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Seaweeds rehydration and boiling: Impact on iodine, sodium, potassium, selenium, and total arsenic contents and health benefits for consumption

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ABSTRACT

Considering the importance of seaweeds for the development of sustainable and innovative food products, this study aimed to characterize the impact of hydrothermal processing on iodine, sodium, potassium, selenium, and arsenic concentrations of four seaweed species (*S. latissima*, *L. digitata*, *U. pinnatifida*, and *C. crispus*) and on the associated health risks-benefits for consumers. These elements revealed a common pattern for leachable fractions of iodine, total arsenic, and selenium: *L. digitata* ≥ *S. latissima* > *C. crispus* > *U. pinnatifida* after rehydration and boiling during different periods. The behavior for sodium was: *S. latissima* > *L. digitata* > *C. crispus* > *U. pinnatifida,* and for potassium: *U. pinnatifida* > *L. digitata* > *S. latissima* > *C. crispus*. Generally, the species that attained more significant losses were *S. latissima* and *L. digitata*. A health-relevant sodium/potassium ratio below 0.7 was found for all species except for *U. pinnatifida*. In some species, the risk-benefit analysis revealed that high iodine and arsenic levels might promote risks for consumption, even after 20 min boiling, but 5 g of processed *U. pinnatifida* could contribute to adequate iodine, sodium, potassium, and selenium intakes for all population groups. Standardized processing treatments of seaweeds can open new opportunities for the sector.

1. Introduction

Seaweeds are quantitatively the primary biomass in the ocean, with 25 000–30 000 species already known (Qin, 2018). With the growth of the sustainable attitude by consumers, seaweeds have become one of the primary raw material of interest since ocean farming is seemingly more sustainable than land-based agriculture (Tiwari and Troy, 2015). World production of seaweeds comes from two sources: harvesting from wild stocks and aquaculture (including land-based culture and farming) (Ferdouse et al., 2018). The cultivation of seaweeds requires no fresh-water, chemical fertilizer, or land. Considering energy conversion rates from one trophic level to the next, seaweeds farming is much more efficient energetically and nutritionally than animal farming (Qin, 2018). Data from FAO (Ferdouse et al., 2018) demonstrate that the vast majority (~83%) of seaweeds harvested and cultured in the world are consumed by humans, either as a direct food source or as a food additive (White and Wilson, 2015).

Like all food products, sea vegetables need regulation to ensure the quality and safety of their use for consumers. France was one of the first European countries to establish regulation concerning the use of marine seaweeds as a food source (with 21 macroalgae and 3 microalgae authorized as vegetables and condiments) (CEVA, 2014). However, so far, there are only recommendations from the food safety authority that are not legally binding (Circuncisão et al., 2018).

Seaweeds are a rich source of proteins and minerals (calcium (Ca), magnesium (Mg), potassium (K), iodine (I), sodium (Na), phosphorus (P), nickel (Ni), chromium (Cr), selenium (Se), iron (Fe), zinc (Zn), and manganese (Mn)) (Gupta and Abu-Ghannam, 2011; Roohinejad et al.,

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2017). No land plant approaches seaweeds as sources of metabolically required minerals (MacArtain et al., 2007; Rupérez, 2002). I, in particular, is an essential element that is known to be very abundant in seaweeds (Roleda et al., 2018; Romarís-Hortas et al., 2011; Yen et al., 2015). Although I levels differ greatly depending on species, it has been reported to vary between 4.3 and 2660 mg/kg wet weight (Roohinejad et al., 2017). In addition, I deficiency has been documented as a global problem since the last century (Lazarus, 2014), with one-third of the world population at risk, particularly those who live in areas with low I concentration in the soil (that includes European countries near the sea) (Roleda et al., 2018). The health benefits of I arise from its fundamental role in the functioning of the thyroid gland and the associated production of thyroid hormones (Wells et al., 2017) with a recommended daily intake (RDI) of 150 μg (WHO, 2001). However, I ingestion at levels above the RDI can also negatively affect human health (Roleda et al., 2018); a tolerable upper intake level (UL) of 600 μg/day I was established in Europe (WHO, 2001). Closely related to I, Se was identified as a component of an enzyme that activates thyroid hormone, and while I is a substrate for thyroid hormone synthesis, the selenoproteins protect the thyroid from oxidative stress (Winther et al., 2020). Se, in addition to being an essential element for humans and having antioxidant and anticancer properties, also presents significant effects against induced neurotoxicity by inorganic mercury, and it is essential for immunity (Moreda-Piñeiro et al., 2013; Ralston and Raymond, 2010). Macroalgae are known as excellent sources of this nutrient, and Moreda-Piñeiro et al. (2013) reported that among the analyzed seafood, macroalgae presented the most satisfactory Se bioavailability results. However, Se contents of edible plants range from negligible to toxic concentrations, which can affect consumer's health (Ralston and Raymond, 2010). Na, one of the minerals present with the highest levels in seaweeds (Pereira, 2018), is an essential regulator of blood pressure, with higher intakes correlated with raised blood pressure, and reduced intakes to excessively low blood pressure. Both low and excessive Na intake was shown to be associated with higher mortality rates (Whelton, 2014a). Concerning K, besides being a physiologically essential nutrient to humans, it is a healthy alternative to the consumption of Na. Their coexistence is essential to prevent adverse health effects, where high Na to low K ratio became the most critical factor in the modern era of hypertension risk. Clinical trials confirm the capacity of dietary Na reduction and the use of K supplements to reduce blood pressure without any harmful side effects (Pereira, 2018; Whelton, 2014b).

Seaweeds, however, may also be a source of toxic metals (Circuncisão et al., 2018), which is a crucial aspect to have also in mind when considering seaweed consumption. Values of the most toxic elements (cadmium (Cd), arsenic (As), mercury (Hg), and lead (Pb)) in the majority of edible macroalgae have been reported below the maximum concentrations allowed for human consumption (Circuncisão et al., 2018; Roleda et al., 2019) except for As, which can be found in significant amounts, particularly in brown seaweeds (Mouritsen et al., 2013). As is associated with several disorders (nephrotoxicity, diabetes, hepatotoxicity, cardiovascular dysfunction, and cancer, mainly at the skin, lungs, and bladder) (Desideri et al., 2016; Rose et al., 2007). The predominant form of As in seaweeds is the organic form that exerts low toxicity (Circuncisão et al., 2018; Roleda et al., 2019; Rose et al., 2007; Sánchez-Rodríguez et al., 2001). Considering the importance of these sustainable bioresources for the development of innovative products by the food industry (and other related sectors), risks and benefits associated with the ingestion of I, Se, total arsenic (tAs), K, and Na (after commonly applied hydrothermal treatments of seaweeds) were analyzed in this research study.

The effects of thermal processing on nutrients, phytochemicals, and contaminants in seaweed food products are yet poorly described (Ho and Redan, 2020). Some studies have already mentioned that procedures such as packaging and drying can affect seaweed's nutritional value, chemical composition, and associated bioactivity (Charles et al., 2020; Chau et al., 2017; Chung et al., 2013; García-Sartal et al., 2013; Grimes et al., 2018; Pereira, 2018; Pina et al., 2014; Stévant et al., 2018a). To the best of our knowledge, the characterization of the influence of the typical in-home washing and cooking procedures on seaweed levels of different elements with a high impact on human health was not yet under scrutiny. Still, Rose et al. (2007) characterized the As levels before and after processing species of hijiki seaweeds, and Nitschke and Stengel, 2016 quantified the I loss in edible Irish seaweeds during processing. These authors analyzed I in red, brown and green seaweeds after harvesting, washing, drying for 72 h, rehydrating for 24 h, and boiling for 20 min. The results revealed that washing and drying almost did not affect I levels, but rehydration and cooking reduced I values by up to 75% (Nitschke and Stengel, 2016). Recently, Nielsen et al. (2020) studied the effect of blanching on *Saccharina latissima* (*S. latissima*), I, amino acids, fatty acids, and other valuable compounds content. Also, Stévant et al. (2018b) suggested that soaking treatments in water at 32 °C can be a way to reduce undesired levels of I and Cd in *Alaria esculenta* and *S. latissima*. Only a few seaweeds are consumed fresh as harvested, and typically seaweeds are dried to avoid spoilage being rehydrated in water before use (Mouritsen et al., 2013).

