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Cultivation conditions, harvest, and hot water treatment affect the sensory profile, safety, and microelement composition of edible seaweeds *Ulva fenestrata* and *Saccharina latissima*

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ABSTRACT

Seaweed has the potential to be a nutritional complement in Swedish diets. This study investigated effects of cultivation method (ocean/tank), medium (seawater/addition of herring production process waters (HPPWs), and early vs. late spring harvest on sensory properties and microelement composition of *Ulva fenestrata* and *Saccharina latissima* related to adequate intake (AI), tolerable upper intake level (UL), and recommended daily intake (RDI).

Ocean-cultivated, early- and late-spring harvest *Ulva fenestrata* and *Saccharina latissima* (*Ulva*-O-early, *Ulva*-O-late, *Saccharina*-O-early, *Saccharina*-O-late), tank-cultivated *Ulva fenestrata* with/without herring production process waters (*Ulva*-T-seawater, *Ulva*-T-HPPWs) were hot water treated (HWT), frozen, and thawed before sensory evaluation. Inductively Coupled Plasma Mass Spectrometry (ICP-MS) was used for microelement composition analysis. Freshly frozen *Ulva fenestrata* (*Ulva*-T-untreated) served as control.

Ulva-T-untreated had stronger flavor- and odor than all other samples. *Ulva*-O-early and *Ulva*-O-late had fine texture, whereas *Saccharina latissima* was significantly slimier than *Ulva fenestrata. Ulva*-O-early and *Ulva*-O-late had low iodine (I), inorganic arsenic (iAs), cadmium (Cd), and lead (Pb), but high vitamin B12, iron (Fe), and magnesium (Mg). *Saccharina latissima, Ulva*-T-seawater, and *Ulva*-T-HPPWs had significantly higher I levels than ocean-cultivated *Ulva fenestrata. Ulva*-T-untreated had ten times more vitamin B12 than HWT *Ulva fenestrata*. The highest levels of Cd and Pb were found in tank cultivated *Ulva fenestrata*, and *Saccharina*-O-early was the highest in Fe and iAs.

The sensory findings and element composition analysis suggested *Ulva*-O-early and *Ulva*-O-late as potential ingredients for food product formulations, while *Saccharina latissima* and *Ulva*-T-untreated, due to their I- and iAs content, are unsuited for consumption, especially by children.

1. Introduction

The potential of whole seaweed as a sustainable food, especially as a source of micronutrients such as Mg, Fe, and vitamin B12 (Jacobsen et al., 2023; Trigo et al., 2025), can play a future dietary role in the prevention of the most common micronutrient deficiencies, iron (Fe) and iodine (I) (Kiani et al., 2022), while contributing to environmental sustainability. In Europe, seaweed is typically consumed by educated, health-conscious women; yet it remains a niche product (Birch et al., 2019; Govaerts and Olsen, 2023). This is likely as a result of limited production volumes (Fredriksson et al., 2023), taste-related barriers (Sandvik, 2018), and safety concerns due to potentially toxic elements (Jacobsen et al., 2023). Sensory quality is the most important aspect when purchasing and consuming safe food (Mouritsen et al., 2017), therefore, seaweed-containing food products should be appealing to the larger population. Early childhood eating habits are widely recognized as foundational for long-term food preferences (Cooke, 2007). Consequently, the early introduction of seaweed-based foods may play a critical role in promoting their acceptance and increasing future consumption. However, along with pregnant women and individuals with thyroid dysfunction, children, due to their lower body weight, represent a consumer group that is particularly vulnerable to potentially toxic

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elements in food (Landrigan et al., 2002). Additionally, food neophobia i.e., the reluctance to try unfamiliar foods, is a common barrier in children (Sandvik et al., 2021), peaking during the ages 2 to 6 years, and thereafter decreasing after the age of 11 (Krupa-Kotara et al., 2024). Thus, seaweed-based food products intended for humans, should not only possess appealing sensory attributes for consumers, but they must also offer nutritional benefits and meet safety standards, especially when it comes to children.

