source of antioxidants for either human or animal consumption. In another study, Devi, Manivannan, Thirumaran, Rajathi, & Anantharaman (2011) evaluated the total antioxidant activity, total phenolic content, and reducing power of crude methanol and diethyl ether extracts of Indian seaweeds (e.g. *Halimeda tuna* ((J.Ellis & Solander) J.V·Lamouroux), *Turbinaria conoides* ((J.Agardh) Kützing), and *Gracilaria foliifera* ((Forsskål) Børgesen)). The highest total phenolic content (1.231 ± 0.173 mg GAE/g) and total antioxidant activity (1.675 ± 0.361 mg GAE/g) were found in *T. conoides* extract. It can be concluded from the studies shown above that, antioxidant extracts from seaweeds are promising agents that can be an alternative to replace synthetic antioxidants such as butylated hydroxyl toluene (BHT) and butylated hydroxyanisole (BHA) by providing an environmentally friendly and safe source for further use in functional foods and by pharmaceutical industries.

4. Antimicrobial properties of seaweeds

The spread of drug resistant pathogens is one of the most serious threats to successful treatment of microbial diseases. Therefore, the search for new molecules and extracts with potential antimicrobial activities is highly sought (Himejima & Kubo, 1991). Seaweed and seaweed extracts have evoked interest as sources of natural products with antimicrobial activities. They have been screened for their potential uses as alternative remedies for the treatment of many infectious diseases (Abu-Ghannam, Rajauria, & Dominguez, 2013). Hundreds of works have been performed and described in the literature to investigate the antimicrobial activities of seaweed extracts, and were well reviewed (Besednova, Kuznetsova, Zaporozhets, & Zvyagintseva, 2014; Gurav, Gulkari, Duragkar, & Patil, 2008; Safhi, 2014; Singh, Kumari, & Reddy, 2015). For this reason, only some works are described in this review paper, in order to give an insight of the recent investigations in this field. For instance, the antibacterial mode of action of 1,8-dihydroxy-anthraquinone, isolated from the red algae *Porphyra haitanensis* (T.J. Chang & B.F. Zheng), against *Staphylococcus aureus* (Rosenbach) has been investigated (Wei et al., 2015). The reported results showed that the isolated molecule strongly inhibited the cell growth in the logarithmic phase, and that this antibacterial activity is related to its interaction with the cell wall and cell membrane. In fact, an increase of the permeability of the cell envelope was reported, which leads to the leakage of cytoplasm and to cell deconstruction. The authors concluded that 1,8-dihydroxy-anthraquinone represents a natural seaweed product that could be further investigated for its antibacterial activity in food safety control and drugs.

In another recent study, the antibacterial and fungicidal activities of marine macroalgae and magnoliophytea from the coast of Tunisia were investigated (Kolsi et al., 2015). Three extracts using hexane, ethyl acetate and methanol were prepared from thirteen marine species: five pheophytea, five cholorophytea, and three magnoliophytea. The antibacterial activities were tested against human pathogenic bacteria (*Escherichia coli* (T. Escherich), *Listeria monocytogenes* (Murray), *Salmonella enterica* (Lignieres), *Agrobacterium tumefaciens* ((Smith & Townsend 1907) Conn.), *Pseudomonas aeruginosa* (Schroeter), *S. aureus*, and *Micrococcus luteus* (Schroeter)), yeast (*Candida tropicalis* (Berkhout), *Saccharomyces cerevisiae* (Meyen ex E. C. Hansen)), and fungi (*Aspergillus niger* (van Tieghem)). The obtained results showed that all extracts exhibited potent antimicrobial activities, and the most important are those extracted from the brown algae. The authors concluded on the potential use of these extracts to treat some human diseases.

Similarly, the antibacterial and synergistic activity of an *E. cava* (brown alga) extract was investigated against the antibiotic-resistant species *Streptococcus parauberis* (Eom et al., 2015). For this purpose, a methanolic extract of *E. cava* was prepared then tested for its antibacterial activity against *S. parauberis*, showing good growth inhibition. In addition, it has been demonstrated that the *n*-hexane soluble fraction of the *E. cava* methanolic extract showed the highest antibacterial effect with a minimum inhibitory concentration ranging from 256 to 1024 μg/ml. The authors concluded that *E. cava* represents a great source of antibacterial molecules.

In another recent study, the efficiency of *Asparagopsis armata* (Harvey) and *Sphaerococcus coronopifolius* (Stackhouse), two species of red algae, as natural sources of antimicrobial compounds has been investigated (Pinteus et al., 2015). Three extracts using methanol, *n*-hexane and dichloromethane were prepared from 12 marine macro-algae (Rhodophyta, Chlorophyta, and Heterokontophyta divisions) from Peniche coast (Portugal) and evaluated for their antibacterial (against *Bacillus subtilis* (Ehrenberg) and *E. coli*) and fungicidal activities (against *S. cerevisiae* as model). The obtained results showed that the highest antibacterial activity against *B. subtilis* was obtained by the *A. armata* methanolic extract (10 mm, 100 μg/disc), followed by the *S. coronopifolius n*-hexane extract (8 mm, 100 μg/disc), then by the *A. armata* dichloromethane extract (12 mm, 300 μg/disc). However, no activity was noticed against *E. coli*. On the other hand, it has been shown that *S. coronopifolius* revealed high fungicidal activity against *S. cerevisiae* when applying *n*-hexane ($IC_{50} = 40.2$ μg/ml), dichloromethane ($IC_{50} = 78.9$ μg/ml), and methanolic ($IC_{50} = 55.18$ μg/ml) extracts. The authors concluded about the potential of these seaweed extracts as interesting natural sources with antimicrobial properties.

Similarly, the antimicrobial activity of macroalgae extracts from the Moroccan Atlantic coast was investigated (El Wahidi, El Amraoui, El Amraoui, & Bamhaoud, 2015). Ten marine macroalgae collected from the Moroccan's Atlantic coast were used to prepare dichloromethane and ethanolic extracts, which were tested for their antimicrobial activities against the human pathogenic bacteria: *B. subtilis*, *S. aureus*, *E. coli*, and *P. aeruginosa*, as well as against the two pathogenic yeasts: *Candida albicans* ((C.P. Robin) Berkhout) and *Cryptococcus neoformans* ((San Felice) Vuill.). The obtained results showed great and various inhibitory activities depending on the seaweed species and the solvent used. It has been shown that *Cystoseira brachycarpa* (J. Agardh), *Cystoseira compressa* ((Esper) Gerloff & Nizamuddin), *Fucus vesiculosus* (Linnaeus), and *Gelidium sesquipedale* ((Clemente) Thuret) exhibited the highest antimicrobial activities with a broad spectrum of microbial growth inhibition. The authors concluded about the promising potential of these seaweeds as sources of antimicrobial compounds.

The application of phlorotannin extracts is attractive because of their reported antifungal activity against different yeast and dermatophyte strains (Lopes, Andrade, & Valentão, 2015). Lopes et al. (2012) evaluated the antibacterial and antifungal activities of phlorotannin purified extracts, obtained from ten dominant brown seaweeds of the occidental Portuguese coast. They reported that the extracts were more effective against Gram-positive bacteria and *Staphylococcus epidermidis* (Winslow & Winslow) was found to be the most susceptible species. Regarding antifungal activity, *Trichophyton rubrum* ((Castel. (it)) Sabour.) was the most sensitive species. Phlorotannin purified extracts were demonstrated as a potent pharmacological alternative for the treatment of a wide range of microbial infections. Similar results were reported by Lopes, Pinto, Andrade & Valentão (2013) who evaluated the antifungal activity of three different brown seaweeds. The purified phlorotannin extracts displayed fungistatic and fungicidal activity against yeast and dermatophytes, respectively.

Furthermore, laminarin extracted by ultrasound from the Irish brown seaweeds *Ascophyllum nodosum* (Linnaeus) and *Laminaria hyperborea* ((Gunnerus) Foslie) was tested for its antimicrobial activity (Kadam et al., 2015). Ultrasound-assisted extraction of laminarin was carried out using 60% ultrasonic power amplitude and 0.1 M hydrochloric acid, during 15 min. High concentrations of laminarin (5.82% and 6.24%, dry weight basis, from *A. nodosum* and L. *hyperborea*, respectively) were recorded. After purification, laminarin fractions were tested for their antibacterial activities, showing great bacterial growth inhibition against *S. aureus*, *L. monocytogenes*, *E. coli*, and *S. typhimurium*.

5. Hydrocolloid properties of seaweeds

Hydrocolloids are generally employed for their physical functions in stabilizing emulsions, viscous behavior, gelation, suspensions and foams, and control of crystal growth. The viscosity depends considerably on the preparation method. High temperature is particularly adverse, and the pH needs to be between 6 and 7 (Chapman, 2012). Seaweeds provide numerous several hydrocolloids to the food or pharmaceutical industries (Evans & Critchley, 2014). Hydrocolloid content in seaweeds is influenced by numerous biological, physical, and environmental factors (i.e. harvest period, species, and extraction method), which could have a significant impact on the functional properties of the polysaccharides (Rioux & Turgeon, 2015). Most of the hydrocolloids found in seaweeds are located in the cell wall. The most important are agar, alginates, and carrageenan.

Agar has been used since the seventeenth century in Japan (Armisen, 1995). This hydrocolloid is mainly extracted from the red algae genera *Gelidium* and *Gracilaria* (McHugh, 2003), widespread around the coasts of Chile, India, Japan, Madagascar, Mexico, Morocco, Senegal, Spain, Philippines, Portugal, and the southern United States (McHugh, 1991). *Gelidium* and *Gracilaria* cell walls hold around 20–30% and 15–20% of agar, respectively (Freile-Pelegrín, Robledo, & García-Reina, 1995; Santelices & Doty, 1989). Other genra such as *Pterocladia* (mainly found in Portugal and New Zealand) and *Gelidiella* (found in Egypt, Madagascar, and India) are also used as sources of agar (Rioux & Turgeon, 2015). Agar is mainly used for its thickening and gelling properties. It has the ability to hold high amounts of soluble solids such as sugars. Due to its high melting temperatures, as well as its ability to hold into sugar to prevent crystallization, agar is highly sought in the food industry to prepare icings and bakery glazes (Kohajdová & Karovičová, 2009). The low gel strength matrix formed by agar is a property that makes its use feasible in a wide range of applications, including in liquid and spreadable foods (e.g. soft-texture confectionery)

(Kowalski, Lukasiewicz, Juszczak, & Sikora, 2011), as fat replacers, as cryoprotectants that minimize the damages occurring during the freezing/thawing process (Pereira-Pacheco, Robledo, Rodríguez-Carvajal, & Freile-Pelegrín, 2007), and as edible films (The, Debeaufort, Voilley, & Luu, 2009).

