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Effect of processing on texture and microstructure of the seaweed *Durvillaea antarctica*

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Abstract
The algae *Durvillaea antarctica* (*cochayuyo*) is the most popular edible seaweed in Chile and shows extensive variability at the marketplace. The objective of this study was to characterize the sample of *D. antarctica* and modify its original structure and texture by processing: hydrothermal (HT; 40, 60, and 80 °C, for 30, 60, and 90 min), freezing and thawing cycles (F/T; 1 to 3), ultrasound (US; 10, 50, and 100% power for 5, 10, and 15 min), and high pressures (HPP; 200, 400, and 600 MPa for 1, 2, and 3 min). Seaweed mainly contained (g per 100 g) 9.7 protein, 51.5 carbohydrates, and 0.1 lipids. Main free amino acids found were (mg per 100 g) alanine (347.52), glutamic acid (182.14), and aspartic acid (120.14). A 60% softening effect on the texture of *D. antarctica* occurred when the hydrothermal method was applied at 80 °C for 90 min. HPP at a pressure of 600 MPa in 1 to 3 min produced a 50% reduction in texture. US and F/T cycles had minor or no effect at all. Softening correlated well with microstructural changes revealing damage at the cellular level. HT processing is a simple method to soften this seaweed at home, while HPP may become an interesting alternative to pre-process the algae before commercialization as a ready-to-cook product. Further studies should involve changes induced by processing on nutritional value and sensorial perception.

Keywords *Durvillaea antarctica* · Phaeophyta · Texture · Microstructure · Processing · Hydrothermal · Freezing/thawing · Ultrasound · HPP

Introduction

Edible seaweeds are receiving special attention in Western countries as healthy food and a gastronomic ingredient in soups, salads, side dishes, and entrees (Josse 2015). Furthermore, in a time of dramatic climate changes, cultivation of seaweeds is more sustainable than edible plant agriculture. They require no freshwater, land, or chemical fertilizers, and absorb 20% more carbon dioxide than they produce (Tiwari and Troy 2015). However, scientific studies of culinary uses of seaweeds are quite scarce and limit their potential extensive use as foods (Mouritsen 2012).

Durvillaea antarctica, also known as bull kelp or "cochayuyo," is the most popular edible seaweed among Chilean consumers, and its direct consumption amounts to about 0.5 kg per capita (FAO 2018). This brown kelp contains 10–12% protein, 1–4% lipids, and over 50% dietary fiber on a dry weight basis (Ortiz et al. 2006). Seaweeds are known for their variability in chemical composition depending on the area of growth, season, environmental conditions, etc. Among main chemical components that vary are antioxidants as tocopherols (Ortiz et al. 2006), fatty acids (Nelson et al. 2002), and amino acids (Tiwari and Troy 2015).

Durvillea antarctica is sun-dried at the collection places in the coast, and the long dry stems are folded and commercialized as tied bundles. Common culinary preparation involves soaking overnight with a little vinegar followed by boiling in water for around 20 min. The cooked fronds are cut into bite-sized pieces and sautéed or simmered with other ingredients. There is scant information on the texture of whole seaweeds. However, studies of their incorporation in products such as beef patties, frankfurters, pizzas, pasta, muffins, and bread are starting to become available (Brownlee et al. 2012; Choi et al. 2015; del Olmo et al. 2018; Mamat et al. 2018). Although the texture may be a major factor in the acceptability of seaweeds, there are almost no studies in the English scientific literature at this respect. In a search in Food Science and Technology Abstracts (accessed on 14

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May 2019), only the title of one article referred to textural evaluation of macroalgae (i.e., *Nori*), but the main text was in Japanese (Ono et al. 1993). Cooked *D. antarctica* has a leathery, fibrous texture (Wassilieff 2009) and exhibits stickiness, which is appreciated by the Japanese, but may not be a desirable textural trait for Westerners (Tanaka 1986). Softening of *D. antarctica* by processing methods other than hydrothermal or cooking in water would be highly desirable to induce new textural characteristics and/or having a ready-to-cook product. Soft texture seaweeds are also highly desirable in the Orient for the elderly having difficulties in mastication and swallowing (Aguilera and Park 2016).