Two edible seaweed species relevant within the European context due to their established protocols for ocean- and land-based cultivation are *Saccharina latissima* and *Ulva fenestrata*,also known as sugar kelp and sea lettuce (Stedt, Trigo, et al., 2022; Toth et al., 2025). It is well known that cultivation conditions impact seaweed growth and its chemical composition, which also applies to these two species (K. Stedt, Pavia, et al., 2022; Steinhagen et al., 2022; Toth et al., 2020; Vilg et al., 2015). Although *S. latissima* and *U. fenestrata* differ from each other in terms of micro- and macronutrient composition, in the case of ocean-based cultivation, seasonality is the dominant source affecting the previous parameters. For instance, harvesting *U. fenestrata* in early spring (i.e., mid-March) compared to standard harvest (i.e., late spring/mid-April) led to a biomass with higher total protein and total fatty acids as well as lower content of potentially toxic elements, including lead (Pb), inorganic arsenic (iAs), and cadmium (Cd) (Wendin et al., 2024). This came at the expense of a lower biomass yield and lower Fe content in the biomass (Steinhagen et al., 2022). When it comes to sensory profiles as a function of early and late harvest, no reported study has investigated possible sensory differences between *S. latissima* harvested during early vs. late spring. One study previously evaluated dried *U. fenestrata* harvested at three time points; mid-February, early April, and mid-May. The authors reported similar sensory profiles for the two earlier harvests of *U. fenestrata* (Wendin et al., 2024). To mitigate limitations linked to seasonality, land-based cultivation enables controlling and optimizing e. g., the seaweed life cycle and biomass composition (Hafting et al., 2012). Optimization could, for example, be via the addition of seafood production process waters fertilizers to the seawater. One example is marinated herring production process waters (HPPWs) which are generated in large quantities, and tend to be abundant in ammonium and inorganic phosphorus, both being important for protein accumulation and seaweed growth (Stedt, Steinhagen, et al., 2022). Such a circular strategy, involving HPPWs, increased crude protein content in *U. fenestrata*, reaching over 30% on a dry weight basis (K. Stedt, Gustavsson, et al., 2022; Steinhagen et al., 2024). The resulting biomass contained all the essential amino acids above reference levels, while the concentration of toxic elements, iAs, Hg, Pb, and Cd, only posed dietary limitations at high intake levels (~90–160 g dw per day) (K. Stedt et al., 2022). The resultant tank-cultivated biomass from this strategy has yet to be analyzed for its sensory profile. Previous works on *U. fenestrata* have evaluated this aspect but using a hybrid cultivation strategy with sea-based cultivation followed by post-harvest tank-cultivation (Stedt, Steinhagen, et al., 2022). The authors reported that the main sensory differences were color- and odor-related, with biomasses cultivated with HPPWs exhibiting a higher intensity of green pigmentation and total odor (K. Stedt et al., 2022).

The previously cited sensory studies on *U. fenestrata* (Wendin et al., 2024; Stedt, Steinhagen, et al., 2022) have investigated the sensory profile of freshly frozen, freeze-dried or oven-dried biomasses; in one case using emulsions as vehicle (Wendin et al., 2024). However, hot water treatment (HWT) of *U. fenestrata* has the potential to become an industrial practice in Sweden and may fulfill similar functions as it does in conventional vegetable processing – specifically, reducing microbial load (Wirenfeldt et al., 2022) and inactivating endogenous enzymes, such as lipoxygenase (Kuo et al., 1996, 1997) which are likely to contribute to undesirable sensory attributes including bitterness and rancidity. These sensory changes are yet to be confirmed in the literature. An additional expected outcome of treating *U. fenestrata* hot water is a reduction in saltiness, being a typical trait for seaweed, caused by the leaching of minerals (e.g., Na and K) and free amino acids (Krook et al., 2023) Moreover, determining the sensory profile and micronutrient composition of wet *U. fenestrata* provides a foundation for evaluating its competitiveness as a nutritious and tasty ingredient in food formulations. This, in turn, may support the expansion of its use beyond current niche dried products, and therefore its broader integration into European diets (Rauf Dahlstedt et al., 2025).