The most widely produced algal polysaccharides are alginates, also called alginic acid or algin. They are extracted from the cell walls of brown seaweeds (Kohajdová & Karovičová, 2009). Alginate is mainly composed of 1,4-β-D-mannuronic acid and α-L-guluronic acid, representing thus a linear polymer. This composition may differ from a variety to another. *A. nodosum*, for example, contains 60% mannuronic acid and 40% guluronic acid (Qin, 2008). Unlike agar, alginates do not melt at high temperatures, and form cross linked gels. They are therefore used in several restructured meat and vegetable products (Bixler & Porse, 2011), as well as baked products (Upadhyay, Ghosal, & Mehra, 2012). Some other food applications of alginate include its use alone or in combination with other hydrocolloids, especially in ice creams and frozen desserts (Haghighimanesh & Farahnaky, 2011; Patel, Jana, Aparnathi, & Pinto, 2010), as well as in reduced fat products, where it stabilizes the mixtures and provides higher viscosity, longer melting time and better organoleptic properties (Patel, Jana, Aparnathi, & Pinto, 2010). It has been reported that alginate has an appetite regulator potential and thus could be used as a supplement (Jensen, Knudsen, Viereck, Kristensen, & Astrup, 2012). However, its incorporation into breakfast bars does not show significant differences as an appetite suppressant, compared to the control (Mattes, 2007). Alginate was also found to be efficient as a coating film in microwave cooked chicken nuggets, improving the heat distribution and thus shortening the cooking time (Albert, Salvador, & Fiszman, 2012). Sodium alginate was also used as a coating agent of bream, showing great results with additional antioxidant capacity, which could retard the decay of the fish and improve its shelf-life (Song, Liu, Shen, You, & Luo, 2011). Coating foods with alginate improved the sensory quality and reduced the loss of water. It has also been reported that adding alginate to melon acts as a carrier for antimicrobials, which improved its shelf-life (Raybaudi-Massilia, Mosqueda-Melgar, & Martín-Belloso, 2008). Alginate was also applied as a carrier for the antibrowning agents such as ascorbic acid and citric acid, which preserved the color of fresh cut Kent mangoes and improved the antioxidant potential (Robles-Sánchez, Rojas-Graü, Odriozola-Serrano, González-Aguilar, & Martin-Belloso, 2013).

Carrageenans constitute a class of sulphated polysaccharides that are synthesized in red seaweeds. The sulphate groups define the carrageenans by their number and position on repeating galactose units. The ability to form networks with milk proteins, even at low concentrations of 0.01%, constitutes one of the most useful properties of carrageenans (Bixler & Porse, 2011). Due to their gelling, emulsifying, thickening and stabilizing properties, carrageenans and semi-refined carrageenans are usually used in the food industry. Carrageenans are commonly used as an ingredient in dairy products such as ice cream (Haghighimanesh & Farahnaky, 2011), yoghurt (Ayub, 2004), cheese (Černíková et al., 2010), and milk based products (Bixler, Johndro, & Falshaw, 2001). Some other works reported the use of carrageenans in bakery products such as bread (Shon, Yun, Shin, Chin, & Eun, 2009), and as a coating film to extend the shelf-life of fresh chicken breast (Seol, Lim, Jang, Jo, & Lee, 2009).

6. Effect of seaweeds and seaweed extract addition on the nutritional, textural, and organoleptic properties of food products

6.1. Nutritional, textural, and organoleptic properties

6.1.1. Meat products

Over the past decades, meat products have been under many investigations due to the associations reported between their consumption and the risk of different diseases (e.g. ischaemic heart disease, cancer, hypertension and obesity). Therefore, preparation of meat-based functional foods is being seen as an opportunity to improve the image of meat, address consumer needs and update the nutritional and dietary goals (Jiménez-Colmenero, 2007). This condition is prompting the emergence of new "healthier" meat products. Most physiologically active substances come from plants, and when combined with other foods such as meat, they can help provide a food with functional effects. Generally, meat is low in dietary fiber; thus, adding ingredients containing high fiber content such as seaweeds to common meat products would be beneficial. Up to now, several studies evaluated the effect of seaweeds and seaweed extract incorporation on nutritional, textural and organoleptic properties of meat products (e.g. pork, beef, and fish products) (Table 1).

6.1.1.1. Pork products.

Recently, the anti-oxidative potential of laminarin (L), fucoidan (F), and an L/F seaweed extract was evaluated in pork homogenates and in horse heart oxymyoglobin (Moroney, O'Grady, Lordan, Stanton, & Kerry, 2015). The DPPH activity of fresh and cooked minced pork containing L, F, and L/F, as well as the bioaccessibility post *in vitro* digestion was measured, and the theoretical cellular uptake of antioxidant components of L/F was examined in a transwell Caco-2 cell model. Fucoidan was found to be a more potent free radical scavenging antioxidant than laminarin due to the existence of sulphate groups and anionic charge. Moreover, cooking and digestion processes strongly affected the antioxidant potential of F and L/F. Compared to F, the L/F extract revealed higher antioxidant activity in minced pork meat, after cooking and post digestion. A decrease of 44.15% and 36.63% in DPPH antioxidant activity after 4 and 20 h, respectively, showed theoretical absorption of L/F antioxidant compounds. The results of this study demonstrated the feasibility of using brown seaweed *Laminaria digitata* ((Hudson) J.V·Lamouroux) extracts containing fucoidan to increase the antioxidant activity of functional cooked meat products and improving the human antioxidant defense systems (Moroney, O'Grady, Lordan, Stanton, & Kerry, 2015).

A similar study was conducted by Moroney, O'Grady, O'Doherty, & Kerry (2013) who investigated the effect of addition of seaweed extract containing polysaccharides (L and F) on the quality and shelf-life of fresh and cooked minced pork patties. A spray-dried seaweed extract containing L (9.3%) and F (7.8%) (L/F extract) from seaweed was directly added to minced pork at different levels (e.g. 0.01%, 0.1% and 0.5% (*w*/*w*)). Fresh and cooked minced pork patties were stored for up to 14 days at 4 °C in modified atmosphere packs containing 80% O_2:20% CO_2 and 70% N_2:30% CO_2, respectively. It was found that addition of seaweed extract did not improve the quality parameters of the fresh minced pork patties. As a function of concentration, the L/F extract decreased the surface redness (a^* values) of fresh patties. The L/F extract (0.5%) exhibited the greatest lipid pro-oxidant activity in fresh patties and significantly reduced the lipid oxidation in cooked patties, which was observed to be related to the pro-oxidant components (sodium, copper, and iron) found in the extract. Moreover, reduced lipid oxidation obtained in cooked pork patties containing the L/F extract (0.5%) proved that heating can increase the antioxidant capacity of seaweed extracts in muscle foods and improve quality parameters probably due to the Maillard reaction and formation of brown melanoidins with antioxidant functionality. Also, no effect on the color, lipid oxidation, texture or sensorial acceptance of pork patties was observed by addition of the L/F extract at a level of 0.01%.

In another study, the effect of natural additives extracted from tea, grape, chestnut, and seaweeds (*U. lactuca* and *Ulva rigida* (C. Agardh)) on the shelf-life of modified atmosphere-packaged pork patties was investigated (Lorenzo, Sineiro, Amado, & Franco, 2014). Seaweed extracts were obtained from the acid hydrolysis liquors. Color, pH, lipid oxidation, and microbial spoilage parameters of raw minced porcine patties were examined during 20 days storage in modified atmosphere packs and compared with BHT and a control batch. Addition of seaweed

Table 1
Effect of edible seaweeds and seaweed extracts addition on food properties.