Therefore, the purpose of this work was to study the impact of macroalgae processing (rehydration and boiling) typically done by consumers and by the industry, on I and Se, but also on Na, K, and total As (tAs) levels, due to their health relevance and characterize the associated health risks and benefits for consumers. The selected species were one Rhodophyta (red seaweed): *Chondrus crispus* (*C. crispus*) and three Phaeophyceae (brown seaweed) species*: S. latissima, Laminaria digitata (L. digitata ('Kombu')),* and *Undaria pinnatifida (U. pinnatifida ('Wakame')*) based on their commercial relevance and availability in Europe.

2. Materials and methods

2.1. Equipment

Ultrapure water (resistivity 18.2 MΩ cm), obtained from a Milli-Q Simplicity 185 system (Millipore, Molsheim, France), was used throughout this work to prepare standard solutions. Tap water was used in the rehydration and boiling experiments to mimic the home-made conditions.

Sample drying was performed in an Excalibur 4900 food dryer (Sacramento, USA).

An ultra-centrifugal mill ZM 200 grinder (Recht, Germany), with a 2.0 mm fixed ring sieve, was used to grind and homogenize the dehydrated samples.

The moisture content was determined in an oven J.P. Selecta, S.A. (Barcelona, Spain).

Microwave-assisted acid digestion was performed in a MARS-X 1500 W (Microwave Accelerated Reaction System for Extraction and Digestion, CEM, Mathews, NC, USA), using 12 polytetrafluoroethylene (PTFE) digestion vessels and temperature (Probe RTP - 300 Plus, CEM; ± 3 °C) and pressure (Digital Pressure Gauge ESP 1500 Plus, CEM; ± 10 psi) control sensors.

The analysis of I, Se, and total As was performed in an inductively coupled plasma - mass spectrometer iCAP™ Q ICP-MS instrument (Thermo Fischer Scientific, Bremen, Germany). A ContrAA 700 high-resolution continuum source flame atomic absorption spectrometer (HR–CS–FAAS, Analytik Jena, Germany) was used for the analysis of Na and K.

2.1.1. Reagents

The following reagents were used: Suprapure 65% (v/v) nitric acid (HNO_3) from Merck, (Darmstadt, Germany), nitric acid 69% (v/v) *p. a.* (HNO_3) from Panreac (Barcelona, Spain), ammonium hydroxide 25% (v/v) (NH_4OH) from Sigma-Aldrich (Steinheim, Germany), standard stock solutions of Na and K (1000 mg/L) from Carlo Erba Reagents (Barcelona, Spain), cesium chloride (CsCl) from Panreac, (Barcelona,

Spain), ICP-MS 200.8-CAL1-1 (Isostandards Material, Madrid, Spain), ICP-MS 200.8-CAL2-1 (AccuTrace Reference Standard from AccuStandard, USA), and Plasma CAL Q.C.N.3 (SCP Science, Canada).

All container materials were washed before use with regular and deionized water, then soaked in a 10% (v/v) nitric acid bath, and finally rinsed several times with deionized water before use.

2.1.2. Seaweeds collection

Seaweed species used in this study were: *C. crispus*, *S. latissima*, *L. digitata* and *U. pinnatifida*. One kilogram of dehydrated *C. crispus, L. digitata* and *U. pinnatifida* was purchased to ALGAplus (Ílhavo, Portugal), ALGAMAR (Pontevedra, Spain) and Trevijano S.L (Navarra, Spain), respectively. In addition, 1.3 kg of dehydrated *S. latissima* were acquired from multitrophic salmon aquaculture in Bergen, Norway. Seaweeds from each selected species were cut into large pieces and mixed to prepare a composite sample. Samples were stored in sealed bags at room temperature in the dark during the entire study.

2.1.3. Seaweeds processing

The composite seaweed samples were submitted to preliminary processes that intended to mimic the homemade cooking techniques performed by consumers. The samples were rehydrated and boiled during different periods (Fig. 1), according to the label instructions of the products. To evaluate the effect of hydration on the elemental composition of seaweeds, *ca.* 5 g of composite sample (in triplicate) were hydrated in 50 mL tap water at room temperature for 5 min and then drained for 5 min. After this step, *ca.* 2 g of the seaweeds were used for moisture determination, and the remaining hydrated seaweeds were used for element determination.

For the subsequent processing steps, three portions of the composite samples (*ca.* 5 g each) were hydrated for 5 min in 50 mL of tap water and drained for 5 min. Then, the hydrated samples were put in boiling water (50 mL tap water), and the desired boiling times (1, 2, 5 and 20 min; time measured when the boiling restarted) were applied. After reaching the desired time, seaweeds were immediately removed, and after a draining step of 5 min, 2 g of the processed samples were used to determine the moisture in the boiled samples, and the remaining seaweed was subsequently dehydrated for 12 h at 41 °C. Finally, dehydrated samples were homogenized by grinding at 8000–12000 rpm using a 2.0 mm sieve and stored until elemental (I, Na, K, Se, and tAs) analysis. All procedures were made in triplicate per species and simultaneously per process.

2.1.4. Leachable fraction

The total leachable fractions (LF) of elementss were determined based on the percentage loss of the element concentration remaining after the rehydration step (Equation (1)) or after 20 min boiling (Equation (2)) against the concentration present in the dehydrated commercial seaweeds (control) (Hou et al., 1997).