Several processing technologies have been applied to enhance the extraction of chemical components from macroalgae but not their texture. Among them are as follows: pulsed electric fields, microwaves, ultrasound, high-pressure homogenization, thermal, non-thermal, and/or enzymatic means (Poojary et al. 2016). However, their application to modify structure-texture relationships is practically not reported. Hydrothermal processing (HT) using hot water not only softens the seaweed but also produces a liquid that can be used as a soup (*dashi*) (Yuasa et al. 2017). Moreover, boiling of some seaweeds increases the bioavailability of proteins but reduces the total phenolic content (Cox et al. 2012; Maehre et al. 2015). Non-thermal technologies are of special interest as food processing methods since they preserve to a large extent the color, flavor, and nutritional quality (Zhang et al. 2018). The application of low frequency (< 200 kHz), high-power ultrasound (US) to many food materials (fruits, vegetables, meat, etc.) causes significant structural disruption and texture softening. Main mechanisms for this action include the localized high pressure and temperature rise that accompanies the collapse of cavitating bubbles, as well as the shearing stresses from the surrounding liquid (Terefe et al. 2016; Carrillo-Lopez et al. 2017). High-pressure processing (HPP) induces microstructural changes and tenderization in various types of tissues by partial disintegration of plant cells, collapse of intercellular spaces, and the release of lytic enzymes such as pectin methyl esterases, whose activity may increase with pressure (Bolumar et al. 2016; Del Olmo et al. 2020). The use of high pressure extends the useful life of algae and preserves the nutritional value and antioxidant capacity. Besides, it modifies the texture by activating alginate lyases in seaweeds that play a role similar to that of pectin methyl esterases in vegetables (Del Olmo et al. 2020). On the other hand, the use of enzyme preparations has been proposed to increase the extraction of hydrocolloids from algae but has not been applied to modify the eating quality (Rhein-Knudsen et al. 2015).

Seaweeds exhibit a large natural variability depending on geographic location, environmental factors, degree of maturity, part of the plant tissue, gender, and season. For example, lipid constituents and amino acids vary significantly with the growing stage (Honya et al. 1994; Marinho et al. 2015). The structure of the algae is also strongly influenced by the season, age, species, and geographic location (Sinurat and Fadjriah 2019). Consequently, a study on the utilization of seaweed as food becomes more relevant if it is accompanied by some chemical, biochemical indicators, and microstructural information of the material utilized (Schiener et al. 2014). Thus, the objective of this study was to assess the effect of thermal and non-thermal processes on the mechanical properties (texture) of *D. antarctica*, characterized by some important chemical components and its microstructure.

Materials and methods

Materials

Dried *Durvillea antarctica* stems were purchased in December 2018 to Algueros de Navidad, a major supplier of this seaweed to the retail market. Seaweeds were harvested in Chorrillos, VI Region, Chile (33° 57′ 0″ S, 71° 49′ 60″ W). The raw material was visually inspected to assure that it came from healthy fronds with firm, smooth, and shiny thallus. All experiments were performed with stems of approximately 1.5–2.0 cm in diameter and cut to 2.0 cm in length.

Seaweed characterization

Proximate analysis

The proximate composition of *D. antarctica* was determined in duplicate samples, according to methods described in AOAC (2012). The ash content was gravimetrically determined after heating at 550 °C in a muffle furnace (AOAC 930.05). Moisture was determined by the oven method at 105 °C (AOAC 934.01). The total protein was determined using the Kejhdal system (N × 6.25) (AOAC 2000.11). The fat content was extracted with petroleum ether in a Soxtec system (AOAC 991.36) and determined by a gravimetric method. The total fiber was determined by the enzymatic-gravimetric method (AOAC 991.43), and finally, carbohydrates were determined by difference. Results are expressed in dry weight (d.w.) basis.

Tocopherol analysis

Tocopherols were determined by triplication in the lipid extracts as described by Ortiz et al. (2006) using high-performance liquid chromatography (HPLC) with fluorescence detection. The HPLC system consisted of a Merck–Hitachi L-6200A pump (Merck, Germany), a Rheodyne 7725i injector with 20 μL sample loop, a Merck–Hitachi F-1050 fluorescence detector, and a Merck–Hitachi D-2500 chromato-integrator. Peaks were detected at 290 and 330 nm excitation and emission wavelengths, respectively.

Tocopherols were identified using external standards (Merck), following the AOCS standard method Ce 8-89 (AOCS 1993).

Fatty acids analysis

Saturated (SATs), polyunsaturated (PUFAs), and monounsaturated (MUFAs) fatty acids were determined in triplicate from the oil fraction using gas chromatography and a flame ionizer detector (HP 5890, Hewlett–Packard, USA), and a 50-m fused silica BPX70 capillary column 0.25 μm film. Temperature was programmed between 160 and 230 °C, rate 2 °C min^{-1}, with hydrogen as carrier and using reference fatty acid methyl esters (FAME) from Merck (Germany), according to Ortiz et al. (2006).