Food product	Type of seaweed	Seaweed added	Type of effect	Reference
Pork products	*Laminaria digitate*	Seaweed extracts: 3 and 6 mg/ml	- Laminarin had no antioxidant activity. - The L/F extract had higher antioxidant activity than F, after cooking and post digestion of minced pork. - A decrease of 44.15% and 36.63% in DPPH antioxidant activity after 4 and 20 h respectively, demonstrated the theoretical uptake of L/F antioxidant compounds. - Seaweed extracts containing F increased the antioxidant activity of the functional cooked meat products.	Moroney, O'Grady, Lordan, Stanton, & Kerry (2015)
		Seaweed extracts: containing L (9.3%) and F (7.8%) at different levels (0.01%, 0.1% and 0.5% (*w*/*w*))	- Addition of seaweed extract did not improve the quality parameters of the fresh minced pork patties. - The L/F extract (0.5%) resulted in the greatest lipid pro-oxidant activity. - No effect on the color, lipid oxidation, texture or sensorial acceptance of pork patties was observed by adding L/F extract at a level of 0.01%.	Moroney, O'Grady, O'Doherty, & Kerry (2013)
	Ulva lactuca and *Ulva rigida*	Seaweed extracts: 1000 mg/kg	- Seaweed extract addition did not affect the pH and microbial growth and delayed the metmyoglobin formation. - Compared to the seaweeds, grape and tea extracts were more effective against lipid oxidation.	Lorenzo, Sineiro, Amado, & Franco (2014)
	Sea Spaghetti (*Himanthalia elongate*)	Seaweed powder: 3.4%	- Seaweed addition was effective at reinforcing water/oil retention capacity, hardness and elastic modulus. - Addition of seaweed alginates prevented thermal denaturation of a considerable protein fraction. - Glass transition temperatures in the range of 55–65 °C was confirmed.	Fernandez-Martin, Lopez-Lopez, Cofrades, & Colmenero (2009)
	Sea Spaghetti (*Himanthalia elongata*), Wakame (*Undaria pinnatifida*), and Nori (*Porphyra umbilicalis*)	Seaweed powder: 5.6%	- Seaweeds addition enhanced the n-3 PUFA but reduced the n-6/n-3 PUFA ratio. - Nori and Wakame addition reduced the thrombogenic index - The concentrations of K, Ca, Mg and Mn were increased. - Addition of Nori enhanced the levels of amino acids. - The samples that contained Sea Spaghetti had higher antioxidant capacity.	López-López et al. (2009)
	Sea Spaghetti (*Himanthalia elongata*), Wakame (*Undaria pinnatifida*), and Nori (*Porphyra umbilicalis*)	Seaweed powder: 2.5% and 5.6% dry matter	- The water- and fat-binding properties were improved - Hardness and chewiness of the cooked products with added seaweed were higher, while springiness and cohesiveness were lower. - Seaweeds addition improved the health benefits of the products by providing dietary fibers and other bioactive components such as antioxidant polyphenols or carotenoids.	Cofrades, López-López, Solas, Bravo, & Jiménez-Colmenero (2008)
Frankfurters and breakfast sausages	Sea Spaghetti (*Himanthalia elongata*)	Seaweed powder: 3.3%	- Combination of seaweed/konjac gel enhanced cooking loss and decreased the emulsion stability in the gel/emulsion systems. - Adding seaweeds and konjac glucomannan provided healthier meat products with lower fat and salt contents. - The physicochemical and sensory characteristics were conditioned when pork backfat was replaced by konjac gel and seaweed was added.	Jiménez-Colmenero et al. (2010)
		Seaweed powder: 5.5%	Although adding seaweed had little impact on the lipid and amino acid profiles, it produced low-sodium frankfurters with high fiber content, better Na/K ratios and rich in Ca.	López-López, Cofrades, Ruiz-Capillas, & Jiménez-Colmenero (2009)
		Seaweed powder: 5%	- The water and fat binding properties improved, lightness and redness decreased and hardness and chewiness of low-fat frankfurters were enhanced. - Seaweed addition resulted in less acceptable products, due to the special flavor of the seaweed. - Shelf-life stability was not affected by the presence of seaweed.	López-López, Cofrades, & Jiménez-Colmenero (2009)
	Sea tangle (*Lamina japonica*)	Seaweed powder: 1, 2, 3, and 4%	- No difference in moisture, protein, and fat contents among the control group and the treatments was found. - The L* and a* values decreased, cooking loss and emulsion stability improved, and hardness, gumminess, and chewiness of the products were increased. - The breakfast sausage containing 1% sea tangle powder had the best physicochemical and sensory properties and the highest overall acceptability.	(Kim et al., 2010)
Beef products	Sea Spaghetti (*Himanthalia elongata*)	Seaweed: 10–40% (w/w)	- Seaweed addition to the patties reduced the cooking losses and increased the tenderness (≈50%), dietary fiber level, total phenolic content, and DPPH radical scavenging activity. - Microbiological counts and lipid oxidation were lower in patties containing seaweed. - Patties prepared with 40% seaweed had the highest overall acceptability due to the texture and mouthfeel improvement.	Cox & Abu-Ghannam (2013a, b)

(continued on next page)

Table 1 (*continued*)

Food product	Type of seaweed	Seaweed added	Type of effect	Reference
	Wakame (*Undaria pinnatifida*)	Seaweed: 3% dry matter	- Addition of Wakame and olive o/w emulsion improved the binding properties and the cooking retention values of moisture, fat, fatty acids and ash. - Healthier beef patty was produced by replacing animal fat with olive-in-water emulsion and/or addition of Wakame.	López-López et al. (2011)
			- Patties prepared with seaweed had less thawing and cooking losses and were softer than those without seaweed. - Incorporation of seaweed changed the microstructure of the products through formation of alginate chains. - Combination of Wakame and olive o/w emulsion provided good technological, sensory and nutritional properties as well as physiological benefits in beef patties.	López-López, Cofrades, Yakan, Solas, & Jiménez-Colmenero (2010)
Chicken products	Sea Spaghetti (*Himanthalia elongata*)	Seaweed: 3% dry matter	- Seaweed addition slightly increased the purge loss but decreased the cooking loss. - Products prepared by seaweed had higher levels of total viable counts, lactic acid bacteria, tyramine and spermidine. - All products were found to be acceptable by a sensory panel and no important changes were observed during chilled storage. - Seaweed incorporation was found to be helpful to maintain the desired properties in poultry steaks with low salt content.	Cofrades, López-López, Ruiz-Capillas, Triki, & Jiménez-Colmenero (2011)
	Wakame (*Undaria pinnatifida*)	Seaweed extracts: 200 mg/kg	- Fucoxanthin supplementation enhanced redness and yellowness in ground chicken breast meat, and inhibited lipid peroxidation in chilling storage after cooking. - Fucoxanthin was found to be a potent ingredient for the improvement of the appearance and shelf-life of chicken meat and its products.	Sasaki et al. (2008)
Seafood products	*Fucus vesiculosus*	Seaweed extracts: 3.7 and 3.8 g per 100 g of dough for the aqueous and ethanol extracts, respectively.	- Addition of aqueous and ethanol seaweed extracts didn't influence lipid oxidation nor the quality of the products. - No off-flavor was observed in any of the samples and low scores in rancid odor and flavor were reported.	Dellarosa, Laghi, Martinsdóttir, Jónsdóttir, & Sveinsdóttir (2015)
		Seaweed extracts: 300 mg PGE/kg	- The *in vitro* experiments showed high reducing capacity, high DPPH radical scavenging properties and a high oxygen radical absorbance capacity of the seaweed extract. - Application of seaweed extract acted against lipid oxidation in fish muscle foods.	Jónsdóttir et al. (2015)
		Seaweed extract and fractions: 300 mg/kg	- Phlorotannin-enriched fraction had higher inhibitory impact on lipid peroxidation than crude 80% ethanol extracts. - The effectiveness of a 300 mg/kg level of a phlorotannin-enriched sub-fraction was comparable to that of 100 mg/kg propyl gallate. - The potential of using oligomeric phlorotannins as novel natural antioxidants in fish and fish products was highlighted.	Wang et al. (2010)
	Cochayuyo, *sea lettuce*, *ulte*, and *red luche*	Seaweed extracts: 30 ml of covering liquid prepared from 500 g of each seaweed in 2 L of distilled water	- The secondary peroxidation in canned salmon was decreased, which was accompanied by a higher PUFA and astaxanthin content retention, and lower scores for oxidized odors. - The possibility of using seaweed extracts as covering liquid for preservation of canned Atlantic salmon, through inhibiting lipid peroxidation, was demonstrated.	Ortiz, Vivanco, & Aubourg (2014)
	Nori (*Porphyra tenera*) and Hijiki (*Hijikia fusiformis*)	Seaweed extracts: 25 and 50 g GAE/g of minced tilapia	- No effect on the chemical composition of the minced tilapia was observed. - The seaweed extracts showed inhibitory influence on total volatile base nitrogen. - No differences in the rancid aroma and only minor differences in the color of the products were detected by the sensory panel. - No bacterial counts during 180 days of frozen storage was observed.	Ribeiro et al. (2014)
	Eucheuma	Seaweed powder: 5, 7.5, 10, 12.5 and 15%	Seaweed powder was incorporated into the fish cutlet up to 10% level without undesirably affecting the appearance, texture and acceptability of the final product.	Senthil, Mamatha, & Mahadevaswamy (2005)
Bread	*Palmaria palmata*	Seaweed protein hydrolysate: 4%	Incorporation of 4% *Palmaria palmate* protein hydrolysate to the wheat bread control did not influence the texture or sensory properties of the bread.	Fitzgerald et al. (2014)
	Kappaphycus alvarezii	Seaweed powder: 2–8%	- Seaweed addition increased the water absorption of the dough and other farinograph parameters. - Addition of seaweed powder reduced stickiness properties. - Bread prepared with seaweed composite flour had higher values of firmness.	Mamat et al. (2014)

Table 1 (*continued*)

Food product	Type of seaweed	Seaweed added	Type of effect	Reference
	Sea Spaghetti (*Himanthalia elongata*)	Seaweed powder: 5–15%	- Maximum phytochemical constituents and acceptable edible texture and color in breadsticks were obtained using 17.07% seaweed and 21.89% white flour. - The highest levels of total dietary fiber (7.95%) and phytochemicals (total phenolic content: 138.25 mg GAE/100 g db and DPPH: 65.01%) were obtained in the optimized sample.	Cox & Abu-Ghannam (2013a, b)
	Myagropsis myagroides	Seaweed extracts: 0.5, 1 and 2%	- The total microbial count in breads made with 2% seaweed extract was decreased. - Increased the quantity of seaweed extract, decreased the lightness and redness and enhanced the yellowness of the breads. - The breads containing 0.5% seaweed extract were more acceptable.	Lee et al. (2010)
Noodle	*Monostroma nitidum*	Seaweed powder: 3 and 6%	- Noodles prepared with 6% seaweed had higher cooking yield. - Seaweed addition produced samples with less tensile strength. - The lowest extensibility was observed in the samples that contained the highest level of seaweed and cuttlefish paste. - Higher water absorption by the seaweed caused softer and spongier textural intensities in the noodles.	Chang, Chen, & Hu (2011)
		Seaweed powder: 4, 6, and 8%	- Higher cooking yields were observed in the noodles. - Softer and spongier textural intensities were obtained. - Textural parameters of noodles were affected not only by addition of eggs and seaweed powder, but also by cooking properties.	Chang & Wu (2008)
Pasta	Wakame (*Undaria pinnatifida*)	Seaweed powder: 100:0; 95:5.0; 90:10; 80:20 and 70:30 (semolina/wakame; w/w)	- Pasta prepared with 10% seaweed had better quality score than 20% level. - Incorporation of seaweed into the pasta improved amino acid and fatty acid profile and the nutritional value of the product. - Fucoxanthin was not affected by the rigorousness of pasta making process and cooking step. - Gluten matrix formation was obtained up to a concentration of 20% seaweed.	Prabhasankar et al. (2009)
Milk	*Ascophyllum nodosum* and *Fucus vesiculosus*	Seaweed extracts: 0.25 and 0.5%	- Water-prepared extracts were more acceptable than ethanolic extracts. - Seaweed extracts were stable in milk and had varying degrees of antioxidant activity before and after *in vitro* digestion. - Addition of seaweed extracts improved the certain milk quality and shelf-life characteristics.	O'Sullivan et al. (2014)
Instant spice	*Eucheuma* (*Kappaphycus alvarezzi*)	Seaweed powder: 15, 20 and 25%	- Incorporation of seaweed powder to spice adjunct enhanced the ash, protein, crude fiber, vitamin E, niacin, vitamin B_2, and lower amount of vitamin B_1 and vitamin A. - Addition of seaweed up to 20% had high consumer acceptability.	Senthil, Mamatha, Vishwanath, Bhat, & Ravishankar (2011)
Pakoda	*Enteromorpha*	Seaweed powder: 5, 7.5, 10, 12.5 and 15%	- Increase in seaweed level enhanced the ash, protein, total dietary fiber, calcium, and iron contents. - Addition of seaweed increased the reducing power and reduced free radical-scavenging activity and the total phenol content. - Pakoda containing seaweed up to 7.5% was sensorily acceptable.	Mamatha, Namitha, Senthil, Smitha, & Ravishankar (2007)

