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Nutritional, physicochemical, and sensory characterization of four common Northern European seaweed species intended for food

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ABSTRACT

Seaweed is depicted as a future food in Western cultures, yet its introduction and expansion to new markets come with several challenges, including food neophobia and limited knowledge about its usability. To address these challenges, this study characterizes sensory perceptions, nutritional content, and physicochemical properties of four common northern European seaweed species, *Saccharina latissima*, *Alaria esculenta*, *Palmaria palmata*, and *Ulva* sp. These species are rich in minerals (25.8–36.8 %) and carbohydrates (29.6–54.6 %), especially dietary fibre (29.8–34.1 %), but have lower levels of dietary protein (6.7–11.4 %) and lipids (1.3–2.4 %). The amino acid profiles almost matched those of complete proteins, but with lower levels of histidine (*Ulva* sp. had also lower levels of lysine). All species were generally perceived to have high taste of saltiness, medium umami, low bitterness and sourness, and no sweetness. Overall, *P. palmata* stood out most from the other species with its red magenta colour, sea and shellfish odour, umami taste, and firm and chewy texture. Contrary, *Ulva* sp. was perceived as the saltiest species, with a lightness in colour and elements of yellow, an odour resembling lemon and fresh grass, and the least crispy, firm, and chewy texture. The two brown species, *S. latissima* and *A. esculenta*, were overall perceived as similar to each other. The mapping of seaweed's attributes in this study can be directly useful as knowledge for the improvement of future seaweed products and their availability in Western food cultures.

1. Introduction

Seaweed consumption is trending in the Western world. Global production nearly increased threefold between 2000 and 2019 [1], magazines allure with catchy headlines, and seaweeds make it to the lists of future foods for healthier people and a healthier planet [2]. It is postulated that seaweed production and consumption have the potential to address some of our time's most urgent challenges and contribute to several of the UN Sustainable Development Goals [3]. However, although seaweed consumption and production are associated with great potential, seaweed foods face different challenges in new Western markets [3–5]. These challenges include for example legal frameworks and novel food regulations, food quality characterization, post-harvest treatment for microbial and chemical food safety, and consumer

characteristics, such as food neophobia. Moreover, research also highlights social aspects of introducing seaweed to new markets, such as the difficulties retailers and consumers encounter, when trying to classify these new foods and integrate them into their everyday life [5].

Today, seaweed polysaccharides are already commonly used in the food industry, due to their technological properties as phycocolloids: e. g., alginates (stabilizing thickening agent (E401 – E405), from brown seaweed), agar (vegetable gelatine, E406) from red seaweeds, and carrageenan (thickening agent, E407) from red seaweeds, which are valued for their gelling, thickening, and stabilizing properties. For many consumers, these utilizations are not visible and labels on packages provide this information in a language that might not be understood in everyday life. Consumers can therefore be unaware of the use of seaweed in their daily food products. Recently, not only extracts, but

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also whole or milled seaweed blades have received interest from Western food industries for use in bakery, dairy, fish, or vegetable-based products. However, the concentration added should be considered to control the sensory quality of the product [6].

Seaweeds have specific sensory properties, with flavours and odours that may be described as marine, crustacean, or green, and tastes of both salt and umami. These properties may be used to include seaweeds in food products with a high potential for gastronomic delicacies [7–10].

Beyond unique sensory properties, seaweeds demonstrate interesting nutritional characteristics. The concentrations of protein range from 5 % to 47 % of the dry biomass (dependent on e.g. season and the type of seaweed), and is a source of all amino acids, of which essential amino acids are reported to represent up to half of the total amino acids [11]. The amount of lipids is low (0.4 % to 4.5 % of dry seaweed biomass), but ω -3 and ω -6 polyunsaturated fatty acids (PUFAs) are a significant part of seaweed lipids, introducing health-beneficial potential [12]. Moreover, seaweeds are rich in dietary fibre (up to 70 % of the dry matter), which are water soluble or insoluble structural, storage, and functional polysaccharides of which many show bioactivity or prebiotic properties. In addition to this, seaweeds are sources of vitamins, minerals, polyphenols, and other bioactive molecules [13]. However, the potential iodine and heavy metal content also raise concerns among researchers and consumers. Hence, food safety poses one potential challenge in introducing seaweeds to Western markets.

The interest in seaweed for food in Sweden and other Nordic countries is also shown through the growing interest in cultivation or harvesting of wild seaweeds in this area. The expectations for a developed aquaculture with seaweed as a future protein source are high, and the environmental benefits are often emphasized. Even if a growing interest in seaweed as a forgotten resource is observed, there are also doubts among many consumers about what seaweeds actually contains. Eating seaweed is still unfamiliar to many people in the Nordic countries, and knowledge of cooking methods and areas of use are quite low, although sushi and seaweed caviar have become more familiar [14]. Even if the contemporary consumer culture is characterized by an interest in new food alternatives, traditional consumption patterns are still structuring our everyday food practices.

Previous research has shown that Swedish consumers are in general positive toward eating seaweed [14,15]. But seaweed has also been described as an ambiguous phenomenon from a consumer perspective [14]; on the one hand viewed as dirty and toxic, and on the other hand as healthy and useful. Seaweed as food is familiar to consumers in various contexts, but mainly while eating out in restaurants. For example, while eating out in “Asian restaurants” consumers expect seaweeds to be on the menu and are familiar with it being integrated into dishes. On the other hand, consumers eating out in restaurants that provide a more “Western” or “Scandinavian” cuisine seem to be surprised about the “unfamiliar” ingredient [14]. In that context, seaweed is currently mainly promoted as local and seasonal food in high-end restaurants that provide the culinary interested consumer with for example New Nordic Cuisine experiences and “wild” as well as “unusual” ingredients [14,16]. In a more everyday context, while shopping, cooking, and eating food at home, consumers’ knowledge of where to buy, and how to integrate seaweeds into their daily diet needs to be expanded [14]. Hereby retailers play an important role in educating consumers and providing seaweed products as well as classifications to aid consumers’ understanding [5]. So far early adopters seem to be consumers that focus on a plant-based diet.

To deeper understand the complexity that connects food production and consumption, interdisciplinary research bringing together different research perspectives is considered necessary [3]. This study unfolds from an interdisciplinary collaboration within the research areas of biotechnology, food and meal science, and social science [17], to better understand the interlinkage between production and consumption related to the introduction and expansion of seaweeds into a Swedish market.

The aim of this study is to explore, by analytical sensory analysis, the sensory properties of dried pieces and powders of four different seaweed species (*Saccharina latissima*, *Alaria esculenta*, *Palmaria palmata*, and *Ulva* sp.) commonly found in northern Europe, and to link them to the biochemical (nutritional) and physicochemical properties. Further, the development and introduction of new seaweed products in Western markets are also discussed. This study investigates the question: ‘how are nutritional content and physicochemical characteristics translated into sensory perceptions of seaweed?’

2. Material and methods

Four different species of dried seaweed were purchased from Connemara Organic Seaweed Company, Ireland. *Saccharina latissima* (L.) C.E. Lane, C. Mayes, Druehl, and G.W. Saunders, 2006, *Alaria esculenta* (L.) Greville, 1830, *Palmaria palmata* (L.) Weber & Mohr, 1805, and *Ulva* sp. (tubular morphology) were selected for the study as they represent common species within the three phyla of marine macroalgae, Ochrophyta (brown), Rhodophyta (red), and Chlorophyta (green), in northern Europe. The wild seaweeds were hand-harvested within 15 miles from the coast of Rossaveal, Ireland, washed in seawater, and dried for 20 h at 38 °C before storage. *S. latissima* (SL), *A. esculenta* (AE), and *Ulva* sp. (U) were harvested in April 2021 and *P. palmata* (PP) was harvested in September 2021, according to the supplier. Dried whole blades (W) and algae powder (P; < 2 mm) were used in this study (Fig. 1). All chemicals were purchased from Sigma Aldrich if otherwise is not stated.