Total and free amino acids analysis

The total and free amino acids (glutamic acid, aspartic acid, and alanine) were determined by a modification of the methods of Alaiz et al. (1989) and Ruiz and Betancur (2011). For total amino acid determination, 200 mg of ground dry seaweed was hydrolyzed with 4 mL HCL (6.0 M) and 400 μL D, L-α-aminobutyric acid in an oven at 110 °C for 24 h. The hydrolysate was brought to 10 mL with 0.1 M HCL for quantification. In the case of free amino acid analysis, 20 mL of water were added to 0.5 g of ground dry seaweed, and the aqueous extract was separated and filtrated after 3.5 h and used for quantification. A sample of 200 μL of the hydrolysate or aqueous extract (depending on total or free amino acids) was dissolved in 2.8 mL of borate buffer (1 M, pH 9.0) and derivatized with 2.4 μL of diethyl ethoxymethylene malonate at 50 °C for 50 min under agitation. Quantification of amino acids was performed in a UHPLC UltiMate 3000 system (Thermo Scientific, USA), following the procedures for the separation of derivatives by Ruiz and Betancur (2011). Free and total amino acids were analyzed by triplicate.

Processing of seaweeds

A scheme depicting the control sample and processing procedures is presented in Fig. 1.

Hydrated control Original dry samples were subsequently hydrated in a ratio 1:35 dried algae to distilled water, pH 6.2–6.4, for 3.5 h at room temperature (until constant weight). Rehydrated samples contained approximately 6.1 g water per gram of dry algae.

Hydrothermal Hydrated seaweed was placed in distilled water to reach a final ratio of 1:5 (hydrated seaweed:water), transferred to plastic bags, and sealed. Bags were then immersed in a thermoregulated bath at 40, 60, and 80 °C for 10, 20, 30, 60, and 90 min.

Freeze-thawing Hydrated samples were placed in plastic bags, vacuum-sealed and frozen in a domestic freezer (− 18 °C) for 23 h, and then thawed at room temperature (20 °C) for 1 h. The F/T procedure was repeated two and three times in different samples (1, 2, and 3 cycles).

Ultrasound Hydrated seaweed was placed in a beaker with distilled water to reach a final ratio of 1:5 (hydrated seaweed:water) and exposed to the action of a sonifier (Model 450 L, Branson Ultrasonic Corp, USA) at a frequency of 20 kHz for 5, 10, and 15 min with an output level of 10, 50, and 100% power. The sonifier tip of 19 mm was placed in the center of the beaker (120 mL) at a depth of 25 mm. The beaker was immersed in a bath of ice water and salt in a 1:4 ratio so that the temperature rise did not exceed 33 °C.

High-pressure processing Samples of hydrated seaweed were packed in plastic bags with distilled water to reach a final ratio of 1:5 (hydrated seaweed:water) and exposed to the action of a high-pressure equipment Hiperbaric 300 (Hiperbaric España, Burgos, Spain) at 200, 400, and 600 MPa during 1, 2, and 3 min, in ALTA HPP Services (Santiago, Chile).

Texture determination

Given the cylindrical shape of the seaweed samples, mechanical properties were analyzed by cutting perpendicular to the main axis with a guillotine blade (HDP/BSG) attached to a TA.XT2 Plus texturemeter (Stable Micro System Ltd., Godalming, UK) equipped with a 5-kg load cell (Fradique et al. 2010). Ten replicates (n = 10) were assayed for each treatment at a speed of 2 mm s^{-1} and at room temperature (ca. 20 °C). The maximum force (N) in the force-strain curves was averaged to represent a proxy of texture.

Microstructure

The microstructure of *D. antarctica* was analyzed by two methods. Untreated algae samples (20 × 20 × 4 mm) were dried at 25 °C and observed with a SkyScan 1272 micro-CT (Bruker, Belgium) operated at a source voltage of 40 kV and a constant source current of 250 μA. Microstructural changes of the processed seaweeds were observed with a scanning electron microscope model TM 3000 (SEM Hitachi, Japan). Samples were freeze-dried, coated with gold/palladium, and observed under a voltage of 15 kV. Photomicrographs were taken at × 40 and × 50.