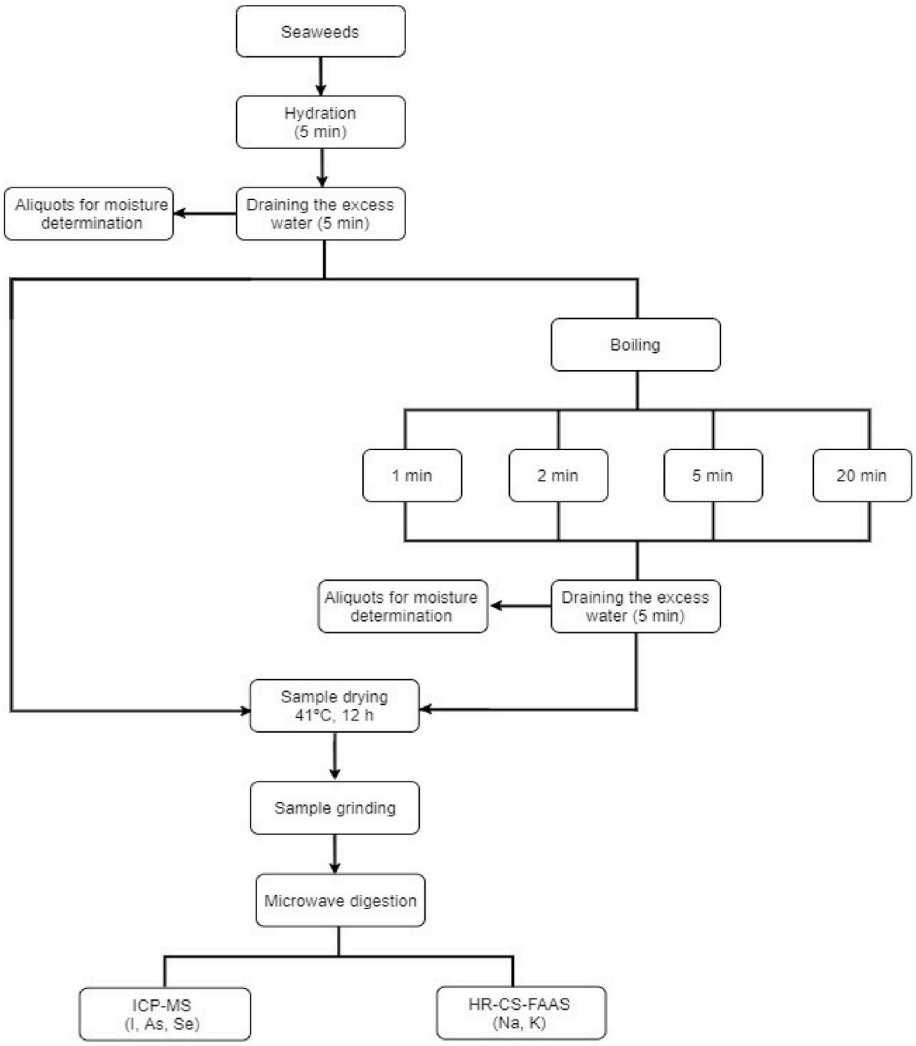


Fig. 1. Schematic flow chart summarising the study design of seaweeds processing.

LF_{cold} (%) = [(element concentration of the commercial dry seaweed - element concentration after rehydration for 5 min) / (element concentration of the commercial dry seaweed)] × 100 (1) or LF_{hot} (%) = [(element concentration of the commercial dry seaweed - element concentration after 20 min boiling) / (element concentration of the commercial dry seaweed)] × 100 (2)

2.2. Chemical analyses

Moisture was evaluated for the dried seaweeds as acquired, after being hydrated, and for the boiled samples using an oven at 105 °C. Moisture content was determined using *ca.* 2 g of each sample according to the official Association of Official Analytical Chemists (AOAC) method (Ensminger, 1976).

For microwave-assisted acid digestion, *ca.* 0.2 g of homogenized sample was weighed in a microwave PTFE vessel, and 10.0 mL of suprapure nitric acid were added. The applied microwave program was as follows: 15 min at 50 °C and 150 psi (10.2 atm) (stage 1), 10 min at 100 °C and 200 psi (13.6 atm) (stage 2), and 15 min at 150 °C and 200 psi (13.6 atm) (stage 3) (Torrinha et al., 2014). After cooling down, the vessels were opened and 2.5 mL of the sample acidic digest were added to 20 mL of NH_4OH (1:1; v/v) solution to further perform I analysis by ICP-MS (LOD 6.75 ng/g dry weight (dw)) (Leite et al., 2017; Pacquette et al., 2013). The remaining digest volume was stored in polyethylene flasks at −20 °C until metal analysis.

Se (LOD 6.04 ng/g dw) and As (1.74 ng/g dw) analyses were carried out by ICP-MS, according to Cabrita et al. (2016), while Na (LOD 0.370 μg/g dw) and K (LOD 0.390 μg/g dw) were analyzed by HR–CS–FAAS according to Oliveira et al. (2015). I, Se, As, Na and K were also determined in the ultrapure and tap water used in the experiments described previously being the detected concentrations below the respective LODs for I, Se, As and K. Concerning Na, this element was quantified in tap water at 0.711 ± 0.056 mg/L, which is about 500–1000 times lower than the values presented by seaweeds being its contribution to adsorption or absorption by the seaweed not significant.

2.2.1. Risk-benefit analysis

The risk-benefit analysis was based on the adequate intake (AI), tolerable upper intake (UL), and acute and chronic reference dose (RfS) established for the determined elements and different population groups (Table S1).

2.3. Statistical analysis

Statistical analyses were performed with IBMS SPSS for Windows, version 26 (IBM Corp., Armonk, N.Y.) (IBM Corp, 2019). The data normality was assessed by Kolmogorov–Smirnov and Shapiro–Wilk tests, and by visual inspection of histograms. Elemental concentrations were expressed as mean ± standard deviation. Comparisons between groups were made using the Mann-Whitney test, and a Bonferroni correction was applied for *post-hoc* corrections, which yielded a level of significance of $p < 0.05$ for the *post-hoc* comparisons of seaweed processing and a value of $p < 0.01$ for seaweed species.

3. Results and discussion

3.1. Effect of seaweeds processing on the moisture

The macroalgae available in the market usually undergo processing by the consumer, i.e., rehydration or boiling, based on label instructions. Moisture results obtained for the four species (Table 1) (before and after processing) were similar to the results found in the literature for the *Laminaraceae* (kelp) family (73–90%) (Guiry, 2011). The (commercial) dehydrated samples presented moisture values close to the label information and were around 10% of total weight. During the rehydration process, the seaweed tissues swell as they absorb water. Simultaneously, some water-soluble components are transferred to the water, representing a loss of total solids (Mišurcová, 2011). Total solids in seaweeds have been identified as proteins, polysaccharides, and polyphenols, including other water-soluble polar compounds (Agregán et al., 2017).

Table 1
Moisture (mean (SD) %; w/w) (n = 3) for the species of macroalgae in the study.

Processing	*U. pinnatifida*	*L. digitata*	*S. latissima*	*C. crispus*
Dehydrated	11.2 (1.2)	13.4 (0.2)	8.5 (0.3)	13.0 (0.1)
H 5 min	75.7 (0.1)	79.0 (0.1)	93.0 (0.1)	69.2 (0.2)
B 1 min	89.0 (0.1)	84.5 (0.1)	91.4 (0.1)	83.4 (0.2)
B 2 min	89.8 (0.1)	87.5 (0.1)	92.7 (0.1)	81.1 (0.1)
B 5 min	92.5 (0.1)	87.5 (0.1)	90.6 (0.1)	84.6 (0.2)
B 20 min	89.3 (0.1)	86.2 (0.2)	94.3 (0.1)	85.5 (0.1)

Processing: Dehydrated: commercialized dehydrated form; H 5 min: rehydration 5 min; B 1 min: boiled 1 min; B 2 min: boiled 2 min; B 5 min: boiled 5 min; B 20 min: boiled 20 min. The water temperature was controlled during boiling (100 ± 2 °C).

Boiling seaweeds has an evident influence on the moisture content in all species apart from *S. latissima*. This observation may be related to the texture and brittleness of this seaweed. More extended boiling periods tend to promote an increase in the moisture content of seaweeds making the mineral content of seaweeds to be drawn out, possibly allowing a lower intake of the elements studied in this work. Throughout this process, the volume of the seaweeds usually also increases to several times that of the dried sample (Mouritsen et al., 2013). Previous studies (Agregán et al., 2017; Fellows, 2009) have shown that water removed from food during dehydration cannot be restored similarly when the food is rehydrated (rehydration is not the reverse of drying). Irreversible effects such as loss of cellular osmotic pressure, changes in cell membrane permeability, solute migration, crystallization of polysaccharides, and coagulation of cellular proteins all are responsible for textural changes and volatile losses (Fellows, 2009). The rate and extent of rehydration depend on the initial drying conditions and the quality of food; the less damage presented by the food sample, the more rapidly and completely the food rehydrates (Fellows, 2009). Dehydrated food products, such as seaweeds, are usually rehydrated before consumption (Cox et al., 2012). The rehydration process is intended to restore the properties of the fresh product (Cox et al., 2012). As reported in previous works, in general, seaweeds' water absorption capacity increases when using higher rehydration temperature from 20 to 100 °C (Cox et al., 2012). According to Cox et al. (2012), the time required to reach a moisture equilibrium content of dried seaweeds decreases as the rehydration temperature increases. This shows that higher temperatures are more effective in reaching a maximum rehydration capacity in shorter periods. The same observation was made in this work, with seaweeds reaching a moisture content equal or higher than the fresh seaweed. Cox et al. (2012) reported that *Himanthalia elongata* could rehydrate with a final moisture content equal or higher than fresh seaweed. The authors concluded that the hydrophilic properties present in this seaweed (even after harvested and dried) could absorb sufficient water at varying temperatures (from 20 to 100 °C) (Cox et al., 2012).