2.1. Sensory analysis

Sensory analysis, including panel selection, descriptive training, and final sensory assessment, was performed in accordance with international standard recommendations (ISO 8586).

Six members of the analytical sensory panel from the sensory unit at Kristianstad University participated in the study. Four species of seaweed, in whole (W) and powdered (P) formulations, were evaluated based on visual appearance (A), odour (O), taste/flavour (F), and texture (T). The training of the panel (ISO 8586), which was planned and carried out by an experienced panel leader, was divided into two sessions of 2 h each. During these sessions, the assessors identified and described sensory attributes related to the seaweed samples. The attributes were further reduced and defined in consensus under the guidance of the panel leader (Table 1). Thereafter the sensory panel was trained for the evaluation by reaching a consensus on how to perform the assessments and how to use the scale. During the final sensory assessment, lasting for 6 h over two days, the panellists assigned each attribute (for all seaweed samples) a value from 0 to 100 on a linear intensity scale. The samples were encoded with three-digit numbers and served in triplicate in a randomized order at room temperature. Water and neutral wafers were served for neutralizing the palate between each serving.

Research carried out in Sweden which includes any processing of sensitive personal data is covered by the Swedish Ethics Review Act. This study includes questions about food perception which, according to the Data Protection Ordinance, are not classified as sensitive personal data. All participants received written and oral information about the analytical test and the contents of the included products, and gave their informed consent to participate.

2.2. Biochemical composition

Composition analysis was performed to biochemically evaluate the nutritional variations between the species. Total solids, ash (minerals) and element speciation, proteins, lipids, and carbohydrates including dietary fibre were analysed.

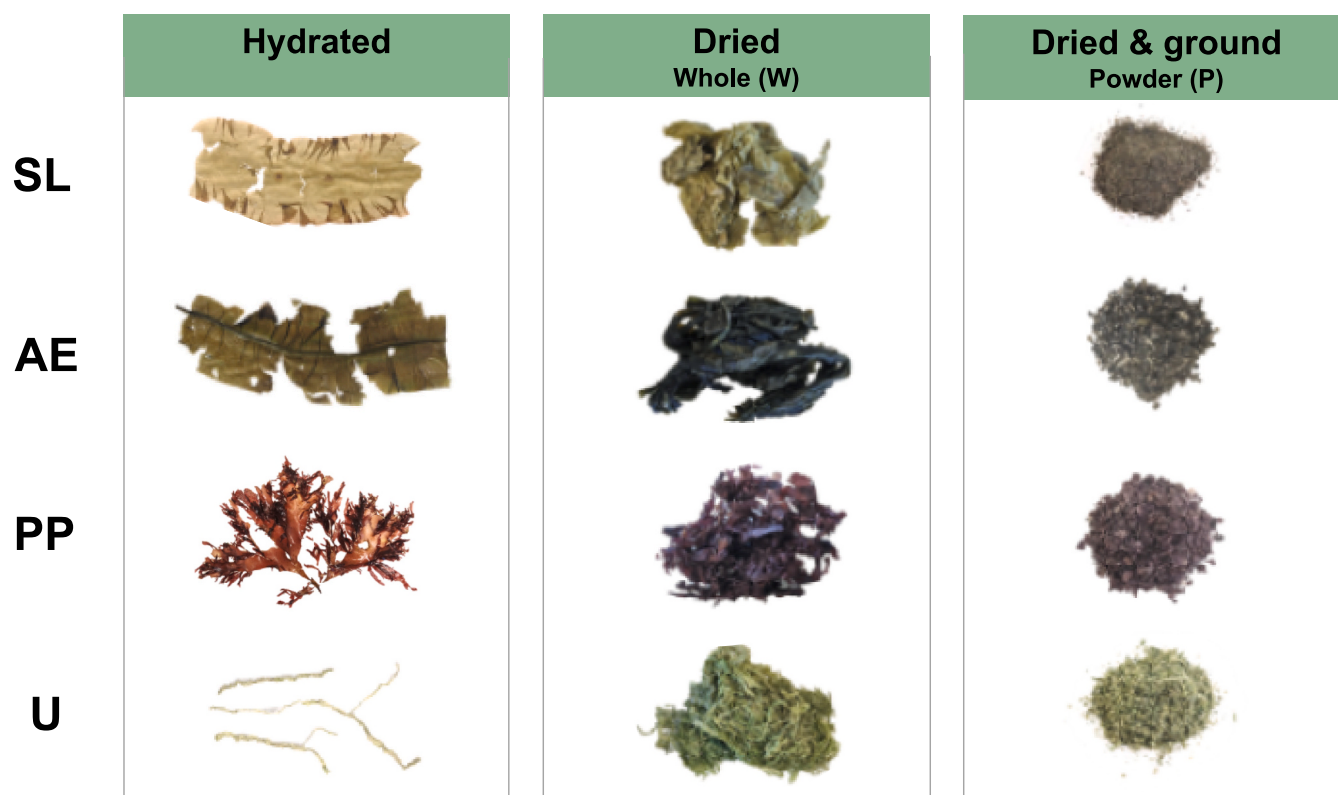


Fig. 1. Images of the four seaweed species in the forms of hydrated, dried (whole, W), and dried and ground (powder, P).

Table 1

Descriptive sensory attributes and their definitions. The attributes were freely translated from Swedish to English by the authors of the paper.

Attribute	Definition
Appearance (A)	
Lightness	Amount of reflecting light
Green	Amount of green colour in sample
Yellow	Amount of yellow colour in sample
Magenta	Amount of magenta colour in sample
Crinkliness (of whole)	Parsley as reference
Milling degree (of powder)	Coarsely grounded pepper and icing sugar as endpoints
Odour (O)	
Grass	Fresh newly cut grass
Sea	Fresh with seaweed
Shellfish	Dried shell
Lemon	Fresh lemon scent
Taste/Flavour (F)	
Taste/flavour intensity	Total flavour intensity of the sample
Saltiness	Basic taste
Umami	Basic taste
Bitterness	Basic taste
Sourness	Basic taste
Grassiness	Fresh newly cut grass
Fish liver oil	Flavour of dietary supplement fish liver oil
Texture (T)	
Crispiness	Firmness and ability to break easily
Chewiness	Elastic resistance from sample
Hardness	Ability to stick together when chewed (firmness of the product)
Adhesiveness	Sticks in the mouth

2.2.1. Total solids, ash, and elemental compounds

Total solids and ash content were gravimetrically determined based on the method by Van Wycken and Laurens (2015) [18]. Total solids were analysed to ensure accurate composition results based on dry weight (DW). Additionally, the analysis of ash provides indications of the overall mineral content in the samples. Crucibles filled with 100 ± 5 mg algal powder ($n = 3$) were heated in an oven at 105°C for 25 h and weighed thereafter to determine the total solid fraction. The same crucibles were then incinerated in a furnace (Nabertherm Controller B180, Germany) for 3 h at $575 \pm 25^\circ\text{C}$ to determine the ash content of the algal samples.

Elemental compounds were analysed by the accredited external laboratory ALS Scandinavia. The algal samples were pre-treated by heated wet digestion in nitric acid (HNO_3) and hydrofluoric acid (HF) before quantification by high resolution inductively coupled plasma mass spectrometry (HR-ICP-MS). Analytes detected from the method include: silver (Ag), total arsenic (As), calcium (Ca), cadmium (Cd), cobalt (Co), chrome (Cr), copper (Cu), iron (Fe), mercury (Hg), potassium (K), magnesium (Mg), manganese (Mn), molybdenum (Mo), sodium (Na), nickel (Ni), phosphorous (P), lead (Pb), sulphur (S), selenium (Se), and zinc (Zn). For the halogenated iodine (I), different volumes and ratios of HNO_3 and HF was used in the sample preparation than for the other elemental compounds. Different weighing and an extra stabilization step by alkalic treatment prior to analysis by HR-ICP-MS was also performed.