L: laminarin; F: fucoidan; DPPH: 2,2-diphenyl-1-picrylhydrazyl; PUFA: polyunsaturated fatty acids; O/W: oil in water emulsion; PGE: phloroglucinol equivalents; GAE: gallic acid equivalents.

extract did not significantly affect the pH and microbial growth and delayed metmyoglobin formation compared to the control. Compared to the seaweeds and chestnut, grape and tea extracts were found to be more effective against lipid oxidation due to their higher concentrations in polyphenolic compounds and more intensive antioxidant activities.

The effect of Sea Spaghetti seaweed and replacing the animal fat with olive oil or a konjac gel on pork meat batter gelation was previously investigated (Fernandez-Martin, Lopez-Lopez, Cofrades, & Colmenero, 2009). Addition of Sea Spaghetti seaweed in all formulations was found to be highly effective for reinforcing water/oil retention capacity, hardness and elastic modulus. Standard and modulated differential scanning calorimetry (DSC and MDSC, respectively) as well as dynamic rheological thermal analysis (DRTA) were applied to *in situ* simulate the batter gelation process. Application of DSC showed that addition of Sea Spaghetti alginates could prevent the thermal denaturation of a considerable protein fraction. Moreover, glass transition temperatures in the range of 55–65 °C was confirmed by MDSC. However, the application of DRTA and TPA showed much stronger alginate-type gels. It was concluded that in addition to health benefits (reducing the fat content, and inclusion of dietary fiber or some bioactive compounds) and economic considerations, the use of some non-meat ingredients can provide valuable information for formulating novel protein mixed gels appropriate in the production of comminuted or restructured meat-like products.

In 2009, another study evaluated the effect of edible seaweeds (e.g. Sea Spaghetti (*Himanthalia elongata* ((Linnaeus) S.F. Gray), Wakame (*Undaria pinnatifida* ((Harvey) Suringar), and Nori (*Porphyra umbilicalis* (Kützing))) addition at a concentration of 5.6%, on fatty acid composition, amino acid profile, protein score, mineral content, and antioxidant capacity in low-salt meat (post-rigor pork meat and pork backfat) emulsion model systems (López-López et al., 2009). It was reported that seaweed addition could enhance the *n*-3 polyunsaturated fatty acid (PUFA) content but reduce the *n*-6/*n*-3 PUFA ratio. Incorporation of Nori and Wakame into the systems significantly reduced the thrombogenic index. Compared to the control samples, meat systems prepared with added seaweeds had lower sodium contents. Generally, the concentrations of K, Ca, Mg and Mn were increased by adding the seaweeds to the products. Unlike Wakame and Sea Spaghetti, addition of Nori enhanced the levels of serine, glycine, alanine, valine, tyrosine, phenylalanine, and arginine in the model systems. Moreover, Sea Spaghetti inclusion increased the sulphur amino acid score by 20%. Also, the antioxidant capacity of the systems and their polyphenol content were increased by addition of seaweeds containing soluble polyphenolic compounds, being especially important in the samples containing Sea Spaghetti.

A similar study was carried out by Cofrades, López-López, Solas, Bravo, & Jiménez-Colmenero (2008) who evaluated the effects of three edible seaweeds (Sea Spaghetti (*H. elongata*), Wakame (*U. pinnatifida*), and Nori (*P. umbilicalis*)) at two different concentrations (2.5% and 5.6% dry matter) on the physicochemical and morphological characteristics of gel/emulsion meat systems. Seaweed addition was shown to improve the water- and fat-binding properties except in the case of Nori added at 2.5%. Compared to the control samples, hardness and chewiness of the cooked products with added seaweed were higher, while springiness and cohesiveness were lower. The type of seaweed influenced the color changes in meat systems. Moreover, depending on the type of seaweeds added, the morphology of the sample was varied due to the differences in the physicochemical characteristics of the seaweed powder used. Samples prepared with brown seaweeds (e.g. Sea Spaghetti and Wakame) had similar behavior and were different from the products formulated with red seaweed (e.g. Nori). Thus, it was concluded that the addition of seaweeds to the meat products, prepared by post-rigor pork meat and fresh pork backfat, is a good strategy to improve the potential health-beneficial properties by providing dietary fibers and other bioactive components such as antioxidant polyphenols or carotenoids.

Nowadays, there is a particular interest in consuming breakfast and frankfurter sausages, and these products have an important market in the world. However, these types of sausages contain high fat levels (as much as 30%) and lipid profiles, which diverge from dietary goals. Up to now, several studies evaluated the feasibility of using edible seaweeds on preparation of low-fat frankfurters, thus containing less calories and less saturated fatty acids (SFA).

For instance, the effect of Sea Spaghetti (*H. elongata*), on the physicochemical (emulsion stability, cooking loss, color, texture, residual nitrite, and microstructure) and sensory characteristics of reduced- and low-fat, low-salt frankfurters prepared with konjac gel as a fat substitute was investigated (Jiménez-Colmenero et al., 2010). Post-rigor pork meat (mixture of *M. biceps femoris*, *M. semimembranosus*, *M. semitendinosus*, *M. gracilis* and *M. adductor*) and fresh pork backfat were used in the formulation. Incorporation of a combination of Sea Spaghetti/konjac gel (accompanied by decrease in salt concentration) significantly enhanced cooking loss and decreased emulsion stability in the gel/emulsion systems. Compared to other samples, addition of Sea Spaghetti/konjac gel decreased the lightness (L*) and redness (a*) values and increased the yellowness (b*). Depending on the proportion of konjac gel applied in the formulation, the effect of adding seaweed on the texture parameters of low-salt frankfurters was found to be different. Moreover, morphological variations in sausage microstructure were observed when fat content was decreased and konjac gel was increased. Incorporation of a combination of Sea Spaghetti/konjac gel resulted in the formation of a more heterogeneous structure. It was concluded that there were some interferences between the effects provided by seaweed and konjac gel on the properties of the frankfurter matrix when a combination of Sea Spaghetti/konjac gel is used (Jiménez-Colmenero et al., 2010).

In another study, the nutritional composition (fatty acid profile, cholesterol, mineral, and amino acid content) of low-fat frankfurters enriched with *n*-3 PUFA (using algal oil to add 400 mg of docosahexanoic acid (DHA)/100 g of product) affected by the addition of seaweed (5.5% Sea Spaghetti) and the partial substitution (50%) of animal fat by olive oil (as a source of monounsaturated fatty acid (MUFA)) or combinations of olive oil and seaweed was investigated (López-López, Cofrades, Ruiz-Capillas, & Jiménez-Colmenero, 2009). They found that, although adding seaweed had little impact on the lipid and amino acid profiles of frankfurters, it produced low-sodium frankfurters with high fiber content, better Na/K ratios and rich in Ca.

A similar study was conducted by López-López, Cofrades, & Jiménez-Colmenero (2009), who analyzed the physicochemical and microbiological properties of low-fat (10%) and *n*-3 PUFA-enriched frankfurters as affected by the addition of seaweed (5% Sea Spaghetti), partial substitution (50%) of animal fat by olive oil, and chilled storage (41 days at 2 °C). Seaweed addition was found to improve the water and fat binding properties, decrease the lightness and redness and enhance the hardness and chewiness of low-fat frankfurters enriched with *n*-3 PUFA, while the effect of olive oil was less pronounced. This process occurred despite the decrease of NaCl in the formulation. Although replacing pork backfat with olive oil provided acceptable sensory characteristics in frankfurters (similar to control), seaweed addition resulted in less acceptable products, due to the special flavor of the seaweed. Moreover, formulation and storage time was reported to impact on the total viable count and lactic acid bacteria count. In other words, sausages containing olive oil and seaweed had the highest total viable count from day 14 of storage, and lactic acid bacteria were the predominant microflora. The feasibility of using seaweeds in the formulation of healthier meat products to overcome technological problems associated with low-salt products was demonstrated in this study.

Breakfast sausages are products prepared from fresh or frozen pork, or beef, meat by-products or deboned meat and contain fat, salt, water, and other ingredients (Pearson & Gillett, 1999). Recently, the effect of Sea Tangle (*Lamina japonica* (Areschoug)) powder, a traditional food material in south Asia, on the quality characteristics of breakfast sausages was investigated (Kim et al., 2010). Breakfast sausages containing 1, 2, 3, and 4% sea tangle powder were prepared using fresh pork hams (at 48 h post-mortem) and pork backfat. No difference in moisture, protein, and fat contents between the control group and the treated ones were found. Addition of the sea tangle powder decreased the L* and a* values, improved the cooking loss and emulsion stability, and increased the hardness, gumminess, and chewiness of the products. Moreover, in the sensory evaluations, sample containing 1% sea tangle powder had a lower color score, but received higher scores for flavor, tenderness, and juiciness. The breakfast sausage containing 1% sea tangle powder was demonstrated to have the best physicochemical and sensory properties and the highest overall acceptability.