Statistical analysis

Results of texture determination were statistically analyzed using STATGRAPHICS Centurion XV (StatPoint Technologies Inc., USA). First, the effect of the experimental

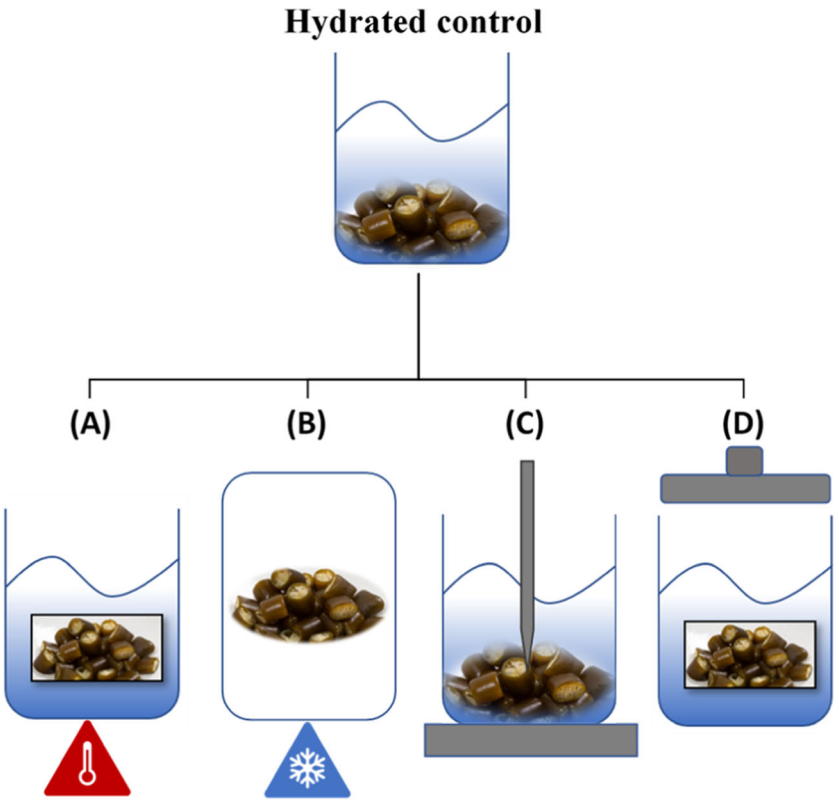

Fig. 1 Scheme showing processing of samples of *D. antarctica*. **A:** Hydrothermal processing at different temperatures and times; **B:** Freeze/thawing for a different number of cycles; **C:** Ultrasound, sonication at different times, and frequencies; **D:** High-pressure processing for several times and different pressures

parameters (time, temperature, cycles, power, and pressure) for each processing method on the texture was evaluated by multifactorial ANOVA, considering the respective levels indicated in the algae processing section. Multiple rank test was applied using Tukey's honestly significant difference (HSD) procedure. Then, the treatments that had the greatest change in texture, in each processing method, were evaluated with one-way ANOVA, considering, in this case, four levels corresponding to each selected treatment. Differences were considered statistically significant when $p < 0.05$.

Results and discussion

Chemical characteristics of the seaweed

Proximate analysis of the *D. antarctica* is shown in Table 1. The average content of protein was 9.7 g (100 g)$^{-1}$ dry seaweed, coinciding with values reported for the same seaweed in other investigations (i.e., 8.2–11.6 g (100 g)$^{-1}$ d.w.; Ortiz et al. 2006; Astorga-España and Mansilla 2014). The protein content of brown seaweeds is generally low (5–15% of the dry weight) in comparison with red and green algae (Fleurence 1999). However, this low protein content is higher than in vegetables like spinach and cauliflower, among others (Vaclavik and Christian 2008). Although the content of lipids in some seaweeds may reach 5% on a dry weight basis (Pereira 2016), in our sample of *D. antarctica*, it was 0.1 (g (100 g)$^{-1}$ dry seaweed). This figure is low compared with that previously reported by Ortiz et al. (2006), probably because the lipid content varies with the maturity stage of the algae and the geographical location (Nelson et al. 2002). As expected, the total carbohydrate content was quite high (51.5 g (100 g)$^{-1}$ d.w.) but less than previously reported (79.93 g (100 g)$^{-1}$ d.w.) by Uribe et al. (2017). The fiber content was low (8.9 g (100 g)$^{-1}$ d.w.) in comparison with other studies of *D. antarctica* (Ortiz et al. 2006 ;Astorga-España and Mansilla 2014).