2.2.2. Total protein and amino acid profiling

Total protein content in algal samples was determined based on the Dumas method for nitrogen analysis by conversion to protein content using a nitrogen-to-protein conversion factor of 5 [19]. Samples of 25 mg ($n = 3$) were combusted with a N/Protein Analyzer Flash EA 1112 Series (Thermo Electron Corp., Waltham, MA, USA). Aspartic acid was used as a reference.

Amino acid profiling was analysed by the accredited external

laboratory ALS Scandinavia, and their partner lab Chatteris (Cambridgeshire, England), according to intern method AM/V/206. Quantification of free and bound amino acids was determined by High-Performance Liquid Chromatography (HPLC) with fluorescence detection together with nitrogen determination by the Dumas method.

2.2.3. Total lipids and fatty acid profiling

Lipid quantification and characterization of free fatty acids were performed gravimetrically and by gas chromatography (GC) [20,21]. Lipid extraction was carried out by adding 200 ± 0.1 mg seaweed powder ($n = 3$) into Teflon™ capped glass tubes, followed by the addition of 3.75 mL chloroform:methanol solution (1:2 v/v, with 0.05 % BHT w/v for stabilization). Each sample was homogenized (IKA® T25 digital ULTRA TURRAX with dispersion tool S 25 N-8 G, IKA-Werke GmbH & Co. KG, Germany) for 2 min at 16000 rpm to facilitate extraction. A two-phase system was created by adding 1 mL acetic acid (0.15 M), 1.25 mL chloroform, and 1.25 mL MilliQ water. The lower phase was collected and transferred to tubes with known weight after centrifugation for 6 min at 970g. The remaining chloroform was evaporated under N_2 at 40 °C for about 30 min until dryness, and total lipid content was subsequently determined gravimetrically. The samples were resuspended in 250 μ L chloroform, and 50 μ L internal standard (5 mg/mL of C17:0 in chloroform) was added to analyse free fatty acids by GC. Preparation of samples for GC analysis was performed by methylation [22] with 2 mL 2 % (w/w) sulfuric acid in methanol for 30 min at 90 °C. Thereafter, 2 mL MilliQ water and 2 mL cyclohexane were added to the samples which were centrifuged for 5 min at 855g. The upper phase was collected and transferred to new tubes, evaporated under N_2 at 40 °C for about 30 min until dryness, and finally resuspended in 250 μ L cyclohexane. Samples were filtered through 0.2 μ m PTFE syringe filters before loading to the GC instrument.

Analysis of fatty acid methyl esters (FAME) was carried out using a Trace 1300 GC with autosampler (Thermo Scientific) equipped with a flame ionization detector (FID) and a Supelco Analytical Nukol fused silica capillary column (15 m $\times$ 0.25 mm i.d. $\times$ 0.25 μ m film thickness). Fatty acids were quantified based on the internal standard and the GLC-463 external standard (Nu-Chek Prep, USA).

2.2.4. Total carbohydrates, including neutral monosaccharides, mannitol, and uronic acids

Analysis of total carbohydrate content, by determination of neutral monosaccharides, mannitol, and uronic acids, in algal samples was based on the method by Van Wychen and Laurens (2015) [23].

Sample portions of 25 mg algal powder ($n = 2$) were mixed with 250 μ L of 72 % (w/w) sulfuric acid (Alfa Aesar, USA) and incubated (Eco-tron, Infors HT, Switzerland) at 30 °C for 60 min at a stirring speed of 250 rpm. The samples were subsequently diluted to 4 % (w/w) H_2SO_4 by the addition of MilliQ water and heat-treated at 121 °C for 60 min followed by centrifugation at 3000g for 5 min to remove the remaining solids. As the last step of sample preparation, the supernatant was neutralized with 0.1 M $Ba(OH)_2 \cdot H_2O$ and filtered into HPLC vials using 0.2 μ m syringe filters.

Analysis of carbohydrates in algal samples was performed using a High-Performance Anion Exchange Chromatography system equipped with Pulsed Amperometric Detector (HPAEC-PAD; Thermo Fisher Scientific, USA) and an analytical column and guard column (Dionex CarboPac PA-20; Thermo Fisher Scientific, Waltham, USA). Isocratic conditions were applied to all samples, with a flow rate of 0.5 mL/min at a temperature of 30 °C. Monosaccharides and mannitol were separated by a mixture of A) MilliQ water (62.5 %), B) 2 mM sodium hydroxide (37.5 %), and C) 200 mM sodium hydroxide for 23 min. Uronic acids were eluted with A) MilliQ water (55 %), B) 1 M sodium acetate in 200 mM sodium hydroxide (15 %), and C) 200 mM sodium hydroxide (30 %) for 15 min. L(–)fucose, D(+)glucose, D(+)xylose, D(+)galactose, L(+)arabinose, D(+)mannose, and D-mannitol, respectively mannuronic acid, guluronic acid, and glucuronic acid were used as references.

2.2.5. Total dietary fibres, including water-soluble and -insoluble fibres

Total dietary fibres, including water-soluble and insoluble fibres, in algal samples, were analysed ($n = 3$) at an accredited external lab (Eurofins Food & Feed Testing, Sweden) using a modified version of the AOAC 991.43 method.

2.3. Physicochemical properties

Texture and colour were analysed to investigate differences between the species in physicochemical terms.

2.3.1. Texture

Texture profile analysis (TPA) of the algal blades was performed using a TVT 300XP texture analyzer (Perten Instruments, Sweden). Texture profile curves were generated by applying a force required to penetrate a piece of algae, fixed between two inserts with hole sizes of 10 respectively 18 mm, using a spherical probe with a diameter of 5 mm. Texture attributes, such as hardness, adhesiveness, resilience, and stickiness, could be deduced from the profile curves generated from a single-cycle test mode. Random sites ($n = 6$) of the algal frond were used for the analysis.

2.3.2. Colour

The colour of the algal blades was assessed using a portable spectrophotometer CM-700d (Konica Minolta, Japan). Random sites ($n = 10$) of the algal frond were selected for analysis. The spectrophotometer measured specular component excluded (SCE) $10^\circ/D65$ and generated a spectrum between 400 and 700 nm, as well as L^* , a^* , and b^* values from the CIELAB colour space. L^* render the lightness of a sample while a^* and b^* designate colour directions, where $+a^*$ is the red direction, $-a^*$ is the green direction, $+b^*$ is the yellow direction, and $-b^*$ is the blue direction. Black and white surfaces served as controls for the measurements.

2.4. Statistical analysis

Descriptive statistics were applied to all obtained data. Two-way ANOVA ($p < 0.05$) having assessors and products as fixed factors, with Tukey's post hoc test, was performed to determine if attributes from sensory analyses significantly differed between the seaweed samples. Different letters (a-d) were used to indicate significant differences between samples. One-way ANOVA ($p < 0.05$) was used for the corresponding analysis of biochemical and physicochemical properties. Pearson correlation analysis of average values was carried out to determine if attributes significantly correlated between the seaweed samples. Correlations coefficients larger than 0.7 ($r \geq |0.7|$) were considered to indicate a strong relationship between two variables. The open-source statistical tool, JAMOVI [24], was used for ANOVA and Pearson correlation. RStudio was used to plot PCA (principal component analysis) score plots to evaluate and visualize panel performance and product similarities.

3. Results

3.1. Biochemical composition

Composition analysis was performed to biochemically evaluate the nutritional variations between the species (Table 2). Generally, the total carbohydrate content was high in all species (29.6 ± 1.1 to 54.6 ± 2.6 g/100 g DW), with a sugar fraction (remaining fraction, including sugar alcohols, after subtracting fibres from total carbohydrates) particularly high in *S. latissima* (sugar kelp) and *P. palmata* (dulse). The levels of dietary fibres, particularly water-insoluble fibres, were high in all four species. The carbohydrate profiles after hydrolysis (Table S1) shows that the two brown seaweed species (*S. latissima* and *A. esculenta*) were built of similar carbohydrate and fibre structures, with a generally high

Table 2

Nutritional composition of four different species of seaweed: *S. latissima* (SL), *A. esculenta* (AE), *P. palmata* (PP), and *Ulva* sp. (U). Results are reported as g/ 100 g $\pm$ standard deviation and are based on the algal dry weight (DW). Significant ($p < 0.05$) differences are indicated by letters (a-d).