6.1.1.2. Beef and chicken products.

The effect of adding Sea Spaghetti (10–40% *w*/*w*) as a source of antioxidants and dietary fibers on the physicochemical, microbial and sensory traits of cooked beef patties was recently investigated throughout chilled storage (Cox & Abu-Ghannam, 2013a). Seaweed addition to the patties significantly reduced the cooking losses and increased the tenderness (≈50%) compared to patties without seaweed. Microbiological counts and lipid oxidation were found to be lower in patties containing seaweed. Moreover, after 30 days storage, no bacterial growth was observed in the samples treated with >20% seaweed, and the lipid oxidation levels were lower than in the control patties. Compared to the control, incorporation of Sea Spaghetti into the patties significantly enhanced the dietary fiber level, total phenolic content, and DPPH radical scavenging activity. Moreover, sensory analysis showed that aroma, appearance, texture and taste of the seaweed patties were acceptable by consumers. Patties prepared with 40% seaweed had the highest overall acceptability due to the texture and mouthfeel improvement. Therefore, it was concluded that adding seaweed in the formulation of beef patties could enhance the nutritional and technological quality along with an acceptable sensory quality.

In another study, chemical composition changes, with special reference to fatty acids, as influenced by cooking, were evaluated in low-salt (0.5%)/low-fat patties (10%) with added Wakame (3%) and partial or total replacement of pork backfat with olive oil-in-water (o/w) emulsion (López-López et al., 2011). They reported that the addition of Wakame and olive o/w emulsion could improve the binding properties and the cooking retention values of moisture, fat, fatty acids and ash, which were close to 100%. Partial and total replacement of animal fat with olive o/w emulsion decreased the saturated fatty acids, while total replacement reduced the contents in polyunsaturated fatty acids. Moreover, product formulation affected the fatty acid concentration in cooked patties. For instance, unlike the case of animal fat patties, olive oil addition to the cooking process enhanced SFA, MUFA and PUFA (linolenic acid and linoleic acid) contents. The cooked patties with seaweed and partial or total replacement of pork backfat by o/w emulsion and with added seaweed were less calorie-dense and had lower SFA levels, while samples with olive oil had higher MUFA levels. Thus, they demonstrated that a healthier beef patty could be produced by replacing animal fat with olive oil-in-water emulsion and/or addition of Wakame.

Another study was carried out by López-López, Cofrades, Yakan, Solas, & Jiménez-Colmenero (2010), who evaluated the characteristics of beef patties with low-salt (0.5%) and low-fat (<10%) contents during frozen storage affected by addition of Wakame (3%) and partial or total replacement of pork backfat with olive o/w emulsion. Patties with Wakame were found to have less thawing and cooking losses and to be softer than those without seaweed. A softening influence induced by olive oil emulsion was only observed in patties without seaweed. Lipid oxidation and microbiological counts in reformulated products did not affect the frozen stability. Although seaweed addition enhanced mineral contents, all samples had the same Na/K ratio. Incorporation of Wakame changed the microstructure of the products through formation of alginate chains. The organoleptic properties of the patties were found to be acceptable to consumers. In the course of frozen storage, no significant changes were observed in the target properties due to the different treatments. Thus, it was concluded that Wakame and olive o/w emulsion could induce good technological, sensory and nutritional properties as well as physiological benefits in beef patties.

In addition to beef products, characteristics of restructured poultry steaks affected by incorporation of Sea Spaghetti (3% dry matter) combined with NaCl reduction and a microbial transgutaminase/caseinate (MTGase/caseinate) system as a cold binding agent were investigated during chilled storage (Cofrades, López-López, Ruiz-Capillas, Triki, & Jiménez-Colmenero, 2011). Seaweed addition resulted in a slight increase in purge loss but decreased cooking losses in the products. MTGase/caseinate addition did not influence the water-binding properties. The Kramer shear force of raw products was increased by incorporating seaweed and the MTGase/caseinate system and made the product easier to handle. However, such effect was not observed in cooked products. Products prepared by seaweed had higher levels of total viable counts, lactic acid bacteria, tyramine, and spermidine. All products were judged acceptable by a sensory panel. Moreover, no important changes in the target properties were observed during chilled storage due to the composition. Addition of transglutaminase was demonstrated to be a valid alternative for making stable raw restructured products for storage at low temperature, and Sea Spaghetti incorporation was found to be helpful in maintaining the desired properties in poultry steaks with low salt content.

Another study was conducted to evaluate the effect of fucoxanthin (a major carotenoid in algae) addition on lipid peroxidation and meat color in ground chicken breast meat during chilled storage, before and after cooking (Sasaki et al., 2008). Fucoxanthin was incorporated into the ground samples at a content level of 200 mg/kg. In the storage test before cooking, fucoxanthin did not affect the thiobarbituric acid reactive substances (TBARS) on days 1 and 6, the L* value decreased, while the a* and b* values increased. In the storage test after cooking, fucoxanthin decreased the TBARS values on days 1 and 6. Moreover, fucoxanthin reduced the L* value and enhanced the a* and b* values, which was similar to that which occurred in the storage test before cooking. The authors concluded that fucoxanthin is a potent ingredient for improving the appearance and shelf-life of chicken meat and products derived thereof.

6.1.1.3. Seafood products.

Several studies evaluated the effect of seaweed incorporation on nutritional, sensorial and textural properties of seafood products (Table 1). Recently, the sensory quality and lipid oxidation of enriched fish cakes after the addition of high quality lipids (long chain ω-3 PUFA (*n*-3 LCPUFAs)) and seaweed extracts as natural antioxidants, were studied (Dellarosa, Laghi, Martinsdóttir, Jónsdóttir, & Sveinsdóttir, 2015). It was found that the addition of aqueous and ethanol seaweed extracts did not affect either lipid oxidation or the quality of the products. Moreover, no off-flavor was observed in any of the samples and low scores in rancid odor and flavor were reported.

In another study, the ability of different *in vitro* antioxidant assays to predict the efficiency of cod protein hydrolysate and brown seaweed (*F. vesiculosus*) ethyl acetate extract on lipid oxidation in haemoglobin-fortified washed cod mince and iron-containing cod liver oil emulsion was investigated (Jónsdóttir et al., 2015). The *in vitro* experiments revealed high reducing capacity, high DPPH radical scavenging properties and a high oxygen radical absorbance capacity of the seaweed extract, which also inhibited the oxidation of lipids and proteins in the cod model system. A high metal chelating capacity was observed using cod protein hydrolysate, which was found to be efficient against oxidation in the cod liver oil emulsion. Application of seaweed extract, as a great natural antioxidant, was found to have the potential to act against lipid oxidation in fish muscle foods, while cod protein hydrolysates were reported to be more promising for fish oil emulsions. These authors concluded that the efficiency of the *in vitro* assays for prediction of the anti-oxidative properties of new natural ingredients in food products is dependent on the knowledge about the food systems, especially the main pro-oxidants present.

Ortiz, Vivanco, & Aubourg (2014) studied the effect of different seaweed extract (e.g. cochayuyo, sea lettuce, ulte, and red luche) incorporation, as covering liquids, on the lipid and sensory quality of canned Atlantic salmon (*Salmo salar* (Linnaeus)). After 170 days of canned storage at 40 °C, all kinds of fish samples were reported to have an acceptable oxidized odor and characteristic flavor scores. Contrary to what was observed for the control sample, addition of seaweed extracts decreased the secondary peroxidation in canned salmon, which was accompanied by a higher PUFA and astaxanthin content retention, and lower scores for oxidized odors. Moreover, employing different seaweed extracts as covering liquids in canned Atlantic salmon did not have any significant effect on sensory parameters. Thus, the possibility of using seaweed extracts as covering liquid for preserving canned Atlantic salmon, through inhibiting lipid peroxidation, was demonstrated in this study.

Tilapia is the most commonly used fish in aquaponic systems due to its high availability, fast growth, resistance to stress and diseases, and easy adaptation to the indoor environment (Liang & Chien, 2013; Rakocy, Masser, & Losordo, 2006). Generally, minced tilapia can be prepared using a mechanical separation method (FAO/WHO, 1994). However, this process generates a product with a larger surface area, which consequently makes it susceptible to physical, chemical, and microbiological changes in a short time. Recently, the feasibility of using Nori and Hijiki seaweeds as natural additives, instead of synthetic preservatives to improve the shelf-life and quality of minced tilapia was evaluated (Ribeiro et al., 2014). The application of the seaweed extracts was found to have no effect on the chemical composition of the minced tilapia. The seaweed extracts showed inhibitory influence on total volatile base nitrogen. Moreover, no differences in the rancid aroma, and only minor differences in the color of the products, were detected by the sensory panel. The treatments of the minced tilapia samples showed no bacterial counts during 180 days of frozen storage and remained within the standards of quality.

Wang et al. (2010) investigated the effects of seaweed (*F. vesiculosus*) extract and fractions towards haemoglobin-catalyzed lipid oxidation in a washed cod muscle system and cod protein isolates during ice storage. It was reported that the phlorotannin-enriched fraction had higher inhibitory impact on lipid peroxidation than the crude 80% ethanol extracts. The effectiveness of a 300 mg/kg level of a phlorotannin-enriched sub-fraction was found to be comparable to that of 100 mg/kg propyl gallate, a highly effective synthetic antioxidant in muscle foods. Thus, the great potential of oligomeric phlorotannins as novel natural antioxidants in fish and fish products was demonstrated in this study.

In another study, the effect of using seaweed (*Eucheuma*) powder on the quality of fish cutlet was studied (Senthil, Mamatha, & Mahadevaswamy, 2005). Physicochemical properties of seaweed including soluble solids, water and oil holding capacity were evaluated. Then, *Eucheuma* powder was added at different concentrations (5, 7.5, 10, 12.5, and 15%) as an ingredient in the formulation of fish cutlet and the physicochemical characteristics of fish cutlet were studied. *Eucheuma* powder was found to have a high water holding and swelling capacity. It was demonstrated that *Eucheuma* powder could be incorporated into the fish cutlet up to a 10% level without undesirably affecting the appearance, texture and acceptability of the final product.