Morphology and composition also influence moisture levels. Some Rhodophyta species may have a relatively low water content than other macroalgae types (Cox et al., 2012). The red seaweeds *C. crispus* presented a value of 69.2% when rehydrated (during 5 min in the present study), which is lower than the reported value of 84% after hydrating for 30 min (Pina et al., 2014), probably due to the different hydration periods applied in both studies. Likely, moisture equilibrium was not achieved during the rehydration process using water at room temperature (Cox et al., 2012). Pina et al. (2014) reported a moisture content of 90.6% for boiled seaweed, which is similar to the value obtained in this work.

3.2. Concentration of I, tAs, Se in processed seaweeds

Seaweeds are abundant in essential elements, but in many species, toxic metals that can affect human health are also present (Biancarosa et al., 2018; Circuncisão et al., 2018; Rupérez, 2002; Sánchez-Rodríguez et al., 2001; Soares et al., 2017). The I content was one of the focus of the study, and even though the ingestion of this component is essential, excessive ingestion can be dangerous to human health. Thus, one of the purposes of this work was to measure I levels in seaweed to assess that the adequate intake day (AI) of I was not exceeded after consuming processed seaweed. Besides I, the quantification of Se had the same purpose (Pereira, 2018). Concerning As, the goal was to ensure that the levels were below the UL. I, tAs, and Se contents determined in the dehydrated (commercial form of seaweed as obtained) and the rehydrated seaweeds, and throughout all the processing steps, are presented in Table 2.

The genus *Saccharina* and *Laminaria* are species that can accumulate I in the range of 3–10 g/kg dry weight (dw) (Lüning and Mortensen, 2015), being the most active accumulators of I among living organisms (Küpper et al., 2008). Besides family and species, several factors are responsible for different patterns of I accumulation in macroalgae, such as the location, salinity, tidal amplitude, and temperature (Schiener et al., 2015). The series that describes I levels in the characterized seaweeds before processing is: *L. digitata* > *S. latissima* > *C. crispus* > *U. pinnatifida*. The evaluation of I contents demonstrated that the commercial *L. digitata* presented a lower quantity (4228 (46) μg I/g dw) when compared with those reported in the literature, that can reach 10×10^6 μg I/g dw (Ar Gall et al., 2004; Circuncisão et al., 2018; Roleda et al., 2018). This could be justified by variations of I levels in the aquatic environment, the impact of the origin (wild or farmed) (the species analyzed in this study were farmed, so the expected I levels are lower), or losses during the processing of seaweeds before commercialization (Lüning and Mortensen, 2015). *S. latissima* presented I values of 2510 (47) μg I/g dw. In literature, the reported quantities varied between 958 and 46×10^5 μg I/g dw (Biancarosa et al., 2018; Cabrita et al., 2016; Circuncisão et al., 2018). This variation could be justified by the environmental factors, as previously described (Pereira, 2018). Considering the Rhodophyta class, *C. crispus* revealed one of the highest I level (Biancarosa et al., 2018). The obtained value of 775 (56) μg I/g dw agreed with those found in literature, $245–20\times10^4$ μg I/g dw. The same was observed for *U. pinnatifida* [238 (4) μg I/g dw vs 220–300 μg I/g dw] (Circuncisão et al., 2018; Kolb et al., 2004; Rupérez, 2002).

The applied processes (rehydration and boiling) reduced the amount of I in all species considerably due to its water-soluble form, except for *C. crispus*. Comparing the different dried seaweeds, all samples presented different I values. After the rehydration at room temperature, all species (except for *C. crispus*) exhibited a significant reduction of concentration (*L. digitata*: 43.1%, *S. latissima*: 7.6%, *U. pinnatifida*: 27.3%). Moreover, after boiling for 1 and 2 min *L. digitata* and *S. latissima* presented reduced concentrations (32.3% vs 29.8%), though not significantly different between both species. This behavior might be explained by the fact that they belong to the same family and are morphologically similar. However, after 5 and 20 min of boiling, I values were statistically different when comparing these two species. When analysing the results of processing for each species, the concentration of the elements generally decreases with the increasing of boiling time. Some exceptions were observed for I for example in *U. pinnatifida* [B 2 min, 118 (17) μg/g dw; B 5 min, 170 (21) μg/g dw and B 20 min, 161 (4) μg/g dw], *S. latissima* [B 2 min, 1628 (35) μg/g dw; B 5 min, 2339 (50) μg/g dw; B 20 min, 1128 (52) μg/g dw] and *C. crispus* [H 5 min, 754 (18) μg/g dw; B 1 min, 824 (21) μg/g dw; B 2 min, 552 (19) μg/g dw; B 5 min, 724 (10) μg/g dw, B 20 min, 779 (34) μg/g dw]. After boiling, seaweeds were drained for 5 min to eliminate excess water, but no washing step was performed. Therefore, the viscous liquid could still be present on the surface of the seaweed tissues, and the co-extracted elements present in the viscous fluid could contribute to the observed values. Also, the natural variability of seaweeds' mineral elementary content depends on the growth stage, algal tissue sampled, and sampling site (Hou et al., 1997; Roleda et al., 2018; Sánchez-Rodríguez et al., 2001), helping to explain the discrepancies observed. These factors can also explain the variability observed for tAs and Se. The thermal process can damage the integrity of plant tissue, particularly cellular membranes. The increase of the rehydration temperature can cause the degradation of seaweed's texture and promote a significant loss of the mechanical resistance of samples. This excessive softening of tissues can affect mass transfer (Cox et al., 2012).

Regarding *U. pinnatifida* and *C. crispus*, a different behavior was detected because no effect of the increase of the temperature and duration of the rehydration step on I levels was noted. As reported by Hou et al. (1997), in some species, I is mainly organically bounded to the seaweeds tissues and, although boiling damage the plant tissues, this is not sufficient to degrade the organic molecules and free the I. Still, to ensure that the amount of I ingested does not represent a health risk, the boiling or even the rehydration procedures must be applied by consumers, mainly in brown seaweed species, where reductions can be more significant.

Seaweeds are known to contain high concentrations of As compared to terrestrial plants (Rose et al., 2007). The series that describes the order of tAs levels in the characterized seaweeds before processing were: *L. digitata* > *S. latissima* > *U. pinnatifida* > *C. crispus*. Overall, the highest levels of tAs were found in brown seaweeds as expected (reported values for tAs in brown seaweeds vary between 21 and 120 μg/g dw (Biancarosa et al., 2018), while red seaweed showed the lowest values (Circuncisão et al., 2018). Different levels of As in seaweeds could be attributed to retention and excretion capacities associated with each seaweed species (Farías et al., 2007). A literature review revealed tAs

Table 2
Concentrations of I, tAs, and Se (mean (SD) μg/g dw) in the characterized seaweeds before and after different processing steps.