[g/ 100 g DW]	SL	AE	PP	U
				
Solids [g/100 g powder]	91.1 $\pm$ 0.3 ^a	89.9 $\pm$ 0.2 ^b	93.9 $\pm$ 0.6 ^c	93.8 $\pm$ 0.6 ^c
 Ash (minerals)	26.5 $\pm$ 0.2 ^a	32.9 $\pm$ 1.0 ^b	25.8 $\pm$ 1.0 ^a	36.8 $\pm$ 0.5 ^c
 Protein	8.1 $\pm$ 0.1 ^a	11.4 $\pm$ 0.1 ^b	10.0 $\pm$ 0.3 ^c	6.7 $\pm$ 0.2 ^d
 Lipids	2.4 $\pm$ 0.1 ^b	1.7 $\pm$ 0.1 ^a	1.7 $\pm$ 0.1 ^{ac}	1.3 $\pm$ 0.1 ^c
Saturated fatty acids ¹	0.21 $\pm$ 0.0 ^a	0.22 $\pm$ 0.1 ^a	0.15 $\pm$ 0.0 ^{ab}	0.08 $\pm$ 0.0 ^b
Unsaturated fatty acids ¹	0.29 $\pm$ 0.1 ^{ab}	0.34 $\pm$ 0.1 ^a	0.20 $\pm$ 0.0 ^b	0.08 $\pm$ 0.0 ^c
Carbohydrates	53.4 $\pm$ 1.4 ^a	36.3 $\pm$ 0.9 ^b	54.6 $\pm$ 2.6 ^a	29.6 $\pm$ 1.1 ^b
 Water-soluble fibres	7.1 $\pm$ 2.8 ^{ab}	3.9 $\pm$ 1.2 ^a	8.2 $\pm$ 0.8 ^{ab}	10.4 $\pm$ 2.1 ^b
 Water-insoluble fibres	22.7 $\pm$ 1.7 ^{bc}	30.2 $\pm$ 1.4 ^a	25.7 $\pm$ 1.2 ^b	21.9 $\pm$ 1.0 ^c
 Sugars ²	23.7 $\pm$ 2.5 ^a	2.2 $\pm$ 1.3 ^b	20.7 $\pm$ 3.1 ^a	-2.7 $\pm$ 3.0 ^b

¹ Identified and integrated fatty acid methyl esters (FAME) ² Remaining carbohydrates detected after acid hydrolysis (including sugar alcohols).

content of mannitol, glucose, as well as guluronic acid and mannuronic acid (both constituents of alginate). The profile for the red seaweed (*P. palmata*) differs with high levels of galactose (constituent in carrageenan and agar) and xylose, whereas the green *Ulva* species showed high levels of arabinose, glucose, xylose (ulvan), and glucuronic acid (ulvan). Carbohydrate analysis further detected three relatively large unknown peaks in the *Ulva* sp. sample, one neutral monosaccharide and two uronic acids. The unknown monosaccharide is likely rhamnose, as it is a frequent component in the backbone of the green polysaccharide ulvan [13]. The uronic acids are potentially iduronic acid and eventually aldobiuronic acid [13,25].

Similar to carbohydrates, the ash (minerals) content was high in all species (25.8 $\pm$ 1.0 to 36.8 $\pm$ 0.5 g/100 g DW) (Table 2). Calcium, potassium, magnesium, sodium, sulphur, and iodine was particularly high in all seaweed species (Table S2). Iodine in *S. latissima*, and cadmium in *A. esculenta* were observed at levels above limits according to the European commission [26] and/or French Agency for Food, Environmental and Occupational Health & Safety (ANSES) [27].

The protein content ranged between 6.7 $\pm$ 0.2 in *Ulva* sp. and 11.4 $\pm$ 0.1 g/ 100 g DW in *A. esculenta* (Table 2). Comparison of the amino acid profiles with the essential amino acid (EAA) profile of a complete protein, showed that all EAAs in the studied species met the limits except for histidine, which is slightly below limit (Table S3). Also, *Ulva* sp. had too low amount of lysine. Glutamic acid and aspartic acid were generally high in all species. EAAs represent between 35 % in *Ulva* sp. to 38 % in *A. esculenta* of all amino acids.

Finally, low lipid content (1.3 $\pm$ 0.1 to 2.4 $\pm$ 0.1 g/ 100 g DW) was observed in all species (Table 2). Unsaturated fatty acids (FA) ranged from 42.8 % of total FAs in *Ulva* sp. to 59.4 % of total FAs in *A. esculenta* (Table S4). Levels of ω -3 were highest in *P. palmata* with 36.2 % of total FA and the ω -6 content was highest in *S. latissima* with 22.3 % of total FA.

3.2. Physicochemical properties

The analyses were performed to understand the variations of texture

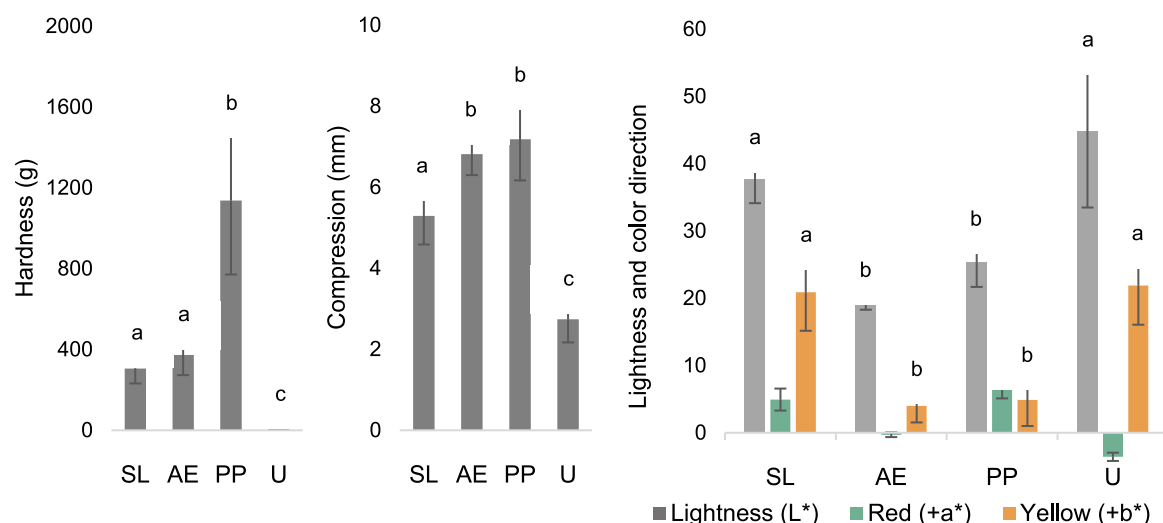


Fig. 2. Texture and colour results. For exact mean values see Table S5. *S. latissima* (SL), *A. esculenta* (AE), *P. palmata* (PP), and *Ulva* sp. (U).

and colour between the four species (Fig. 2, Table S5). The hardness of soaked seaweed pieces differed considerably between the four species, with *P. palmata* being very hard (1137.5 ± 366.3 g) and *Ulva* sp. very soft (56.7 ± 22.3 g). Compression followed a similar pattern as hardness, but with less difference between the species. Resilience and stickiness were low. The different species come in different shades according to the colour analysis.