6.1.2. Bakery products

Bakery and dough products are the most widely consumed foods in the world and have great potential for delivery of marine functional ingredients (Kadam & Prabhasankar, 2010). Up to now, several studies evaluated the effect of seaweed powders or seaweed extracts' incorporation on the physicochemical and nutritional properties of these products (Table 1). Recently, the textural and sensory effects of bread formulated using a *Palmaria palmata* (Linnaeus) protein hydrolysate with *in vitro* renin inhibitory properties was investigated (Fitzgerald et al., 2014). Four formulations were prepared including 1) wheat flour control bread, 2) control bread containing 4% *P. palmata* protein hydrolysate, 3) buckwheat bread consisting of a blend of wheat and buckwheat (70:30), and 4) buckwheat bread containing 4% *P. palmata* hydrolysate. Incorporation of 4% *P. palmata* protein hydrolysate to the wheat bread control did not influence the texture or sensory properties of the bread.

In an effort to improve the physicochemical and nutritional properties of bread, the effect of red seaweed (*K. alvarezii*) powder incorporated (2–8%) with wheat flour to produce bread was evaluated (Mamat et al., 2014). The breads prepared with and without seaweed powder are shown in Fig. 2. Compared to bread produced without the use of seaweed powder, no change in the quality of the final product was observed by using up to 8% of *K. alvarezii* powder to replace wheat flour. It was found that addition of *K. alvarezii* powder could increase the water absorption of the dough and other farinograph parameters. Addition of seaweed powder reduced dough stickiness properties and the bread produced with seaweed composite flour had higher values of firmness. The authors proved that *K. alvarezii* has a great potential to be used as a part of the ingredients in bread making.

Optimization of incorporating *H. elongata* to enhance the phytochemical content of breadsticks was carried out by Cox & Abu-Ghannam (2013b) using response surface methodology (RSM). It was reported that seaweed concentrations have the most significant influence on the phytochemical properties of the breadsticks when 17.07% of *H. elongata* was incorporated into the flour. The higher levels of

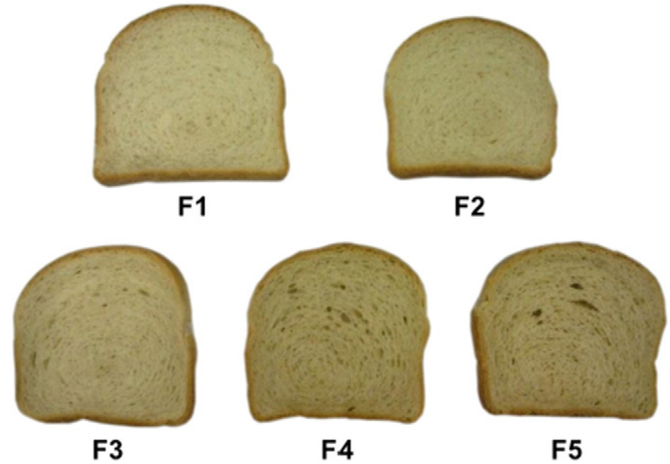

Fig. 2. Seaweed bread prepared with different percentages of seaweed powder. F1: control, F2: 2% seaweed, F3: 4% seaweed, F4: 6% seaweed, F5: 8% seaweed.
(Adapted from Mamat et al., 2014.)

total dietary fiber (7.95%) and phytochemicals (total phenolic content: 138.25 mg GAE/100 g dry basis and DPPH: 65.01%) were obtained in the optimized sample. Moreover, a sensory panel assessed the acceptability of the seaweed breadsticks in terms of aroma, color, texture, taste, and overall acceptability. No significant differences were observed between the seaweed breadsticks and the control sample, thus demonstrating the acceptability of using fiber-rich seaweed bakery products. In another study, Lee et al. (2010) evaluated the shelf-life and quality of breads made with 0.5, 1, and 2% of *Myagropsis myagroides* ((Mertens ex Turner) Fensholt) fermented ethanol extracts (MOEs). They reported a significant reduction (≈1.6 log cycles) in the total microbial count of the breads with 2% MOE, compared to samples without MOE. During the storage period, no significant difference was observed in the pH value of the samples containing MOE and the control sample. Increasing the quantity of MOE was associated with decreasing the lightness and redness, and enhancing the yellowness of the breads. In terms of sensory evaluation, the breads containing 0.5% MOE were more acceptable compared to the breads without MOE. Thus, it was suggested that the incorporation of 0.5% *M. myagroides* to breads has a good influence on improving the shelf-life and the overall quality of the products.

Pasta is an important dish from a nutritional and gastronomic point of view. Prabhasankar et al. (2009) prepared pasta with Wakame as an ingredient at different ratios (100:0; 95:5.0; 90:10; 80:20 and 70:30 (semolina/wakame; *w*/*w*)). Then, the *in vitro* antioxidant properties, total phenolic content, fatty acid composition, fucoxanthin and fucosterol contents were analyzed. The sensory analysis clearly showed that pasta prepared with 10% seaweed had a better quality score compared to the 20% level. The total phenolic content was between 0.10 and 0.94 mg gallic acid equivalents (GAE)/g, while total antioxidant activity varied from 0.16 to 2.14 mg ascorbic acid equivalents (AAE)/g. Moreover, DPPH and superoxide radical scavenging activities of sensorial acceptable pasta were of 7.71% and 4.56%, respectively. Compared to the control (1:15.2), the ratio of *n*-3 to *n*-6 fatty acid in Wakame incorporated pasta was 1:3.4. Fucoxanthin was not destroyed using the heat process involved in pasta preparation and cooking. Microstructure studies demonstrated that addition of Wakame (up to 20%) could increase the interaction between starch granules and the protein matrix and consequently improved the quality of pasta.

Noodles are a famous traditional food around the world, which is widely consumed in south Asian countries. Textural properties (e.g. firmness, elasticity, and resistance to cooking loss) are the most critical characteristics of cooked noodles that need to be considered (Bhattacharya, Zee, & Corke, 1999). Up to now, several studies have been conducted to improve the textural properties of noodles using seaweeds. For instance, Chang, Chen, & Hu (2011) investigated the changes in the quality of fresh noodles prepared with green seaweed (*Monostroma nitidum* (Wittrock)) and cuttlefish paste. Noodles prepared with 6% seaweed were found to have higher cooking yields due to an increase in water absorption during cooking. This effect is related to the fibers and polysaccharides of the seaweed. However, textural properties of cooked noodles decreased by increasing the seaweed levels. Seaweed addition produced samples with less tensile strength, while the higher cuttlefish paste replacement resulted in firmer noodles. The lowest extensibility was observed in the samples containing the highest level of seaweed and cuttlefish paste. It was reported that the textural parameters were affected not only by cuttlefish paste replacement and seaweed incorporation, but also by the cooking properties. Higher water absorption by seaweeds resulted in softer and spongier textural intensities of the noodles. The effect of seaweeds and cuttlefish paste on improving the qualities of the Chinese fresh noodles was demonstrated in this study (Chang, Chen, & Hu, 2011).

Another study was conducted to evaluate the effect of the incorporation of green seaweed (*M. nitidum*) powder at different concentrations (e.g. 4%, 6%, and 8%) on the texture and quality properties of Chinese fresh egg noodles (Chang & Wu, 2008). Incorporation of seaweed powder was reported to enhance the crude fiber contents of raw fresh noodles. Due to the water absorption during cooking of the seaweed, higher cooking yields were observed in the noodles. Higher water absorption by the seaweed resulted in softer and spongier textural intensities in the noodles.

Chang, Chen, & Hu (2011) evaluated the changes in quality of fresh noodles prepared with seaweed and cuttlefish paste. Green seaweed (*M. nitidum*) was incorporated (0%, 3%, and 6%) in noodles, and liquid eggs were replaced by cuttlefish paste in 0, one-third, two-third and full replacement. Seaweed addition produced samples with less tensile strength, while the highest cuttlefish paste replacement showed the firmer noodles. Moreover, noodles prepared with the highest level of additional seaweed and replacing cuttlefish paste had the lowest extensibility. The textural parameters were affected not only by cuttlefish paste replacement and additional seaweed, but also by cooking properties. Similarly to the results reported by Chang & Wu (2008), higher water absorption by the seaweed led to softer and spongier textural properties in the noodles.

6.1.3. Other products

In addition to meat and bakery products, few studies also evaluated the effect of seaweed addition on nutritional, textural and sensorial properties of other food products. For instance, recently, novel dairy products were produced by adding seaweed (e.g. *A. nodosum* and *F. vesiculosus*) extracts, prepared from different solvents, to milk (O'Sullivan et al., 2014). 100% water or 80% ethanol extracts of *A. nodosum* as well as 60% ethanol extract of *F. vesiculosus* were used in this study. The effect of seaweed extracts on the appearance of milk is shown in Fig. 3. It was reported that the greenness and yellowness of fortified milk samples were enhanced by addition of ethanolic extracts prepared from both seaweeds. Ethanolic extracts from *F. vesiculosus* provided antioxidant functionality in milk similar to the phloroglucinol standard. Moreover, the seaweed extract type or concentration had no influence on the quality parameters (e.g. microbiology). Sensory evaluation showed that compared to the ethanolic extracts, water-prepared extracts were more acceptable as functional ingredients in milk. Seaweed extracts were found to be stable in milk and showed different degrees of antioxidant activity before and after *in vitro* digestion. Milk enriched with seaweed extract did not display cellular antioxidant activity, thus indicating lower biological activity of the extracts in milk. It was then concluded that the addition of seaweed extracts to milk could improve certain milk qualities and shelf-life characteristics.

In another study, steamed edible red seaweed *Eucheuma* (*K. alvarezzi*) powder was used at different concentrations (15%, 20%, and 25%) in the preparation of an instant spice adjunct (Senthil, Mamatha, Vishwanath, Bhat, & Ravishankar, 2011). Incorporation of *Eucheuma* powder to the spice adjunct enhanced the ash, protein and crude fiber content. Moreover, the spice adjunct enriched with *Eucheuma* powder had a high amount of vitamin E (72.96 mg/100 g), a low amount of niacin and vitamin B_2 (3.36 and 0.68 mg/100 g, respectively), and a low amount of vitamin B_1 and vitamin A (0.04 and 0.03 mg/100 g, respectively). Sensory analysis of the spice adjunct revealed that the addition of *Eucheuma* up to 20% had high consumer acceptability. Metallized polyester was determined as the packaging material based on the equilibrium relative humidity (ERH) studies. It was demonstrated that the *Eucheuma* powder could be used as an ingredient in the preparation of the spice adjunct to enhance its nutritional quality.