Seaweeds have a low-fat content (1–5% d.w. basis), but their essential fatty acids are higher than in most edible plants (Vaclavik and Christian 2008). Table 2 shows that the

Table 1 Proximate analysis* of dry *Durvillaea antarctica*

Proximate analysis	g (100 g)$^{-1}$ d.w.	Method
Moisture	9.2	AOAC 934.01
Ash	25.5	AOAC 930.05
Protein	9.7	AOAC 2000.11
Lipids	0.1	AOAC 991.36
Total fiber	8.9	AOAC 991.43
Carbohydrate	51.5	By difference

d.w. dried weight

* Means of samples ($n = 2$)

Table 2 Fatty acid content* in dry *Durvillaea antarctica* sample

Fatty acids	Methyl ester (%)
Saturated	9.2
Monounsaturated	25.5
Polyunsaturated	9.7

* Means (n = 3)

composition of fatty acids (total SATs, MUFAs and PUFAs) of *D. antarctica* is similar to that obtained by Ortiz et al. (2006). Slight variations could be attributable both to environmental and genetic differences (Honya et al. 1994; Nelson et al. 2002). According to Ortiz et al. (2006), the principal PUFAs contained in this seaweed are ω-3 and ω-6, and among MUFAs, the fatty acid C18:1ω-9 is of relevance. The occurrence of these fatty acids (principally ω-3 and ω-6) is important in human nutrition (Di Pasquale 2009).

Seaweeds are, in general, a good source of α, β, γ, and δ-tocopherol and its isomers, liposoluble metabolites that act as vitamin E precursors (Jensen 1969). Main tocopherols in *D. antarctica* (Table 3), were α- and β-tocopherols (total 44 μg g^{-1} lipid). However, from a nutritional standpoint, α- and β-tocopherols are the important ones (Wagner et al. 2004).

The total and free content of the glutamic, aspartic, and alanine amino acids is shown in Table 4. These three amino acids were found in high concentrations. In their free forms, these amino acids play an important role in the flavor of seaweeds (Mouritsen et al. 2012). Free glutamic acid was present at 182.1 mg $(100\ g)^{-1}$ d.w., which is important since its sodium salt form (monosodium glutamate, MSG) is the main umami compound that gives flavor to several foods (Ikeda 2002; Kurihara 2015). Like MSG, aspartic acid (120.1 mg $(100\ g)^{-1}$ d.w.) and alanine (347.5 mg $(100\ g)^{-1}$ d.w.) both generate umami flavor, but in less intensity (Kurihara 2015).

Textural analysis of processed samples

Hydrothermal processing

Figure 2a shows a continuous decrease in maximum force (texture softening) of the seaweed as time and temperature of cooking water increased. After 90 min, the texture of *D. antarctica* decreased between 10 and 60% at 40 and 80 °C, respectively, compared with the control (time zero). Significant differences were found between temperatures ($p < 0.001$). Between times of 10 and 20 min, and between the times of 60 and 90 min, there were no significant differences ($p = 0.125$) in maximum force. According to an evaluation of instrumental and sensory texture of the brown alga *Himanthalia elongata* cooked at 100 °C, it took at least 30 min to soften the seaweed, so it becomes edible. The texture was reduced from 45 to 32 N mm^{-1} (Cox et al. 2012).

Table 3 Tocopherols content* of *Durvillaea antarctica*

Tocopherols	μg g^{-1} lipid
α-Tocopherol	12.13 ± 0.10
β-Tocopherol	31.92 ± 2.41
γ-Tocopherol	0.51 ± 0.00
δ-Tocopherol	0.45 ± 0.00

* Means ± standard deviation (n = 3)

Table 4 Total and free amino acid contents of *Durvillaea antarctica*

Amino acids	Total (mg $(100\ g)^{-1}$ d.w.)	Free (mg $(100\ g)^{-1}$ d.w.)
Aspartic acid	867.83 ± 5.18	120.14 ± 0.23
Glutamic acid	1005.98 ± 5.75	182.14 ± 0.28
Alanine	827.80 ± 3.72	347.52 ± 1.00

Means ± standard deviation (n = 3)
d.w. dried weight

Freeze-thawing processing

Figure 2b shows the texture data for the three freeze-thaw cycles applied. The texture of the *D. antarctica* remained almost constant during the 3 cycles applied (no significant differences $p > 0.449$ between them and the control). Charoenrein and Owcharoen (2016) reported that texture in mango was reduced 20% after an initial F/T cycle and then remained constant after the following cycles. It is well known that vegetables exhibit a significant deterioration in texture (softening) after freezing and thawing due to the destruction of cellular tissue (Reid 1980; Fuchigami et al. 1995; Yamada et al. 2002). Since fresh vegetables contain large amounts of water, it is believed that the formation of ice crystals in water inside cells induces an expansion of the cell volume and the perforation of membranes resulting in damage to cellular structures (Pearce 2001 ; Ohnihisi et al. 2003; Jha et al. 2019).