3.3. Sensory properties

The four species differed overall in appearance, odour, taste/flavour, and texture (Fig. 3). For the pieces of dry whole algal blades, panellists considered all species to have high sea odour, taste intensity, saltiness, and hardness. *S. latissima* and *Ulva* sp. were perceived to have a lighter colour and more yellow features than other species. Both *S. latissima* and

A. esculenta were perceived to have higher crispiness and lower curliness in the comparison. Additionally, *A. esculenta* was considered the darkest (together with *P. palmata*), and greenest of all species, with the lowest elements of sea odour. *P. palmata* distinguished itself by its dark magenta colour, with the least element of yellow and green. It had an enhanced flavour of umami, and fish liver oil compared to the seaweed with the lowest score (top left panel in Fig. 3), and a stronger odour of shellfish (dried shell) than all species. Additionally, the texture of *P. palmata* was perceived as the hardest (together with *A. esculenta*) and the chewiest. Finally, *Ulva* sp. was perceived as the saltiest (but not distinguishable from *S. latissima* and *P. palmata*), with a higher flavour of grassiness (similar to *A. esculenta*). It had an odour resembling lemon and fresh grass. Panellists perceived *Ulva* sp. as more curly than other species and with a lightness in colour with elements of yellow. The texture was perceived the least crispy, hard, and chewy.

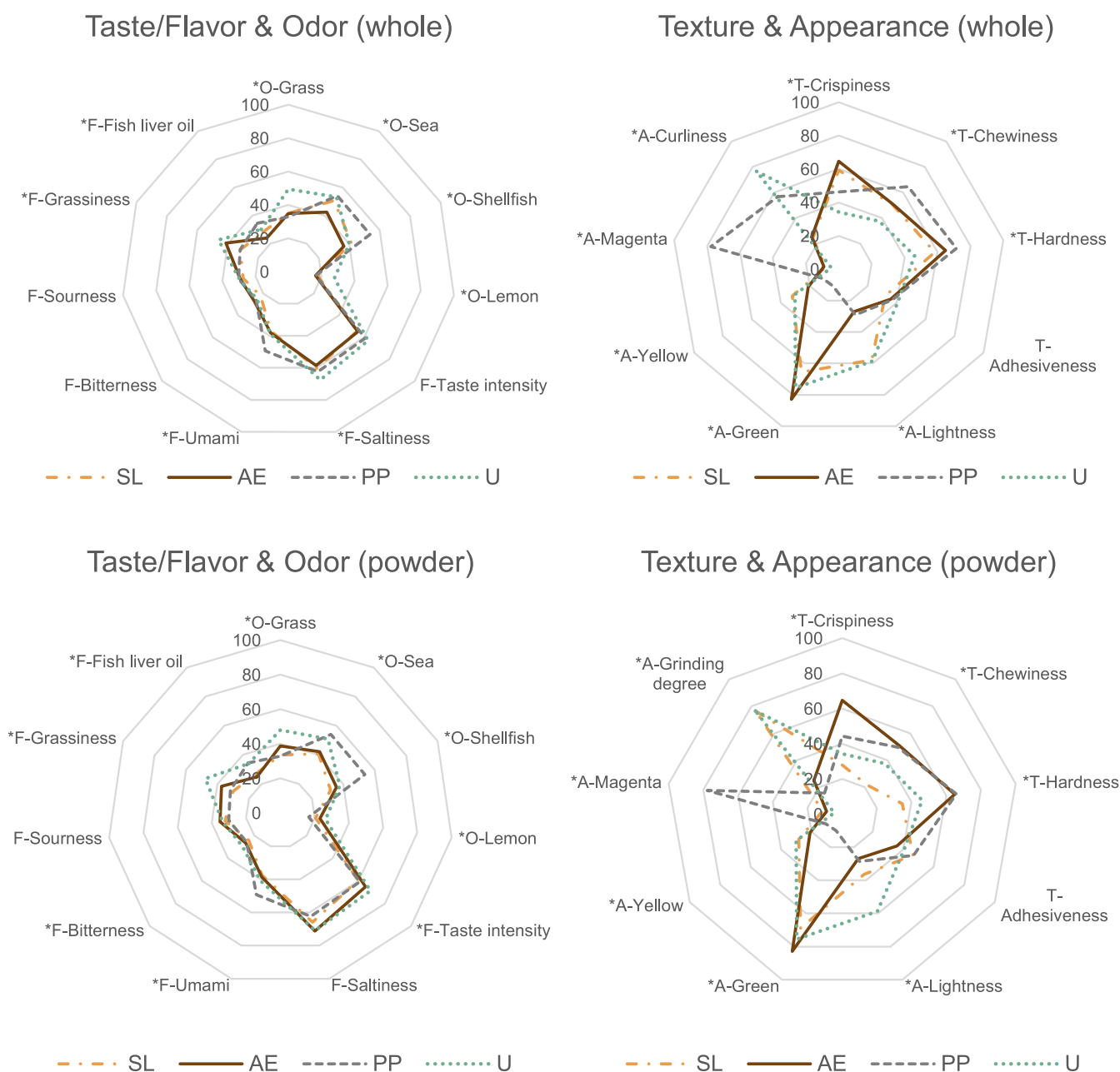


Fig. 3. Whole frond and powder separately. Visualization of mean values from the sensory test which is summarized in Table S6-S7. Asterisk (*) indicates significant ($p < 0.05$) differences between species. For the distribution of significant differences, see Table S6-S7. *S. latissima* (SL), *A. esculenta* (AE), *P. palmata* (PP), and *Ulva* sp. (U).

Tukey's pairwise comparison of whole pieces of seaweed and powder for the respective species demonstrated that the organoleptic profiles were overall similar (Fig. 4). However, for *S. latissima* and *A. esculenta*, all texture attributes and lightness of colour differed between the two formulations. Whole *S. latissima* was perceived to have significantly ($p < 0.05$) higher sea and shellfish odour than the corresponding powder. For *A. esculenta*, the perceived taste intensity and saltiness increased significantly ($p < 0.05$) when milling the seaweed, whereas the colour seemed less green in powdered form. The chewiness of *P. palmata* and the crispiness of *Ulva* sp. decreased in powder compared to whole pieces.

The performance of the panellists and similarities between products are compared and visualized in PCA score plots (Fig. S1-S2). For both whole and powdered seaweed, it can be observed that *P. palmata* was distinguished from the other seaweed types. *S. latissima* and *A. esculenta*, which have biological similarities, tend to overlap to the greatest extent in the score plots.

3.4. Correlations between sensory data and physicochemical/chemical measurements

Studying of potential correlations, by the use of Pearson correlations,

was performed to investigate the occurrence of any potential relations between the properties analysed. Accordingly, correlation analysis was performed in three steps: comparing all attributes for 1) whole seaweed (Table S8) and 2) powder formulation (Table S9), as well as 3) comparing sensory attributes between the two formulations (Table S10). All three correlation analyses resulted in matrices with many high Pearson correlation coefficients ($r \geq |0.7|$) but with varying probability (significant * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$, and also insignificant $p \geq 0.05$).

Colour properties correlated well between the lab analyses and the analytical panel's perceived impression. However, some correlations were without significance. 'A-lightness' and 'L*' correlated with $r = 1.0$ ($p < 0.05$) and $r = 0.7$ for whole and powder formulation, respectively. For the red and green colour tones, the correlation coefficients for 'A-magenta' and 'a*' were $r = 0.7$ (whole) and $r = 0.8$ (powder), and 'A-green' and 'a*' were $r = -0.8$ for both formulations. For the yellow colour tones, the correlation coefficients comparing 'A-yellow' and 'b*' were $r = 0.9$ (whole) and $r = 0.7$ (powder). Similarly, green colours correlate negatively with red nuances. For whole seaweed, a more yellow sample correlated with lightness in colour ('A-yellow' and 'L*' had $r = 0.9$, and 'A-lightness' and 'b*' had $r = 1.0$ ($p < 0.001$)). Accordingly,