Processing	*U. pinnatifida*	*S. latissima*	*L. digitata*	*C. crispus*
I				
Dehydrated	238 (4)^{a,A}	2510 (47)^{a,B}	4228 (46)^{a,C}	775 (56)^{a,D}
H 5 min	173 (17)^{b,A}	2319 (62)^{b,B}	2406 (149)^{b,B}	754 (18)^{a,C}
B 1 min	160 (16)^{b,A}	1812 (35)^{c,B}	1724 (45)^{c,B}	824 (21)^{a,C}
B 2 min	118 (17)^{c,A}	1628 (35)^{d,B}	1629 (15)^{c,B}	552 (19)^{b,C}
B 5 min	170 (21)^{b,A}	2339 (50)^{ab,B}	1539 (33)^{cd,C}	724 (10)^{a,D}
B 20 min	161 (4)^{b,A}	1128 (52)^{e,B}	945 (15)^{e,C}	779 (34)^{a,D}
Se				
Dehydrated	2.62 (0.16)^{a,A}	11.5 (0.4)^{a,B}	8.91 (0.14)^{a,C}	6.25 (0.31)^{a,D}
H 5 min	2.37 (0.19)^{ab,A}	3.22 (0.15)^{b,B}	3.44 (0.09)^{b,B}	7.85 (0.51)^{b,C}
B 1 min	2.05 (0.07)^{b,A}	3.47 (0.09)^{c,B}	3.47 (0.10)^{c,C}	11.6 (1.1)^{c,D}
B 2 min	1.64 (0.04)^{c,A}	2.35 (0.14)^{d,B}	2.29 (0.14)^{c,C}	4.57 (0.12)^{d,D}
B 5 min	1.55 (0.03)^{c,A}	1.76 (0.07)^{c,B}	2.82 (0.15)^{cd,C}	11.0 (0.3)^{c,D}
B 20 min	0.68 (0.01)^{d,A}	1.57 (0.20)^{c,B}	0.90 (0.08)^{e,C}	11.1 (0.2)^{c,D}
tAs				
Dehydrated	42.8 (0.4)^{a,A}	68.1 (4.0)^{a,B}	79.3 (2.7)^{a,C}	13.2 (0.5)^{a,D}
H 5 min	29.8 (0.9)^{b,A}	47.1 (0.9)^{b,B}	55.8 (1.0)^{b,C}	11.3 (0.1)^{b,D}
B 1 min	36.2 (0.8)^{c,A}	41.8 (0.9)^{c,B}	41.8 (0.8)^{c,C}	8.82 (0.18)^{c,D}
B 2 min	26.5 (1.4)^{bd,A}	38.9 (0.6)^{c,B}	35.1 (1.4)^{c,C}	8.54 (0.17)^{c,D}
B 5 min	29.6 (1.3)^{bd,A}	45.9 (1.3)^{d,B}	35.6 (1.3)^{c,C}	9.62 (0.19)^{d,D}
B 20 min	24.7 (0.7)^{d,A}	28.3 (0.3)^{e,B}	25.9 (0.9)^{d,C}	10.5 (0.1)^{e,D}

Processing: Dehydrated: commercialized dehydrated form; H 5 min: rehydration 5 min; B 1 min: boiled 1 min; B 2 min: boiled 2 min; B 5 min: boiled 5 min; B 20 min: boiled 20 min *Within columns for each element, significant differences between processing are shown by different lower case (Mann-Whitney *U* test using a Bonferroni critical value of $p < 0.05$). ** Within lines, significant differences between seaweeds species are shown by different upper case (Mann-Whitney *U* test using a Bonferroni critical value of $p < 0.01$).

concentration for *U. pinnatifida*, 32–70 μg/g dw, *L. digitata*, 27–49 μg/g dw, *S. latissima*, 28–120 μg/g dw, and *C. crispus*, 4–26 μg/g dw. In the present study, the obtained tAs concentration values were: 42.8 μg/g dw for *U. pinnatifida*, 79.3 μg/g dw for *L. digitata*, 68.1 μg/g dw for *S. latissima,* and 13.2 μg/g dw for *C. crispus*. These results agree with the previous studies (Biancarosa et al., 2018; Circuncisão et al., 2018; Kolb et al., 2004; Pereira, 2016; Rupérez, 2002).

The first step that consumers usually take before macroalgae consumption is washing and rehydrating, following the label instructions. After 5 min of rehydration, the values obtained show that this step is very efficient in tAs removal for all seaweeds species (*L. digitata*: 29.7%, *S. latissima*: 30.8%, *U. pinnatifida*: 30.4% and *C. crispus*: 14.4%). Total As after rehydration was greater in *L. digitata* (79.3 μg tAs/g dw) and lower in *C. crispus* (13.2 μg tAs/g dw) as already reported in other studies (Desideri et al., 2016; Kolb et al., 2004; Rose et al., 2007). *U. pinnatifida* results show that between the rehydration and boiling processes, as also observed for I, overall, no marked differences were detected. The other species revealed significantly lower values during thermal processing, particularly after boiling over 20 min. In the report of Rose et al. (2007), tAs and inorganic As were quantified after preparation and cooking, following the product packaging labels. The authors reported that for every treated macroalgae species, iAs and tAs decreased during preparation and cooking (Rose et al., 2007). Considering that cooking implies a boiling period, the obtained results were in accordance with this study.

All dried species in this study presented significant differences in Se concentrations. *U. pinnatifida* and *L. digitata* revealed the lowest Se amounts, whereas *S. latissima* showed the highest Se levels, followed by *C. crispus*. However, a higher content was quantified for these species (11.5 (0.4) μg Se/g dw and 11.6 (1.1) μg Se/g dw, respectively) when compared to reported values (0.06–1.3 μg Se/g dw and 0.07–0.3 μg Se/g dw, respectively) (Biancarosa et al., 2018; Circuncisão et al., 2018; Kolb et al., 2004). This may indicate that these seaweeds were farmed in an inorganic Se-enriched environment (Yan et al., 2004). Significant differences were promoted by boiling for all species for 1 min, but a longer duration did not always imply significant differences for this element. Studies about Se incorporation in seaweeds are scarce, but several reports show that Se accumulation is achieved by active biotransformation of selenite into amino acid-Se molecules (Yan et al., 2004), becoming part of phycocyanin's (Huang et al., 2007; Li et al., 2001; Schiavon et al., 2017). Phycocyanins, together with allophycocyanin, and phycoerythrin are the main classes of phycobiliproteins present in cyanobacteria and red seaweeds (Pina et al., 2014). Phycobiliproteins are chromo-proteins with pigments that absorb light, being a component of chlorophyll. Pina et al. (2014) studied phycobiliproteins, carotenoids (b-carotene and lutein), volatile compounds, and antioxidant activity in dried, hydrated, boiled, and steamed *C. crispus* seaweed. The results showed a significantly higher level of phycocyanin in hydrated and boiled samples when compared with dried samples. Considering that Se is bound or chelated by phycocyanin, the behavior reported in this study seems to corroborate Se values obtained in our work for *C. crispus*.

3.2.1. *Leachable fraction of I, As and Se in processed seaweeds*

The attained leachable fractions of I, As and Se are presented in Fig. 2. The analysis of I leachable fractions revealed that macroalgae present significantly different values between the rehydration and boiling steps and among species. These results show that both *L. digitata* and *S. latissima* contain a significant amount of water-soluble inorganic I with a range of leachable fractions of 43.1–77.6% and 7.6–55.0%, respectively. On the contrary, *U. pinnatifida* revealed a smaller fraction difference (27.3–32.5%). Nielsen et al. (2020) reported a reduction of up to 88% of I content after blanching *S. latissima* in water at ≥ 45 °C and ≥30 s. Lüning and Mortensen, 2015 reported a transfer of approximately two-thirds (66%) of total I in *S. latissima* to the cooking water after only 2 min of boiling. *L. digitata* presented the most substantial decrease in I levels during rehydration. Besides having the highest amount of I, some studies confirm that this species is also the one in which this element occurs mainly in the inorganic form (*ca.* 93%) (Hou et al., 1997). In contrast, *Rhodophyta* species, like *C. crispus*, showed a different behavior. Besides the lowest loss of I to water (0.0%–2.8%), the variation throughout processing was not significant (Fig. 2), with the primary loss occurring during rehydration (2.8%).