Ultrasound processing

Figure 2c shows changes in the texture of *D. antarctica* after the sonication treatment at three power levels (10, 50, and 100%) and for three processing times. It was determined that the texture of the sonicated samples did not present significant differences with the texture of the sample without sonication. There were only significant differences (p = 0.023) in the texture between the treated samples (powers 10 vs 50% and 100%) within the initial (5 min) and final time (15 min) of sonication. It can be surmised that in the first minutes of ultrasound processing, swelling of the alginate in the seaweed produced a damping and insulating effect on the ultrasound

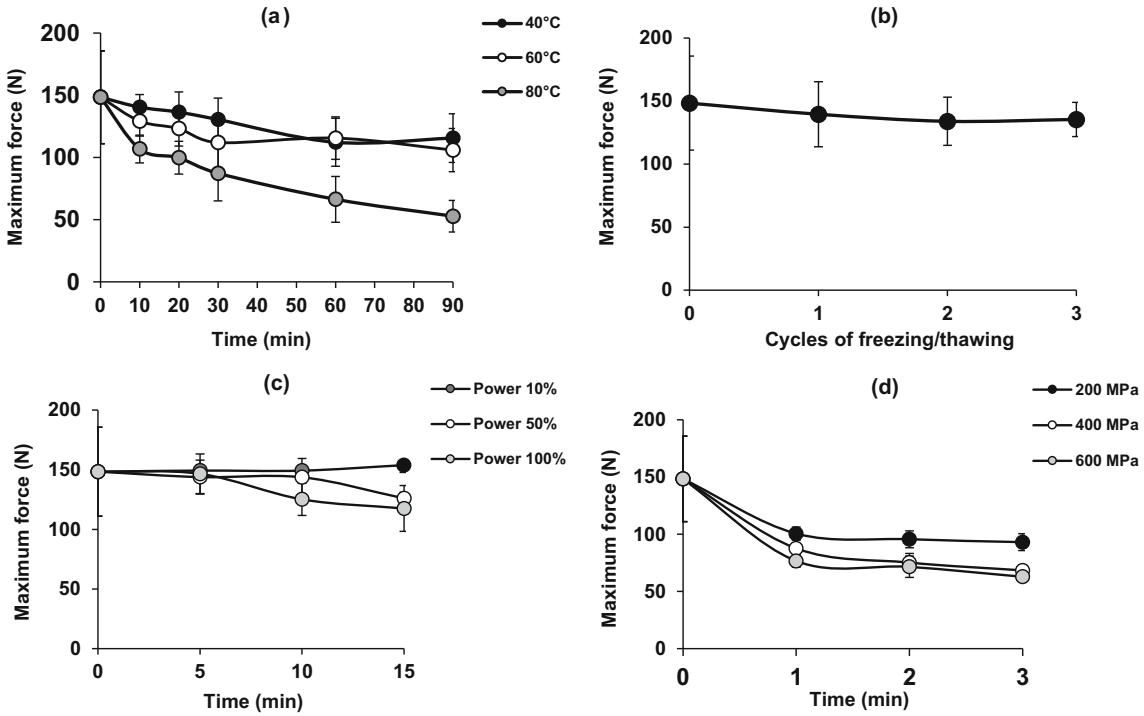

Fig. 2 Texture (average of maximum force) of the control (time 0) and samples subjected to (**a**) hydrothermal processing, (**b**) freezing/thawing cycles, (**c**) ultrasound processing, and (**d**) high-pressure processing

waves. Many studies in brown algae report significant effects of ultrasound pretreatments in promoting the extraction of hydrocolloids (alginates and carrageenans), bioactive compounds, pigments, etc. (Kadam et al. 2013, 2015; Youssouf et al. 2017; Zhu et al. 2017). These studies suggest that ultrasound may also have effects on softening of seaweeds and thus affect the texture.