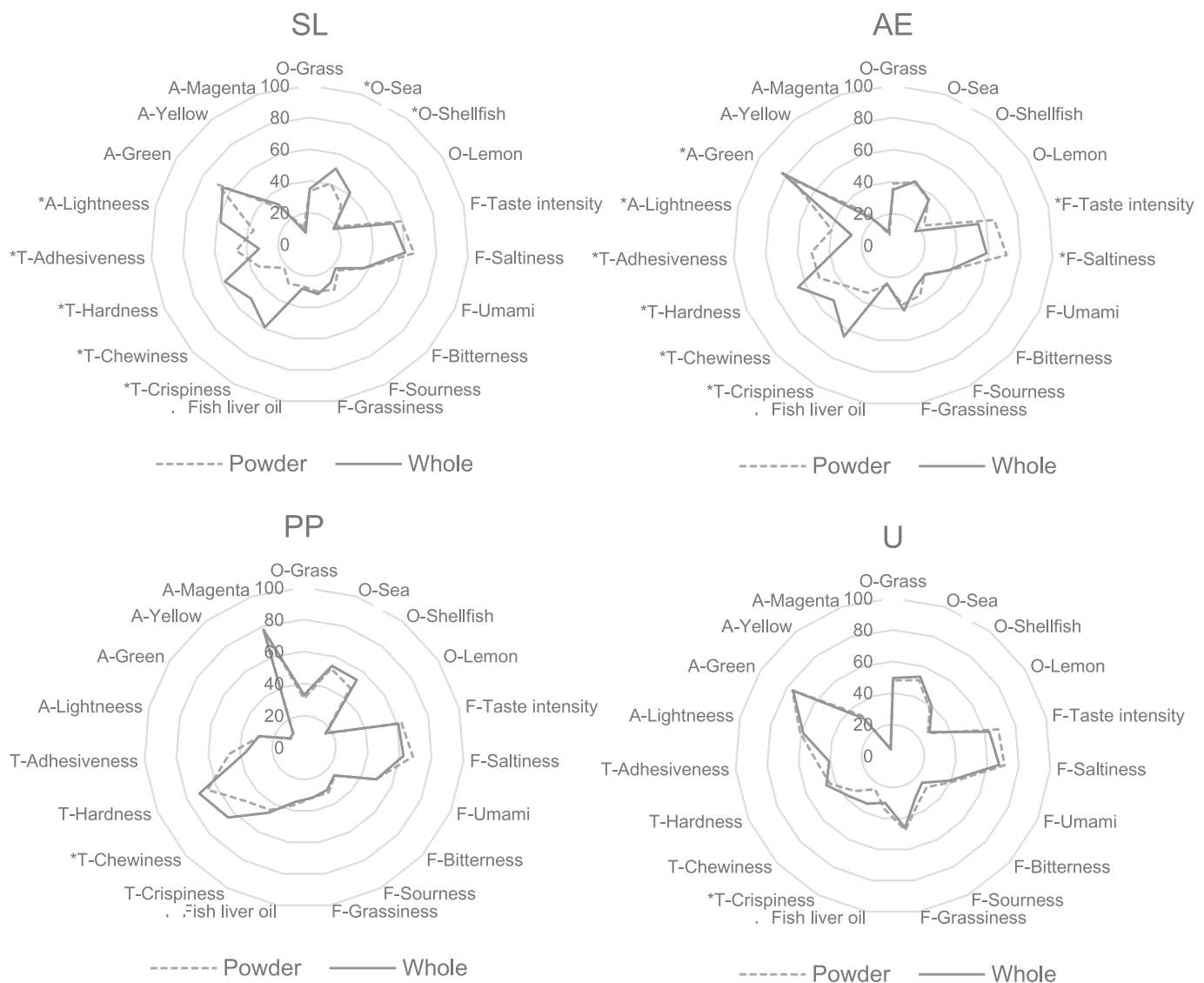


Fig. 4. Comparison of whole frond and powder. Visualization of mean values from the sensory test which is summarized in Table S6-S7. Asterisk (*) indicates significant ($p < 0.05$) differences between formulations. For the average values and distribution of significant differences, see Table S6-S7. *S. latissima* (SL), *A. esculenta* (AE), *P. palmata* (PP), and *Ulva* sp. (U).

as can be deduced from Table S10, colour attributes for whole and powder correlated well, except for lightness.

Texture properties are mainly interesting for the seaweed's whole form. Accordingly, any correlation between the corresponding attribute for the two formulations was absent or poor. From Table S10 it can be read that correlation ($r = 0.7$) is only observed between the hardness of whole pieces and powder ('T-W-hardness' respectively 'T-P-hardness'). However, as seen in Table S8-S9, 'T-chewiness' and 'T-hardness' ($r = 1.0$ ($p < 0.05$) for whole and $r = 1.0$ ($p < 0.01$) for powder), and 'hardness' and 'T-chewiness' ($r = 1.0$ ($p < 0.05$) for whole) seem to correlate, indicating that the two texture attributes are perceived similar. For whole seaweed, 'hardness' and 'T-hardness' correlated with a value of $r = 0.9$. Similarly, 'compression' correlated with 'T-crispiness' ($r = 0.7$), 'T-chewiness' ($r = 0.9$), and 'T-hardness' ($r = 1.0$ ($p < 0.05$)). The values of 'resistance' and 'stickiness' were negligible. Physicochemical properties did overall not evidently correlate with biochemical properties. Consequently, the correlation matrix for whole seaweed did not clearly indicate what biochemical properties underly the perceived and lab-analysed texture properties.

Like physicochemical properties, attributes related to the taste/flavour of seaweeds cannot be clearly correlated to specific biochemical properties. Noteworthy is that 'F-saltiness' correlated poorly with 'ash' ($r = 0.5$ for whole and $r = 0.8$ for powder). 'F-umami' did not correlate with 'protein' ($r = 0.3$ for whole and $r = 0.2$ for powder). Also, 'F-fish liver oil' did not correlate with 'lipids' ($r = -0.2$ for whole and $r = -0.6$ for powder). Corresponding flavour attributes for whole and powdered seaweed (for example, 'F-W-umami' and 'F-P-umami') correlated to some extent, except for saltiness, bitterness, and sourness.

Comparing odour attributes with biochemical properties was difficult as no analyses of volatile compounds were performed in this study. However, it can be observed that odour attributes obtained an overall low score by the panel, with scores below 50 except for 'O-sea' for whole *S. latissima* as well as whole and powdered *P. palmata*, and 'O-shellfish' for whole *P. palmata*. Additionally, corresponding odour attributes for whole and powdered seaweed (for example, 'F-W-lemon' and 'F-P-lemon') correlated well but not at a significant level, indicating similarities between the two formulations' odour.

Overall, correlation within some specific groups of attributes was observed. Flavours and odours related to grass ('O-W/P-grass' and 'F-W/P-grassiness') tended to relate to each other and to lemon ('O-W/P-lemon') and bitterness ('F-W/P-bitterness'). However, lemon did not correlate with sourness. Similarly, the flavours and odours related to sea ('O-W/P-sea', 'O-W/P-shellfish', and 'F-W/P-fish liver oil') tended to relate within the group and to the flavour umami ('F-W/P-umami').

4. Discussion

From the consumer perspective seaweed has been described as an ambiguous phenomenon [14]. With this contradictory starting point, this study has investigated the sensory perceptions of dried blades from four different species of seaweed, addressing the question; how can nutritional content and physicochemical characteristics translate into sensory perceptions?

To start with, the descriptive words developed by the analytical panel gave an indication of the general perceptions of the seaweeds. Attributes of the dried seaweed samples identified and described by the panel were categorized in appearance, odour, taste/flavour, and texture. Appearance, texture, and taste included colours, structures, and the basic tastes. The odour and flavour descriptions revolved around grass and sea associated attributes. It was interesting to note that the panel made connections to organisms that come from the sea and organisms that come from land, for example associations to shellfish and fish liver oil as well as grass and lemon were made. To aid the introduction of seaweeds to new markets, organizations, such as retailers, could aid classifications for consumers by relating new seaweed foods to already existing and familiar categories and spaces in the stores, such as the fish

or seafood counters. Associations to grass could indicate potential retail space among vegetables, mushrooms, fruits, or other freshly grown ingredients. Hence, the product location in the store can nudge consumers into ways of using new products by linking them to familiar ones and provides a chance for food providers to take an active role in promoting seaweeds as a new food.