The total leachable fractions of As with a 5 min rehydration and throughout the process (hydration to 20 min boiling) were significantly different between species: *L. digitata:* 29.7–67.4% > *S. latissima:* 30.8–58.4% > *U. pinnatifida*: 30.4–42.4% > *C. crispus*: 14.4–20.2%. *S. latissima* and *L. digitata* were the most affected species, while *C. crispus* had a smaller loss of As during rehydration and boiling for 20 min.

The total leachable fraction order of Se (H 5 min- B 20 min) was *L. digitata:* 61.5–89.9% ~ *S. latissima:* 72.1–86.4% > *U. pinnatifida*: 9.7–74.1% ≫ *C. crispus*: 0%. *C. crispus* featured no Se transfer to water when boiled, probably due to the species complexation of Se to phycocyanin (Huang et al., 2007; Li et al., 2001; Schiavon et al., 2017).

In conclusion, the results revealed a series common to all microelements (I, tAs, and Se): *L. digitata* ≥ *S. latissima* > *C. crispus* > *U. pinnatifida*. This confirms the role of speciation, complexation, and subcellular localization of I, tAs, and Se in the seaweed species investigated (Hou et al., 1997; Nitschke and Stengel, 2016).

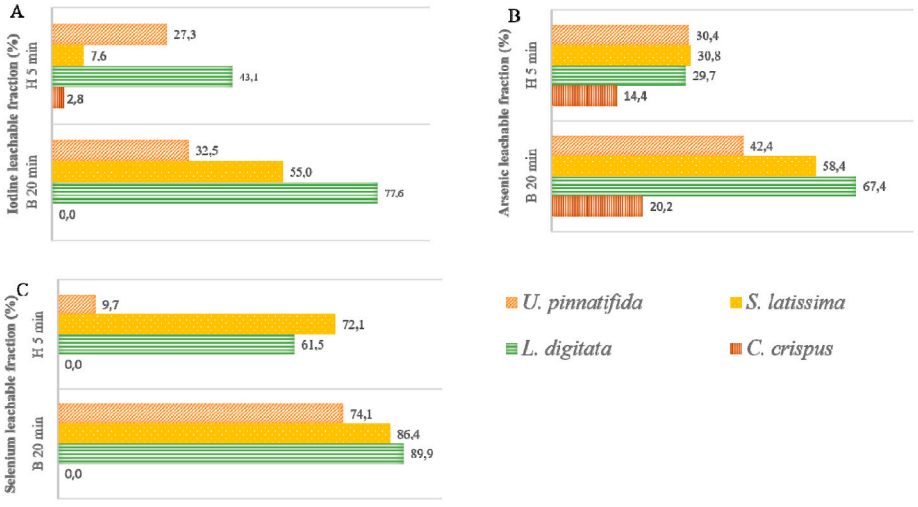


Fig. 2. Leachable fraction of Iodine (A), Arsenic (B), and Selenium (C) in the four species of macroalgae (*U. pinnatifida, S. latissima, L. digitata,* and *C. crispus*) in the 5 min rehydration (H 5 min) and 20 min boiling (B 20 min) steps.

3.3. Concentrations of Na and K in seaweeds after processing

The Na and K values obtained throughout the processing, boiling, and rehydrated seaweeds are presented in Table 3. Significant differences were found for Na between all characterized species (Table 3). Concentrations in the dehydrated samples (total content of Na and K), were in general higher (up to 50%) than those previously reported for: *U. pinnatifida* 48.8–64.9 mg/g dw; *L. digitata* 27–38.2 mg/g dw; *S. latissima* 24 mg/g dw; and *C. crispus* 12–42.7 mg/g dw (Biancarosa et al., 2018; Cabrita et al., 2016; Circuncisão et al., 2018; Kolb et al., 2004; Pereira, 2016; Rupérez, 2002). Some variability within processing was also observed (Table 3), namely for Na in *S. latissima*, *L. digitata* and *C. crispus*. As described previously for other elements, macroalgae composition varies with environmental factors. The packaging process and dehydration method can justify some variations in the specific case of Na in commercial dehydrated samples (Nitschke and Stengel, 2016) since a significant amount of Na is found in the seaweeds surface. Nevertheless, all species revealed significant differences throughout the processing steps, with more significant losses (50–60%) after 20 min boiling. Hou and Yan, 1998, reported a decrease of Na for the brown seaweed *Sargassum kjellmanianum* of around 77% after three times leaching with water.

L. digitata was the species with higher total K content (126 (2) mg K/g dw) as expected according to the literature review (53–113 mg K/g dw) (Biancarosa et al., 2018), followed by *S. latissima* with 94.6 (2.6) mg K/g dw (reported values between 25 and 120 mg K/g dw) (Biancarosa et al., 2018). Specifically, *U pinnatifida* exhibited 53.0 (2.1) mg K/g dw, agreeing with the levels found in the literature (59.9–68.1 mg K/g dw (Lüning and Mortensen, 2015)) while *C. crispus* (49.2 (0.8) mg K/g dw) displayed higher contents than the previously reported (13.5–31.8 mg K/g dw (Biancarosa et al., 2018). Moreover, it was possible to verify that some boiling periods, particularly 1, 2, and 5 min, did not promote significantly different data. There are no studies on seaweed K behavior during cooking for these species to the best of our knowledge. However, Hou et al. (Hou and Yan, 1998), reported for the brown seaweed *Sargassum kjellmanianum,* a decrease of K of around 77% after leaching three times with water.

Some variability within processing was also observed, for K in *U pinnatifida*. As referred previously for I, tAs, and Se, these discrepancies may be related to the natural variability of the elements within algal tissues (Hou and Yan, 1998; Roleda et al., 2018; Sánchez-Rodríguez et al., 2001) and the viscosity of the solutions after processing.

Table 3
Concentrations of Na and K (mean (SD) mg/g dw) in the seaweeds *U. pinnatifida*, *S. latissima*, *L. digitata* and *C. crispus* obtained after different processing.

Processing	*U. pinnatifida*	*S. latissima*	*L. digitata*	*C. crispus*
Na				
Dehydrated	93.6 (1.3)^{a,A}	54.8 (2.2)^{a,B}	50.1 (0.8)^{a,C}	39.1 (0.7)^{a,D}
H 5min	94.6 (2.0)^{a,A}	21.3 (3.1)^{b,B}	31.2 (1.0)^{b,C}	19.4 (0.5)^{b,B}
B 1min	45.6 (2.4)^{b,A}	30.3 (0.5)^{c,B}	19.3 (0.9)^{c,C}	17.6 (0.8)^{c,C}
B 2min	46.1 (1.7)^{b,A}	21.9 (0.6) ^{bc,B}	22.6 (0.4)^{d,B}	17.9 (0.7) ^{bc,C}
B 5min	40.5 (1.5)^{c,A}	44.5 (2.9)^{b,A}	22.2 (0.1)^{d,B}	20.1 (0.9) ^{bd,C}
B 20min	36.0 (1.1)^{d,A}	26.7 (0.6) ^{bd,B}	19.7 (0.8)^{c,A}	21.1 (0.8)^{d,AC}
K				
Dehydrated	53.0 (2.1)^{a,A}	94.6 (2.6)^{a,B}	126 (2)^{a,C}	49.2 (0.8)^{a,A}
H 5min	31.4 (2.6)^{b,A}	80.1 (1.9)^{b,B}	87.6 (1.24)^{b,C}	43.2 (2.6)^{b,D}
B 1min	34.5 (1.0)^{b,A}	76.2 (1.9)^{c,B}	76.2 (3.2)^{c,C}	30.5 (1.2)^{c,D}
B 2min	21.4 (0.3)^{c,A}	74.7 (1.5)^{d,B}	72.5 (1.5)^{c,B}	35.7 (0.3)^{d,C}
B 5min	25.4 (0.7)^{d,A}	73.3 (0.7)^{d,B}	69.8 (1.1)^{c,C}	36.4 (0.8)^{d,D}
B 20min	22.2 (0.9)^{e,A}	67.0 (0.9)^{e,B}	62.1 (0.4)^{d,C}	38.8 (0.5)^{e,D}

Processing: Dry: commercialized dehydrated form; H 5 min: rehydration 5 min; B 1 min: boiled 1 min; B 2 min: boiled 2 min; B 5 min: boiled 5 min; B 20 min: boiled 20 min *Within columns for each element, significant differences between processing are shown by different lower case (Mann-Whitney *U* test using a Bonferroni critical value of $p < 0.05$). ** Within lines, significant differences between seaweeds species are shown by different upper case (Mann-Whitney *U* test using a Bonferroni critical value of $p < 0.01$).