High-pressure processing

Figure 2d shows changes in maximum force for the different applied pressures and times. The figure demonstrates that major softening of the tissue occurred between 0 and 1 min processing for all pressures applied. The texture of the *D. antarctica* decreased between 30 and 50% as higher pressures were applied for 3 min. Statistically, there were significant differences ($p < 0.0001$) among all three pressures (200, 400, and 600 MPa), however, small by visual inspection. Del Olmo et al. (2019) subjected the brown seaweed *Laminaria ochroleuca* (*kombu*) to pressures of 400 and 600 MPa for 5 min obtaining contradictory results. In the first case, texture (maximum force) increased by 10%, and for 600 MPa, texture decreased by 10%. Although it is known that high-pressure technology can alter the cellular permeability of fruits and vegetables and promote cellular disintegration to different extents, the effect on the texture of seaweeds needs further research.

Microstructure

The micro-CT image in Fig. 3a exhibits the fine detail of a cross-section of the dried *D. antarctica* as purchased. The cylindrical thallus is composed of a thick outer cortex (OC) and the interior medulla (IM) consisting of thin septa separating air chambers similar to the cells of a honeycomb, allowing the seaweed to float on the sea surface (Rothäusler et al. 2012). SEM photomicrograph of the hydrated control (Fig. 3b) shows three important structures in the cross-section of the seaweed: the cortical zone (CZ) formed by a radial row of large cells, the intermediate medullary zone (MZ) of interwoven hyphae, and the central core (CC) formed by air-filled cavities separated by septa. The structure observed in this study reflects what has been previously reported for the cross-section structure of the species (Goecke et al. 2012)

Figure 3c to f are scanning electron photomicrographs of *D. antarctica* after processing. As stated in the introduction, there are practically no studies on the effects of processing on the microstructure of seaweeds and its relation to the texture (at least in the English scientific literature). Thus, the closest references for comparison are studies on fruits and vegetables. Hydrothermal treatment (Fig. 3c) induced the detachment of the intermediate medullary zone from the cortical zone, a possible explanation for texture softening reported in Fig. 2. Cooking induces separation of the cell walls and marked tissue damage in vegetables and their softening (Paciulli et al. 2016). The microstructure of the freeze/thawed samples (Fig.