Based on their unique biochemical properties, seaweeds are considered a healthy and nutritious food resource [28]. It should be highlighted that this study only provides a snapshot of the nutritional, physicochemical, and sensory properties of the four species, since chemical composition is well known to vary dependent on many factors such as harvest location, time, species, and processing procedures [29–32]. Accordingly, our study showed that all species generally have low levels of saturated fat. The general low levels of lipids are also beneficial from a shelf-life perspective as they are less likely to cause rancidity of stored seaweed. Dietary fibre content corresponded to about a third of the nutritional content. Especially high are the water-insoluble fibres, making seaweed a promising prebiotic. This could be considered when developing new seaweed food products, and emphasized in the introduction to new markets. Additionally, the high levels of minerals can exert health benefits for human consumption. Lomartire, Marques and Gonçalves (2021) [28] describe seaweed as a good resource of vitamins (A, B₁, B₂, B₉, B₁₂, C, D, E, and K) and essential minerals (calcium, iron, iodine, magnesium, phosphorus, potassium, zinc, copper, and manganese). High levels of these elements were confirmed in all species. The levels of protein were moderate in all species and varied between 6.7 and 11.4 g/100 g DW, which were calculated from the nitrogen content by using a conversion factor of 5. The limitation of such conversion is that it is not precise for all materials, but a factor of 5 has in general shown to represent seaweed well [19,33]. Interestingly, although the amino acid profiles differed between the four species, they proved to meet the levels for complete proteins well. However, levels of histidine were slightly below limit for all species and *Ulva* sp. had depreciated level of lysine. These seaweeds could be complemented with histidine rich food, such as seeds, whole wheat pasta, beans, and tofu.

Further understanding of the nutritional content in different seaweed species can guide product developers to bring forth healthy and useful products containing seaweed. According to the pilot consumer study by Wendin and Undeland (2020) [15], Swedish consumers would prefer consuming seaweed in a dish, bread, or snack. As example, the high levels of dietary fibres observed in all species in the current study suggest that the addition of seaweed as an ingredient in bread could improve the product's healthiness. Further, understanding of the nutritional content can also help understand the sensory behaviour of the seaweed species.

From the sensory analysis, it was observed that the intensity of the basic tastes followed a common pattern in all species. According to the analytical panel, the studied seaweed species had generally high saltiness, medium umami flavour, low bitterness and sourness, and no sweetness. Low bitterness and high taste/flavour intensity can be explained by the high levels of salt [34], which affects other tastes. Carbohydrate analysis demonstrated that some of the seaweed species comprised high levels of sugars, as high as 23.7 % DW in *S. latissima* and 20.7 % DW in *P. palmata*. However, in *S. latissima* the sugar fraction comprises to a large extent of mannitol with a relative sweetness of about half of sucrose [35], and mannuronic acid which is a part of the gel-forming alginate. This might be the reason for the absence of perceived sweetness of seaweeds, although the sugar content was observed to be high.

In contrast to the lack of perceived sweetness, saltiness was considered the most dominant basic flavour. The saltiness was perceived higher in powder compared to the whole form, but only to a significant level ($p < 0.05$) for *A. esculenta*. In the correlation matrix, 'F-saltiness' and 'ash' did not relate (whole) or correlate without significance (powder). However, the assessment of saltiness in Table S6–7 and the content of ash in Table 2, show that the levels are higher in *Ulva* sp. and

A. esculenta than in *S. latissima* and *P. palmata*. Different minerals and their morphology can give rise to varying perceived saltiness [36]. The high saltiness can be explained by the high levels of sodium, calcium, and potassium [37]. However, the taste properties of minerals are complex, and many factors may contribute. Some amino acids (Fig. 5), like aspartic acid and glutamic acid can also increase the perceived saltiness of foods. These two amino acids were predominant in the species studied.

Aspartic acid and glutamic acid are also responsible for umami taste (Fig. 5). However, no or poor correlation were observed between 'F-umami' and 'protein' ($r = 0.28$), 'aspartic acid' ($r = 0.66$), and 'glutamic acid' ($r = -0.15$).

The sensory analysis further showed that several described attributes differed between the four different species. Red seaweed (*P. palmata*) clearly stood out from the other species, with significant characteristics of dark magenta colour, with the least element of yellow and green, an enhanced flavour of umami and an odour of shellfish (dried shell). The texture was perceived as the hardest (together with *A. esculenta*) and chewiest, which was also confirmed by physicochemical analysis. The two brown species were in general perceived as similar. However, panellists considered *S. latissima* to have a lighter colour and more yellow features (like *Ulva* sp.) than other species. Both *S. latissima* and *A. esculenta* (whole) were perceived to have higher crispiness and lower curliness in the comparison. Additionally, *A. esculenta* was considered the dark greenest of all species. Finally, *Ulva* sp. was perceived as the saltiest species (but not distinguishable from *S. latissima* and *P. palmata*). It had an odour resembling lemon and fresh grass. These grassy and fruity attributes may relate to prevalence of aldehydes such as hexanal and/or ketones such as beta-ionone [39]. Panellists perceived *Ulva* sp. (whole) as more curly than other species and with a lightness in colour with elements of yellow (similar to *S. latissima*). Its texture was the least crispy, hard, and chewy.

Sensory attributes described in previous studies mainly relate to distinctive marine flavours and odours, salty and umami tastes, as well as bity textures. For instance, fresh *S. latissima* has been described to have an odour of sea, salty taste, some taste of umami, and flavour of boiled vegetables, with a bity texture [40], and to have a salty flavour of fresh sea with crispy, viscous and dissolving texture [41]. Zhu et al. (2022) [39] showed that *A. esculenta* contains aldehydes such as hexanal representing fruity/grassy flavours and benzaldehyde with bitter almond flavour. Beta-ionone and other ketones are common in seafood and aroma composition of seaweeds giving woody and fruity flavours. Dried *P. palmata* has highly salty and low bitter tastes, strong marine (fish, seaweed) odour and flavour, and tough and crunchy texture [42]. The attributes may be influenced by moisture content and storage. The green seaweed *Ulva rigida* has showed [43] characteristics of intensely green, high vegetable taste, medium hard and elastic texture, with a distinctive odour of seaweed and seaside. Seaweed in general, synthesize bromophenols which are described to give rise to an agreeable smell of fresh sea [44]. Another compound, dimethyl sulphide (DMS), a volatile gas formed in the degradation of dimethyl sulfoniopropionate (DMSP) in red and green algae, has on the contrary a disagreeable odour often associated with rotten seaweed. In decaying brown seaweeds and some red species, the counterpart giving rise to the rotten smell, can be assigned to another sulphurous gas, methyl mercaptan [44].

In contrast to the many observed variations between species (Fig. 3), fewer significant differences between formulation types occurred (Fig. 4). Sensory attributes for *P. palmata* and *Ulva* sp. were best retained between the two formulations. Powder and whole pieces of seaweed were overall perceived as similar. This indicates that the flavour or odour is neither significantly enhanced nor reduced in the respective formulations. The drying process may potentially alter the perception of the seaweeds and blur out eventual variations between the formulations. As described by Stévant et al. (2018) [41], the sensory profile can indeed