The analysis of Na and K in seaweeds allowed the calculation of the Na/K ratio. Yang et al. (2011) reported a reduced risk of cardiovascular diseases if a Na/K ratio < 1.0 is observed, showing the importance of this ratio in the human diet. In the current study, a Na/K ratio below 0.7 was found in the seaweeds *S. latissima*, *L. digitata,* and *C. crispus* for all conditions studied, with *U. pinnatifida* the only one with a Na/K ratio >1 (Table 4).

In the species under study, Na/K ratios varied between 0.16 for *L. digitata* (when dried) to 2.16 for *U. pinnatifida* (when boiled for 5 min). WHO (2012) health reports suggest that achieving the guidelines for both the Na and K intakes would yield a Na/K molar ratio of approximately 1.00. Kishida et al. (2020) studied the association between seaweed intake and mortality with cardiovascular diseases and concluded that patients who consumed seaweeds almost daily presented a reduced risk of mortality from these diseases and total stroke. One reason might be associated with the lowering effect of seaweeds on blood pressure (Kishida et al., 2020).

3.3.1. Leachable fractions of Na and K in processed seaweeds

The studied macroelements total leachable fractions are represented in Fig. 3. The percentage loss for K among species and throughout the cooking process were: *U. pinnatifida*: 40.6–58.1% > *L. digitata:* 30.6–50.8% > *S. latissima:* 15.3–29.1% > *C. crispus*: 12.1–21.2%. All species presented a significantly different behavior, although, in all samples, a K transfer was noted during processing.

The order of percentage loss of Na was the following: *S. latissima:* 51.2–61.1% > *L. digitata:* 37.8–60.7% > *C. crispus*: 46.0–50.4% > *U. pinnatifida*: 0–32.0%. *S. latissima* and *C. crispus* revealed a greater Na loss during rehydration when compared with the boiling period. The Na location in the macroalgae could justify this pattern of variation since, in some species, this element is mainly found in the superficial area of the seaweeds, as suggested by other studies (Gutknecht, 1965; Raven, 1976). *L. digitata* and *S. latissima* revealed the highest leachable fraction of this element, 60.7%, and 51.2%, respectively, during the 20 min boiling period. Hou and Yan, 1998 reported a percentage loss for K and Na of 77% for the brown seaweed *S. kjellmanianum* after bleaching three times with water.

When comparing these results with the ones obtained for the microelements analyzed, a different leaching behavior was observed for Na and K, namely: *S. latissima* > *L. digitata* > *C. crispus* > *U. pinnatifida* and *U. pinnatifida* > *L. digitata* > *S. latissima* > *C. crispus*, respectively.

3.4. Risk-benefit analysis

Table 5 represents the calculated percentage intakes (AI and UL/RfD) considering a single ingestion dose of 5 g wet weight (ww) of each seaweed. It is worth noting that tAs was assumed to exist exclusively in the inorganic form (the worst risk scenario).

As represented in the color scale, the I level in all the species epitomizes the risk of macroalgae consumption, mainly when dehydrated. The UL values were mainly superior to 100%. However, some significant

Table 4
Sodium/Potassium mean ratio for the macroalgae species *U. pinnatifida*, *S. latissima*, *L. digitata* and *C. crispus*.

Processing	**Na/K**			
	U. pinnatifida	*S. latissima*	*L. digitata*	*C. crispus*
Dehydrated	1.03	0.36	0.16	0.34
H 5 min	1.32	0.25	0.24	0.39
B 1 min	1.34	0.46	0.29	0.64
B 2 min	1.12	0.32	0.29	0.58
B 5 min	2.16	0.50	0.30	0.49
B 20 min	1.71	0.68	0.32	0.53

Processing: Dehydrated: commercialized dehydrated form; H 5 min: rehydration 5 min; B 1 min: boiled 1 min; B 2 min: boiled 2 min; B 5 min: boiled 5 min; B 20 min: boiled 20 min.

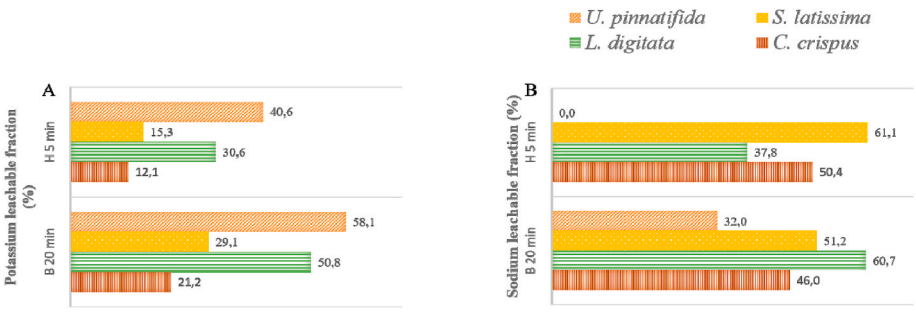


Fig. 3. Leachable fraction of K (A) and Na (B) in the four species of macroalgae (*U. pinnatifida, S. latissima, L. digitata,* and *C. crispus*) in the 5 min rehydration (H 5 min) and 20 min boiling (B 20 min) steps.

decreases were verified throughout the processing, leading to more benefits with extended boiling duration, namely for *U. pinnatifida*. After rehydration and boiling, this species can ensure adequate I intake for all population groups (adults, children (1–3 years) and pregnant/lactating women). For L. *digitata*, the consumption is safe for adults/pregnant women after a boiling period of 20 min (UL: 48%), because I is mainly in water-soluble form, as previously described. Although As concentration in Table 2 is above UL, it is important to emphasize that As measured, was assumed to be in the inorganic form. According to previous studies, the percentage of As in inorganic form ranges from 0.4 to 5.3% of tAs concentration in seafood products (Leblanc et al., 2005). Therefore, even when the upper value reported (5.3%) for inorganic As is used for risk assessment, all seaweeds are likely to be safe for consumption. Nevertheless, data on inorganic As would be precious to refine this assessment based on the attained results.

The obtained results also show that a 5 g ww portion of the characterized species can significantly contribute to the Se AI (adults: *L. digitata* 0–10%, *S. latissima* 1–6%, *U. pinnatifida* 1–5% and *C. crispus* 11–13%; children: *L. digitata* 1–48%, *S. latissima* 5–29%, *U. pinnatifida* 3–24% and *C. crispus* 51–58%; pregnant and lactating women: *L. digitata* 0–9%, *S. latissima* 1–5%, *U. pinnatifida* 0–4% and *C. crispus* 9–10%) without toxicity concerns. The Na and K ingestion does not present any risk and can provide more than 29% (*U. pinnatifida* dried or rehydrated during 5 min) of the adequate daily intake of Na for children and up to 12% of K for children (dried *L. digitata*).