Mamatha, Namitha, Senthil, Smitha, & Ravishankar (2007) studied the potential of using *Enteromorpha* powder, at different concentrations (5%, 7.5%, 10%, 12.5%, and 15%), as an ingredient in the preparation of *Pakoda*, a common Indian product made from chickpea flour. Increasing the seaweed level enhanced the ash, protein and total dietary fiber contents and was accompanied by a nearly 5-fold increase in iron (26.4–126 mg/100 g) and 4-fold increase in calcium content (30.1–124 mg/100 g). No difference was observed in the bioavailability of iron (55–56%) in seaweed and *Pakoda* containing 7.5% seaweed, at intestinal condition (pH = 7.5). However, the bioavailability of iron in *Pakoda* containing seaweed was reported to be slightly higher (27.1%) than that in seaweed at gastric condition (pH = 1.35). Reducing power (155–222 μg/g) was enhanced as the seaweed level increased from 0% to 15%. However, the addition of seaweed reduced the free radical-scavenging activity and the total phenol content. *Pakoda* containing up to 7.5% of seaweed was reported to have a sensory quality comparable with that of Pakoda without seaweed.

7. Potential risks and health-related properties of seaweeds

The surface of seaweeds form a favourable environment for microbes to grow, which depends on the load and diversity between the different seaweed species. Most researches regarding the microbial concerns of seaweeds have an ecologic focus, describing the numbers, varieties and role of bacteria on the seaweed's surfaces. According to the literature, the question about the probable survival of faecal bacteria and possible human pathogens associated to seaweeds has remained unresolved (Duinker et al., 2016). Recently, it has been reported that, only some of the seaweed bacteria have a

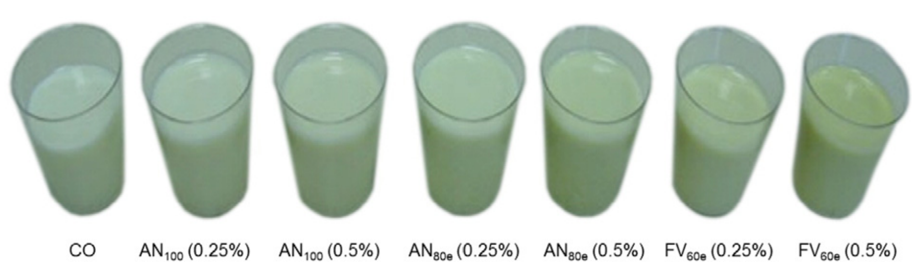

Fig. 3. Milk containing seaweed extracts. AN_{100}: *Ascophyllum nodosum* 100% water; AN_{80e}: *Ascophyllum nodosum* 80% ethanol; FV_{60e}: *Fucus vesiculosus* 60% ethanol. (Adapted from O'Sullivan et al., 2014.)

potential to act as a human pathogen, or may cause challenges during food processing and storage. However, the effect of seaweeds in food borne diseases cannot be expected to be more than other non-filtering marine organisms applied for such purposes (e.g. fish) (Duinker et al., 2016).

Many studies have revealed seaweeds' potential as complementary medicine. Research reports on the therapeutic properties of seaweeds are numerous. For instance, the red, brown and green seaweeds have been shown to have therapeutic properties for health and disease management, such as anticancer (Gomes et al., 2015; Marudhupandi, Ajith Kumar, Lakshmanasenthil, Suja, & Vinothkumar, 2015; Pádua, Rocha, Gargiulo, & Ramos, 2015; Takahashi et al., 2015), anticoagulant (Arata et al., 2015; Castro et al., 2015; Gabriela Das Chagas Faustino Alves, Almeida-Lima, Paiva, Leite, & Rocha, 2015; Shobharani, Nanishankar, Halami, & Sachindra, 2014), anti-inflammatory (Balasubramaniam et al., 2015; Han, Ali, Woo, Jung, & Choi, 2015; Kim et al., 2015; Robertson et al., 2015; Will Castro et al., 2015; Lopes, Daletos, Proksch, Andrade, & Valentão, 2014; Lopes et al., 2012), immunomodulatory (Liu, Shao, Kong, Fang, & Wang, 2013; Pérez-Recalde, Matulewicz, Pujol, & Carlucci, 2014; Sevevirathne, Lee, Ahn, Park, & Je, 2012), thyroid stimulating (Teas et al., 2007), neuroprotective and anti-Alzheimer (Rafiquzzaman et al., 2015; Sevevirathne, Lee, Ahn, Park, & Je, 2012), and tissue healing properties (Fard et al., 2011; Sezer et al., 2008).

β-Glucans are polysaccharide energy stores and important cell wall components of seaweeds. Their antioxidant potential as well as their protective effects against cancer and infectious diseases have been widely studied (Descroix, Ferrières, Jamois, Yvin, & Plusquellec, 2006; Chattopadhyay et al., 2010). The quantity of β-glucans depends on the classification of the seaweed; Frond, Stipe or Holdfast. Moreover, the cell walls of seaweeds are rich in sulphated polysaccharides, which are shown to have beneficial biological activities such as antiviral (Sangha et al., 2011), anticoagulant (Wang, Zhang, Zhang, Hou, & Zhang, 2011), anti-inflammatory (Marques et al., 2012), antiangiogenic (Xu, Dong, Qiu, Cong, & Ding, 2010), anti-adhesive (Cumashi et al., 2007), antioxidative (Rupérez, Ahrazem, & Leal, 2002), and anti-cancer (Synytsya et al., 2010) properties.

Several studies evaluated the health benefits of seaweed's minerals. Intakes of high Na/K ratios have been reported to increase the incidence of hypertension (Taboada, Millán, & Míguez, 2010), while the Na/K ratios of seaweeds are low (e.g. 0.14–0.16 (Matanjun, Mohamed, Mustapha, & Muhammad, 2009) and <1.5 (Rupérez, 2002)). Seaweeds are one of the most important sources of Ca and their intake could be useful to reduce the risk of Ca deficiency, particularly in pregnant women, teenagers, and the elderly people (Iji & Kadam, 2013). Moreover, seaweeds contain high levels of iodine, which can be used as an antioxidant, anti-goiter and anticancer agent (Aceves, Anguiano, & Delgado, 2013; Smyth, 2003).

Currently, cardiovascular diseases (CVD) are among the top health problems in the world and pose a serious challenge to all people who engaged in the prevention and control of these diseases. The World Health Organization (WHO) estimated, that about 23.6 million people will die from CVD in 2030 (World Health Organization, 2015). Thus, for the last two decades, policies and efforts have been advocated to effectively control the burden of fast growing risk factors of CVD. One of the main risk factors of CVD is obesity, which in turn causes most other modifiable risk factors, including dyslipidemia and hypertension (Zalesin, Franklin, Miller, Peterson, & McCullough, 2008) and these are also closely related to atherosclerosis and thrombosis. Another major risk factor for CVD is diabetes. Adults with diabetes have a two to four times higher risk to suffer from heart disease or a stroke than those without diabetes. Up to now, several studies evaluated the antiobesity (Kong & Kim, 2011; Maeda, Hosokawa, Sashima, Murakami-Funayama, & Miyashita, 2009; Okada, Mizuno, Sibayama, Hosokawa, & Miyashita, 2011), antidiabetic (Sharifuddin, Chin, Lim, & Phang, 2015; Unnikrishnan, Suthindhiran, & Jayasri, 2015), antihypertensive (Fitzgerald, Aluko, Hossain, Rai, & Hayes, 2014; Ramirez-Higuera et al., 2014), and antihyperlipidemic (Qi, Huang, et al., 2012; Qi, Liu, et al., 2012) properties of seaweeds and seaweed extracts. The health-related properties of seaweeds and seaweed extracts after incorporation into the food products are summarized in the following subsections.

7.1. Obesity

In few studies, the effects of consuming food products enriched with seaweeds on obesity have been reported (Table 2). For instance, Hall, Fairclough, Mahadevan, & Paxman (2012) investigated the effects of consuming bread enriched with *A. nodosum* on overweight males and found a significant decrease (16.4%) in their energy intake. However, no significant differences in glycaemic or cholesterolemic factors were observed, which suggested that neither delayed gastric emptying nor nutrient encapsulation occurred. Moreover, no significant differences in hunger or fullness were reported by these authors.

In another study, the effects of a fresh-water alga on CVD risk factors in overweight and obese individuals with metabolic syndrome were investigated (Oben et al., 2007). They found that the group fed by 1 fl oz/day of ProAlgaZyme oral infusion during 10 weeks had lower body weight and body fat than a group fed by water placebo. Their study also showed a reduction in blood glucose levels, while a considerable improvement in serum lipid profiles and decrease in markers of inflammation were observed. Thus, it was concluded that the fresh-water alga can modify the cardiovascular risk factors after 10 weeks without side effects.

7.2. Dyslipidemia

The consumption of meat and meat products has been epidemiologically linked to major degenerative diseases, such as coronary heart disease (CHD) (Navas-Carretero et al., 2009) (Table 2). It has been suggested that an increase in dietary intake of antioxidants may reduce the incidence and prevalence of CHD and other degenerative diseases (Iwai, 2008). Recently, the effect of restructured meats (RM) enriched with Wakame or Nori algae on arylesterase (AE) activity and lipoprotein concentration and composition was studied (Olivero-David et al., 2011). It was reported that adding certain seaweeds to meat products can reduce the hypercholesterolemic effect of cholesterol-enriched diets and partially modify the lipoprotein profile. Alga-enriched meat consumption increased the AE activity and maintained the antioxidant position of lipoproteins in rats fed with hypercholesterolemic diets. It was concluded that the RM enriched with Nori can be used in hypercholesterolemic diets to improve the lipoprotein metabolism.