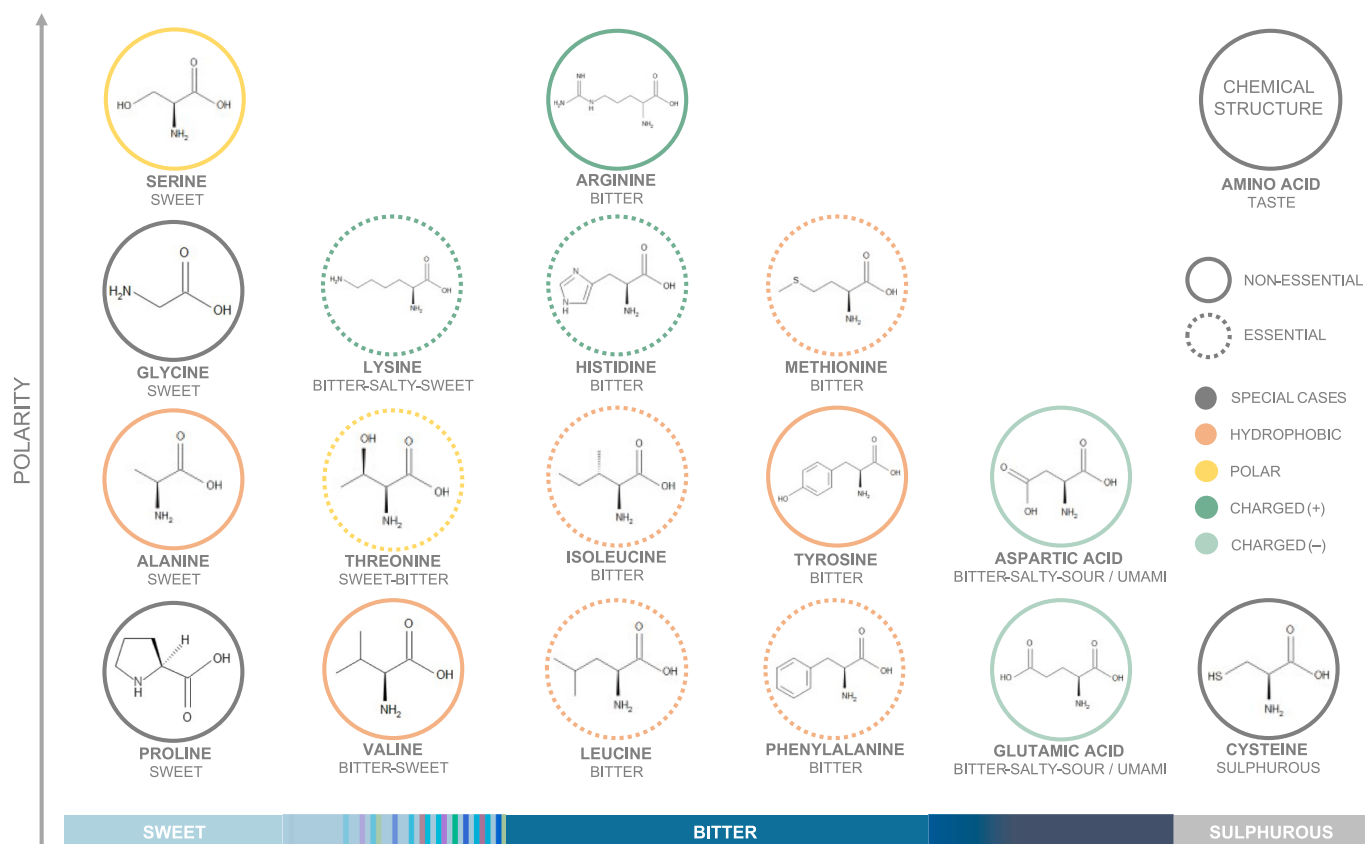


Fig. 5. Predominant tastes of L-amino acids. Figure adapted from Delompré et al. (2019) [37] and Milinovic et al. (2021) [38] and chemical structures were drawn in BIOVIA Draw.

be affected by the processing procedures of the seaweed material. This is important to consider in the mapping of sensory attributes of seaweed species for future food products. Additionally, a high variance in the scores from the sensory study was observed. This can be deduced from the performance of the panel (as seen in the score plot Fig. S1A–2A), which to some extent varies in their way of scoring. Especially for seaweed powder, the scores by panellist number 6 deviated from panellist number 2 and 3, whereas panellist number 1 and 5 overlapped with all. The high variance of scores makes it difficult to evaluate and distinguish between species based on minor variances in average values.

Altogether, biochemical-, physicochemical-, and sensory analyses indicated that several of the studied properties of the four seaweed species significantly differed. Whereas the biological similarity of the two brown species (*S. latissima* and *A. esculenta*) was reflected in the analyses, the red species (*P. palmata*) had the most differentiating attributes from the other seaweed types. This was visualized in the score plots (Fig. S1B, Fig. S2B).

The physicochemical properties of whole seaweed overall agreed well between the lab analyses and sensory study. *P. palmata* was measured and perceived to have the hardest texture whereas *Ulva* sp. was the least hard to chew, according to both tests. A similar result was observed when comparing ‘compression’ and ‘T-chewiness’, as well as the lightness and colour of the seaweed.

Correlation analysis related to seaweed texture further demonstrated several potential relationships. The prevalence of certain monosaccharides seemed to influence the hardness of the seaweed. Glucose (building block in cellulose), as well as galactose, xylose, and uronic acids (building blocks in hemicellulose), were seemingly affecting the hardness [45]. Especially xylose seemed to have an impact on the hardness of seaweed. Hsieh and Harris (2019) [46] have shown that xylose in the red seaweeds *Nemaliales* and *Palmariales* exist in the forms 1,3- β -D-xylans and 1,3;1,4- β -D-xylans (or mixed-linkage xylans). The former occurs in the cell wall as microfibrils similar to cellulose, and the latter occurs in the matrix phase. These structural variations of the cell walls can potentially explain the difference in perceived and measured hardness between the seaweed species. It was further noticed that the fibre content did not correlate with the seaweeds’ textures.

The variations in texture and colour between the different species can further be considered when developing new food products or compose new dishes. Whereas *P. palmata* can serve to enhance chewiness and hardness of food products, the two brown seaweeds (*S. latissima* and *A. esculenta*) could increase crispiness. Contrary, *Ulva* sp. could be considered if the texture of a food product should not be altered considerably. Similarly, the colour of the species should be considered when including seaweeds in food products and dishes, depending on if it intends to blend in with other ingredients or distinguish itself from food matrices. In addition, algae have distinctive physicochemical properties that differ from many terrestrial plants. The differences in chemical composition between macroalgae and terrestrial plants can be explained by seaweeds’ adaption to growth in water, where they are exposed to tidal differences and osmotic stress [45]. This is reflected in their chemical composition and affect their physicochemical properties.

One challenge associated with natural raw materials, is their spatial and temporal changes in composition and quality, which may influence the sensory attributes. This study gives a solid snapshot of four different species from a single harvest site, interlinking nutritional, physicochemical and sensory attributes. However, to understand the sensory and compositional differences of seaweed harvested at different times and locations, more studies relating the quality between different batches must be encouraged in the future. Also, in this study wild seaweed was used. Off-shore cultivated seaweeds can be better controlled regarding for instance growth location and growth cycles, and on-land cultivated seaweed can be even further controlled (e.g., concerning mineral content). This may have impact on the consumers’ product satisfaction.

Overall, Swedish consumers have shown a positive attitude toward

eating seaweed, with environmental sustainability, healthiness, and tastiness as dominating reasons to consider including these sea vegetables in their diet [15]. However, introducing seaweed as food in a Swedish culture without a tradition of its consumption is challenging. Therefore, the interdisciplinary approach in this study is of importance to develop products that fit in the everyday life pattern of consumers. The mapping of attributes related to four common northern European seaweed species can be directly useful in the development of new food applications or as knowledge for the improvement of future seaweed products and their availability, either by industrial stakeholders, the academic community and/or indirectly by consumers. The nutritional values and organoleptic attributes, such as appearances and textures, of seaweeds serve as indicators for how to use seaweeds in the everyday life. The translation of nutritional and physicochemical properties into sensory attributes in this study has served to clarify some mechanisms behind the organoleptic perception of seaweeds. Additionally, knowledge about consumers pattern for shopping, cooking, and eating novel foods such as seaweed should be further investigated for the introduction of seaweed to new food markets.

CRedit authorship contribution statement

Conceptualization, M.J., A.M., C.F., E.N.K. and K.W.; methodology, M.J. and K.W.; formal analysis, M.J. and K.W.; investigation, M.J. and K.W.; resources, C.F., E.N.K. and K.W.; data curation, M.J. and K.W.; writing—original draft preparation, M.J.; writing—review and editing, M.J., A.M., C.F., E.N.K. and K.W.; visualization, M.J.; supervision, E.N.K.; funding acquisition and project administration, C.F., E.N.K. and K.W.

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Declaration of competing interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.algal.2023.103258>.

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