4. Conclusions

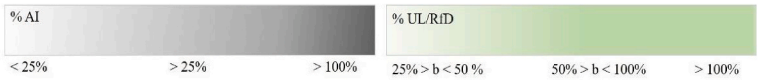
The impact of macroalgae processing (rehydration and boiling) on the levels of I, Na, K, Se and tAs revealed a common pattern for leachable fractions of all microelements (I, tAs, and Se): *L. digitata* ≥ *S. latissima* > *C. crispus* > *U. pinnatifida*. In contrast, a different leaching behavior was perceived for Na and K, namely: *S. latissima* > *L. digitata* > *C. crispus* > *U. pinnatifida* and *U. pinnatifida* > *L. digitata* > *S. latissima* > *C. crispus*, respectively. The more affected species were *S. latissima* and *L. digitata*, disclosing the more significant losses of elements during the processing steps. Some significant dissimilarities in leaching behaviors also needed to be pointed out: *U. pinnatifida* and *C. crispus* showed distinct patterns of variation regarding Na and Se leachability, respectively. Overall, the differences may be due to inter-species differences in the subcellular localization, complexation, retention processes, and speciation of the different elements. The leachable fractions of minerals in seaweeds have been poorly characterized in literature. This study showed that seaweed processing could be an excellent strategy to ensure the delivery of

Table 5
Percentage values for an adequate intake (AI), tolerable upper intake (UL), and reference dose (RfD) for I, As, Se, K and Na for different population groups (Adults, Children (1–3 years) and Pregnant/Lactating) considering a single dose of 5 g ww seaweed.

AI (%)*	*L. digitata*						*S. latissima*						*U. pinnatifida*						*C. crispus*					
	Dehydrated	H 5 min	B 1 min	B 2 min	B 5 min	B 20 min	Dehydrated	H 5 min	B 1 min	B 2 min	B 5 min	B 20 min	Dehydrated	H 5 min	B 1 min	B 2 min	B 5 min	B 20 min	Dehydrated	H 5 min	B 1 min	B 2 min	B 5 min	B 20 min
Adults																								
I	2145	1827	862	656	689	194	705	525	537	431	696	536	213	103	59	35	42	52	797	775	413	347	350	333
Se	10	5	3	2	3	0	6	2	2	1	1	1	5	4	1	1	1	1	13	19	11	6	10	11
K	3	3	2	1	1	1	1	1	1	1	1	1	2	1	1	0	0	0	2	1	0	0	0	0
Na	4	4	2	1	1	1	2	1	1	1	2	1	13	12	3	2	2	2	7	3	2	2	2	2
Children																								
I	3575	3044	1437	1093	1149	323	1176	874	895	718	1159	894	356	171	98	58	71	86	1329	1292	688	579	583	555
Se	48	23	13	9	12	1	29	7	10	6	5	5	24	20	6	5	4	3	58	86	52	26	46	51
K	12	11	7	6	6	4	5	3	4	4	4	2	8	5	2	1	1	2	8	4	2	2	2	2
Na	9	8	4	3	3	1	5	2	3	2	5	3	29	29	7	6	4	5	16	7	4	4	4	4

Pregnant/Lactating																								
I	1609	1370	647	492	517	145	529	394	403	323	522	402	160	77	44	26	32	39	598	581	310	261	262	250
Se	9	4	2	2	2	0	5	1	2	1	1	1	4	4	1	1	1	0	10	15	9	5	8	9
K	2	2	1	1	1	1	1	1	1	1	1	0	2	1	0	0	0	0	2	1	0	0	0	0
Na	4	4	2	1	1	1	2	1	1	1	2	1	13	12	3	2	2	2	7	3	2	2	2	2
UL/RfD (%)*																								
Adults/ Pregnant																								
I	536	457	216	164	172	48	176	131	134	108	174	134	53	26	15	9	11	13	199	194	103	87	87	83
Se	2	1	1	0	1	0	1	0	0	0	0	0	1	1	0	0	0	0	3	4	3	1	2	3
Na	2	1	1	1	1	0	1	0	1	0	1	1	5	5	1	1	1	1	3	1	1	1	1	1
As ** acute	283	271	135	117	114	35	129	80	90	73	112	98	220	190	95	65	51	68	112	88	38	24	24	39
As ** chronic	17	16	8	7	7	2	8	5	5	4	7	6	13	11	6	4	3	4	7	5	2	1	1	2
Children																								
I	1609	1370	647	492	517	145	529	394	403	323	522	402	160	77	44	26	32	39	598	581	310	261	262	250
Se	12	6	3	2	3	0	7	2	2	2	1	1	6	5	1	1	1	1	15	22	13	6	11	13
Na	4	3	1	1	1	1	2	1	1	1	2	1	12	11	3	2	2	2	6	3	1	2	2	2
As acute**	1457	1399	698	604	589	180	664	414	466	375	576	506	1132	977	490	335	264	349	577	452	194	124	126	202
As chronic**	87	84	42	36	35	11	40	25	28	22	35	30	68	59	29	20	16	21	35	27	12	7	8	12

Processing: Dehydrated: commercialized dehydrated form; H 5 min: rehydration 5 min; B 1 min: boiled 1 min; B 2 min: boiled 2 min; B 5 min: boiled 5 min; B 20 min: boiled 20 min. *Single serving portions was considered (5 g ww de macroalgae). ** Assumption: 100% As is iAs.



health-balanced essential micro and macro elements for consumers. A portion of 5 g ww *U. pinnatifida* can contribute to adequate I, Se, Na, and K intakes for all population groups after rehydration and boiling. Moreover, *L. digitata* or *C. crispus* may also contribute significantly to the I (after the processing steps) and Se dietary recommended intakes for adults/pregnant women. The selected seaweeds can help to promote a healthy balance between Na and K. The risk-benefit analysis revealed that the high I and tAs levels in the selected seaweeds, even with a boiling period of 20 min, indicate that parsimonious consumption must be undertaken to ensure that consumers are on the safe side. There are valuable opportunities in a standardized treatment of seaweeds, such as hydrothermal processing. Specific procedures could guarantee the best of the seaweed nutritional capabilities without the detrimental effects of highly toxic elements. This new field of research could improve the seaweeds industry and market, improve dietary patterns, and fight hidden hunger while assuring food safety. In this work, only the effect of hydrothermal processing on the concentrations of several elements was studied but not how processing can affect its bioavailability. As future work, it is necessary to perform bioavailability studies to assess their potential biological effects. Although further research is needed on thermally processed seaweed products, the data presented in this study is highly relevant to inform consumers and optimize in-home processing. Taken all the results together, *U. pinnatifida* showed to be the most appropriate seaweed for consumption, although it presents high I values if consumed dehydrated or only hydrated for 5 min. The best preparation practice for this seaweed is suggested to be washing with running water, hydrating for 5 min and then boiling for at least 1 min (discarding the boiling water) before using in it salads or hot dishes.

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CRediT authorship contribution statement

Helena Correia: Formal analysis, Investigation, Methodology, Writing – original draft. **Cristina Soares:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Validation, Writing – review & editing. **Simone Morais:** Conceptualization, Methodology, Supervision, Validation, Writing – review & editing. **Edgar Pinto:** Methodology, Writing – review & editing. **António Marques:** Conceptualization, Funding acquisition, Investigation, Project administration, Validation, Writing – review & editing. **Maria Leonor Nunes:** Conceptualization, Funding acquisition, Project administration, Validation, Writing – review & editing. **Agostinho Almeida:** Funding acquisition, Methodology, Resources, Validation, Writing – review & editing. **Cristina Delerue-Matos:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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