The human body eliminates cholesterol mostly through bile acid production. Cholesterol 7 α-hydroxylase is known as a rate-limiting enzyme which synthesizes bile acid from cholesterol via catalyzing the formation of 7-α-hydroxycholesterol (Cadenas & Davies, 2000). In humans, cholesterol 7-α-hydroxylase is encoded by the liver cytochrome P450 7A1 (CYP7A1) gene (Cohen et al., 1992). This enzyme is upregulated by the nuclear liver X receptor when cholesterol levels are high (Pandak et al., 2001). Based on this knowledge, Moreira et al. (2011) investigated the effect of diets containing restructured pork (RP) enriched with Sea Spaghetti (*H. elongata*) on cholesterolemia, CYP7A1 expression, liver antioxidant enzyme activities and gene expression as well as the liver antioxidant substrate concentrations. They found that RP enriched with Sea Spaghetti can partially block the effect of the hypercholesterolemic agent and increase the antioxidant enzyme expression.

In another study, the effects of consumption of a diet containing RP–Sea Spaghetti on plasma and white adipose tissue cholesterol along with its influence on the expression of lipoprotein lipase (LPL), acetyl CoA carboxylase (ACC), fatty acid synthase (FAS), and hormone-sensitive lipase (HSL) in white adipocytes of growing rats was investigated (González-Torres et al., 2012). They revealed that the RP–Sea Spaghetti can partially block the dietary hypercholesterolemic effect and change the lipogenic/lipolytic enzyme expression, and reduce the wasting effect of hypercholesterolemia on adipose tissue in rats.

Another investigation was done by Moreira et al. (2013) who showed that the ingestion of seaweed-RP-enriched diets without added cholesterol did not greatly change the plasma cholesterolemia and liver structure. They found that Nori–RP and Sea Spaghetti–RP clearly blocked the hypercholesterolemic effects of the dietary cholesterol but were unable to reduce the incidence of various liver alterations and even increased hepatocellular damage. Moreira et al. (2014) tried to assess the effect of RP enriched with Sea Spaghetti on AE activity and lipoprotein concentration and composition in Wistar rats. Their results showed that feeding the rats with Sea Spaghetti–RP increased the antioxidant capacity within a non-cholesterol enriched diet, while improved the lipoprotein profile within a cholesterol-enriched diet. It was concluded that the diets containing RP enriched with Sea Spaghetti had higher antioxidant activity compared to the control pork diet. Thus, they demonstrated the suitability of consuming Sea Spaghetti-enriched pork as part of a cholesterol-enriched diet.

7.3. Hypertension

Approximately half of the total burden of CVDs is attributed to high blood pressure (Segura & Ruilope, 2012). There are several important factors which contribute to hypertension including: 1) lessening of glomerular filtration rate, 2) increasing renal tubular reabsorption of salt and water, 3) unnecessary activation of renin–angiotensin–aldosterone and sympathetic nervous systems, 4) elevating reactive oxygen species (ROS), and 5) raising the endothelin vasoconstrictor peptide and inflammatory cytokines and decreasing synthesis of endothelial nitric oxide (Hall et al., 2012). Hypertension can be controlled through improving dietary habits and through pharmacological treatments (Hernández-Ledesma, del Mar Contreras, & Recio, 2011) (Table 2). One of the common pharmacological policies to control hypertension and prevent CVDs is to inhibit angiotensin converting enzyme-I (ACE-I) and renin. ACE-I inhibitory drugs such as Captopril, Enalopril, Alacepril and Lisinopril are widely prescribed for the treatment of hypertension (Wijesekara & Kim, 2010). Furthermore, natural renin inhibitory compounds were previously isolated from various food sources such as peptides from peas (Li & Aluko, 2010), and soyasponin I from soybeans (Takahashi et al., 2008). Recently, Fitzgerald et al. (2014) investigated the sensory, physical and nutritional properties of bread enriched with the renin inhibitory *P. palmata* protein hydrolysate. They found that bread containing the hydrolysate retained the renin inhibitory bioactivity after the baking process, compared to the control. Thus, it was concluded that the health value of bread can be improved through the addition of *P. palmata* protein hydrolysate.

7.4. Diabetes

Type 2 diabetes mellitus (T2DM) is a lifestyle-related disease that has been strongly associated with dietary habits (Garcimartín, Benedí, Bastida, & Sánchez-Muniz, 2015). Currently, the rate of mild T2DM cases are specifically increasing due to decreased physical activity, wrong dietary habits and eating diets rich in energy and saturated fats (e.g. fatty meat based-diets) (Zhou, Tian, & Jia, 2012). The results of previous studies also showed that marine seaweeds and their derivatives have potential antidiabetic properties and can partially replace hypoglycemic drugs (Lin & Liu, 2012) (Table 2).

Recently, an *in vitro* experiment was conducted to study the effects of aqueous extracts and suspensions of RP with 5 g/100 g of *P. umbilicalis* (Nori), *U. pinnatifida* (Wakame), or *H. elongata* (Sea Spaghetti) on α-glucosidase activity and glucose diffusion (Garcimartín, Benedí, Bastida, & Sánchez-Muniz, 2015). The inhibition of glucosidase was also assessed in this study. It was hypothesized that seaweed–RP aqueous extracts or suspensions can similarly inhibit carbohydrate digestion

Table 2
The effects of foods containing seaweeds on pre-disposing factors of cardiovascular diseases.

Cardiovascular diseases	Seaweed/food (vector)	Model of study	Type of study	Effects of study	References
Obesity	*Ascophyllum nodosum*/bread	Twelve overweight, healthy males	Single blind, cross-over design, satiety study	Significantly reduced (16.4%) the energy intake. With the absence of adverse side effects.	Hall, Fairclough, Mahadevan, & Paxman (2012)
Dyslipidemia	Nori/pork Wakame/pork	Sixty male growing Wistar rats	Six experimental groups divided in two groups — diets with or without cholesterol	Increase the arylesterase activity. N but not W partially blocked the hypercholesterolemic effect of dietary cholesterol and partially normalised VLDL and LDL lipid levels and composition.	Olivero-David et al. (2011)
	Sea Spaghetti/pork	Forty male growing Wistar rats	Four experimental groups divided in two groups-diets with or without cholesterol	Partially block the effect of the hypercholesterolemic agent and also could increase the antioxidant enzyme expression	Moreira et al. (2011)
	Sea Spaghetti/pork	Forty male growing Wistar rats	Four experimental groups divided in two groups — diets with or without cholesterol	Partially blocked the dietary hypercholesterolemic effect and changed the lipogenic/lipolytic enzyme expression	González-Torres et al. (2012)
	Nori/ pork Sea Spaghetti/pork Wakame/pork	Eighty male growing Wistar rats	Eight experimental groups divided in two groups –diets with or without cholesterol	Seaweed-pork diets without added cholesterol did not significantly change the cholesterolemia and the liver structure while they could block hypercholesterolemic effects of the cholesterol dietary. Nevertheless, they raised hepatocellular damage.	Moreira et al. (2013)
	Sea spaghetti/Pork	Forty male growing Wistar rats	Four experimental groups divided in two groups — diets with or without cholesterol	Increased the arylesterase activity, elevated the antioxidant capacity within a noncholesterol enriched diet, improved the lipoprotein profile within a cholesterol-enriched diet.	Moreira et al. (2014)
Hypertension	*Palmaria palmata*/bread	–	Lab experiment (*In vitro*)	Adding seaweed increased the renin inhibitory protein hydrolysate and renin inhibitory bioactivity was retained after the baking process	Fitzgerald et al. (2014)
Diabetes	Wakame/bread, Chondrus/bread	–	Lab experiment (*In vitro*)	Decreased the rate of white bread starch digestibility however, displayed different effect on glucose retardation index. Chondrus produced a more obvious response	Goni, Valdivieso, & Gudiel-Urbano (2002)
	Rice wine/*Laminaria japonica*	–	Lab experiment (*In vitro*)	Considerable anti-diabetes activity and showed the best overall acceptability, with no seaweed flavor.	Choi et al. (2014)
	Nori/pork Wakame/pork Sea spaghetti / Pork	_	Lab experiment (*In vitro*)	Inhibit carbohydrate digestion or/and absorption. In the end, they claimed that Sea Spaghetti–RP should be selected as an α-glucosidase inhibitor while Nori–RP and Wakame–RP should be considered as glucose diffusion reducers.	Garcimartín, Benedí, Bastida, & Sánchez-Muniz (2015)

or/and absorption. These authors concluded that Sea Spaghetti–RP should be selected as an α-glucosidase inhibitor, while Nori–RP and Wakame–RP should be considered as glucose diffusion reducers. In another study, the anti-diabetic properties of the Makgeolli, the oldest Korean traditional rice wine, was investigated by Choi et al. (2014). Makgeolli fermented with *L. japonica* exhibited considerable anti-diabetes activity and showed the best overall acceptability without the seaweed flavor.

8. Conclusions

Seaweeds are a good source of natural antioxidants, antimicrobials, and hydrocolloid compounds. Several studies demonstrated that the incorporation of seaweeds and/or isolates of seaweeds into the food systems can improve the shelf-life, nutritional, textural, organoleptic, sensorial and health properties of the final products. Nevertheless, the effects differ according to the seaweed species and the amount used in the formulation. Thus, there is a need to optimize the formulation of food products based on seaweeds in their composition. Reviewing the advantages of seaweeds in obesity, dyslipidemia, hypertension and diabetic cases provide strong reasons to include them in regular foods such as meat, bread and beverages. However, more studies need to be conducted to evaluate the effect of functional foods incorporated with either seaweed or seaweed extracts on other diseases such as infections, cancers, and inflammatory disorders. Although enormous literature is available on the *in vitro* antimicrobial properties of seaweeds, only few studies were conducted on their actual use in food products. Thus, this is an area that needs to be considered to evaluate seaweeds' full potential.

In spite of all the efforts conducted for the addition of seaweeds to food products, there are still some difficulties and challenges in their commercialization due to their sensory impact on foods. There is little consumer awareness about the health benefits of seaweeds, sensory changes due to the incorporation of seaweeds and potential pollution of seaweeds with industrial waste or heavy metals which still need to be appropriately addressed before this resource can be used at a large scale. Although not many commercial products exist at present, it is predictable that the joint efforts of industry and research in this field will affect a high number of new functional foods in the market, especially those improving cardiovascular health. To understand the impact of storage conditions on shelf-life, quality and health-related beneficial properties of food products fortified with seaweeds, further studies need to be conducted.

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