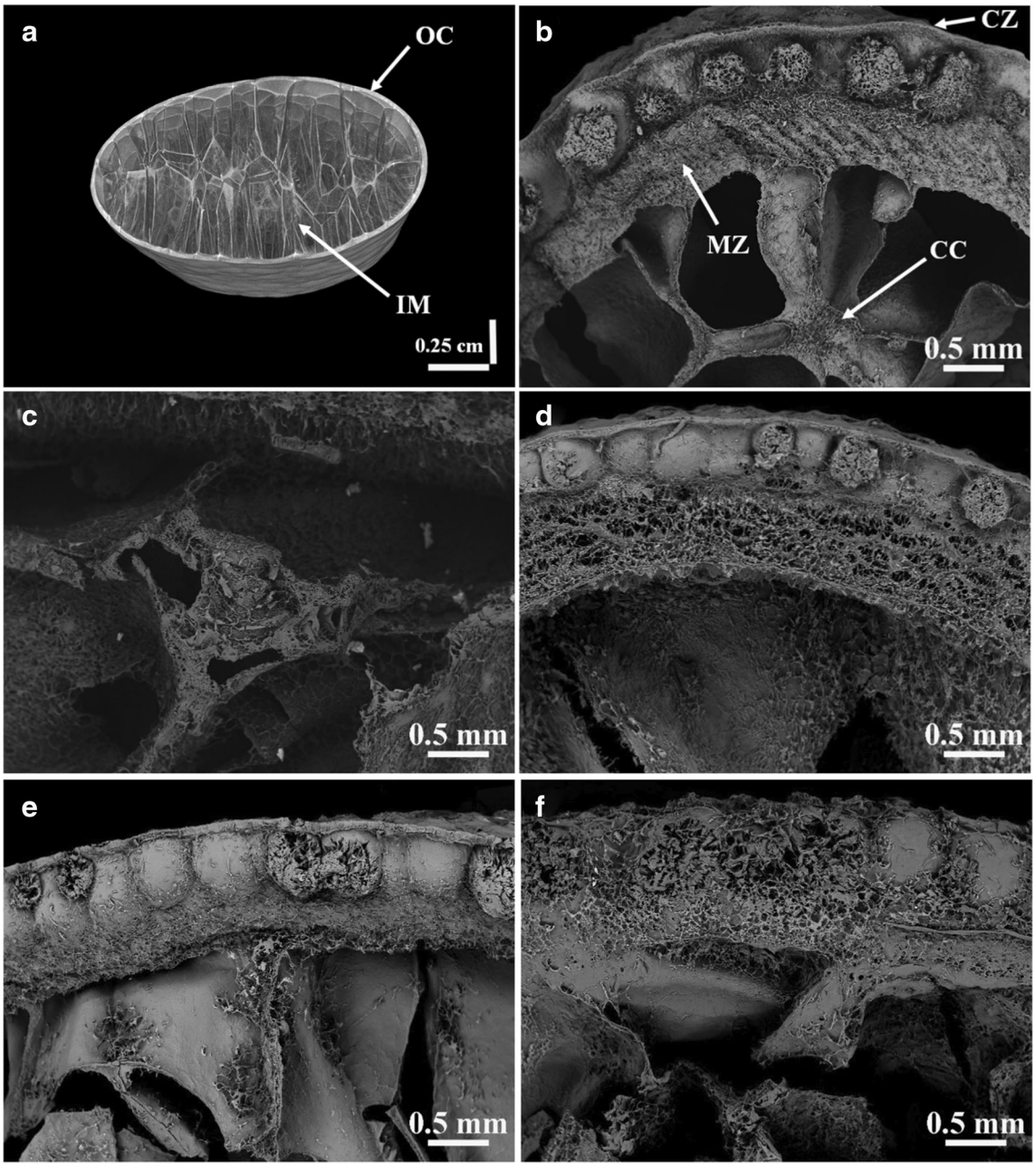

Fig. 3 Images of the microstructure of *Durvillaea antarctica* and effects of processing. **a** Dry seaweed (Micro-CT). Scanning electron microscopy (SEM). **b** Control hydrated seaweed. **c** Hydrothermal processed, 80 °C for 90 min. **d** Frozen/thawed after 3 cycles. **e** Ultrasound processed, 100% power and 15 min. **f** High-pressure processed, 600 MPa and 3 min (OC outer cortex, IM interior medulla, CZ cortical zone, MZ medullary zone, CC central core)

3d) revealed almost no changes with respect to the hydrated control (Fig. 3b). This feature correlates well with texture data in Fig. 2b that shows no significant variations in maximum force even after 3 F/T cycles. These results are in contradiction with F/T studies on fleshy fruits with cellular tissue, where major extensive structural damage due to ice crystallization leads to a reduced firmness (Phothiset and Charoenrein 2013). On the contrary, F/T cycles reinforced the matrix of amorphous tofu (Xu et al. 2016), meaning that a more basic understanding is needed to explain this effect in this seaweed.

It can only be surmised that *D. antarctica* has a stronger and more flexible cellular matrix compared with land plants due to biomechanical requirements of wave-swept seaweeds (Denny and Gaylord 2002). Furthermore, its porous interior and air pockets can better accommodate the expansion of ice crystal formation. Ultrasound processing of *D. antarctica* caused the partial breakdown of the intermediate medullary zone, and some tissue remnants may be appreciated in the interior of the sample (Fig. 3e). Similar microstructural damage was observed using SEM by Nowacka and Wedzik (2016) in carrot

tissue subjected to comparable processing conditions (i.e., 21 kHz for 30 min). Thus, the slight reduction in maximum force after 30 min of application of ultrasound may be explained by the induced tissue damage. Application of high-pressure processing (e.g., from 200 to 500 MPa) to vegetable tissue causes the disruption of the cell walls and the formation of large spaces in the tissue structure (Janowicz and Lenart 2018). Softening of *D. antarctica* samples subjected to high pressures may be explained, at least partly, by the collapse of septa separating the inner air chambers (Fig. 3f).

Conclusions

This article is about the rational application of processing technologies to modify the structure of seaweeds and tailor-make improved or target textures. We found that the application of conventional (HT and F/T) and novel processing technologies (US and HPP) can soften the texture of *D. antarctica* to different extents depending on the value of the variables selected. The biggest softening effect on the texture of *D. antarctica* occurred when the hydrothermal method was applied at 80 ° C for 90 min. HPP at a pressure of 600 MPa and for 1 to 3 min also produced significant changes in texture. Ultrasound and freezing/thawing cycles had minor or no effect at all on texture. These results correlate well with microstructural changes revealing damage at the cellular level. HT processing is a simple method to soften this seaweed in the home kitchen, while HPP may become an interesting alternative to pre-process the algae before commercialization as a ready-to-cook product. Further studies should involve changes induced by processing on nutritional value and sensorial perception.

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