While the micronutrient profile of seaweeds is often highlighted, particularly the content of vitamin B12, it is important to recognize that not all seaweed-derived corrinoids are biologically active in humans. In fact, previous studies have rarely made a distinction between inactive vitamin B12 analogues, (pseudovitamin B12) and true vitamin B12 when analyzing B12 content in seaweed biomass or seaweed-derived products (Marques de Brito et al., 2023). Therefore, specific methods for the identification and quantification of true vitamin B12 is critical when evaluating the nutritional value of seaweed, particularly in diets that may otherwise lack this essential nutrient. The parameters tested were timing of harvest, cultivation system, and cultivation media composition. For wet *S. latissima* biomass, only the effect of timing of harvest was assessed. HWT of *S. latissima* was a built-in factor as it is commonly adopted in the industry for both enzyme inactivation (blanching) and to reduce iodine content, which is extensively covered in terms of its effects on biomass composition and sensory changes (Akomea-Frempong et al., 2021; Krook et al., 2023; Nielsen et al., 2020; Trigo et al., 2023).

This study aimed to investigate how cultivation parameters and HWT post-harvest affect wet *U. fenestrata* biomass in terms of sensory quality, micronutrient content (essential elements and true vitamin B12), and levels of potentially toxic elements. Based on the findings from the study by Wendin et al. (2024), we hypothesized that the sensory profile of the biomass in our study would be retained between early and late spring. We also hypothesized that similar to the study by K. Stedt et al. (2022) the addition of HPPWs to tank-cultivated *U. fenestrata* would affect the color of the biomass and intensify its overall odor. In the present manuscript, a particular emphasis was also placed on assessing the suitability based on nutritional and safety aspects of the seaweeds for inclusion in food products for the most vulnerable consumer group – children. This approach can therefore contribute to a knowledge base for an increased consumption of seaweed from a younger age. Due to available recommended dietary intake (RDI), adequate intake (AI), and upper tolerable intake levels (UL) for different age ranges, we chose to delimit the results and discussion to 7–10-year-old children in elementary school, and past the peak of neophobic eating behavior.

2. Materials and methods

2.1. Seaweed material and taxonomic identification

Seven seaweed biomasses were included in the study, varying in species, cultivation condition, times for harvest within the selected harvest window, and processing (HWT/untreated) (Table 1). There were no measurements of agronomic performance, e.g., harvest yield, plant health, or growth rate. The cultivation conditions were included as a factor for sensory quality and microelement composition of the seaweed samples. Ocean-cultivated *U. fenestrata* and *S. latissima* were harvested from Nordic Seafarm's commercial seaweed farm, located at the Swedish West coast (Skagerrak, Sweden; N 58.64271, E 11.216433). Seedlings of *U. fenestrata* were transplanted to the sea farm between the 20th of September and the 16th of October 2023, and seedlings of *S. latissima* were transplanted between the 8th and 9th of October 2023. *S. latissima* source material was prepared by Nordic Seafarm following the methodology of gametophyte cultivation and seeding of lines as described in Visch et al. (2020), with some minor modifications. Seaweeds were collected from the sea farm on two occasions, corresponding to an early spring harvest and a late spring harvest (Table 1). Abiotic factors of this particular seaweed farm, such as water temperature and

Table 1
Overview of cultivation factors and post-harvest treatments.

Code	Species	Cultivation site	Harvest	Harvest date in 2024	Hot water treatment
Ulva-O-early	*U. fenestrata*	Ocean	Early	15th March	Yes
Ulva-O-late	*U. fenestrata*	Ocean	Late	15th April	Yes
Ulva-T-seawater	*U. fenestrata*	Tank	Late	15th April	Yes
Ulva-T-HPPWs	*U. fenestrata*	Tank with side streams	Late	15th April	Yes
Ulva-T-untreated	*U. fenestrata*	Tank	Late	15th April	No
Saccharina-O-early	*S. latissima*	Ocean	Early	22nd February	Yes
Saccharina-O-late	*S. latissima*	Ocean	Late	15th April	Yes

Ulva = *U. fenestrata; Saccharina* = *S. latissima; O* = ocean; *T* = tank; HPPWs = Herring production process waters.

salinity have been described by Steinhagen et al. (2021, 2022).

For the tank-cultivated *U. fenestrata*, gametophytes were collected from a long-term indoor tank cultivation at Tjärnö Marine Laboratory (TML; N 58.875759, E 11.146216), previously described and taxonomically identified in Toth et al. (2020). The gametophytes were transferred to 40 L tanks ($n = 16$) at a density of 3.125 g wet weight (ww) L-1, totaling 125 g ww tank-1, and cultivated for 14 days at 12 °C, under 16:8 h (L:D) light cycle, and at an irradiance of 100 µmol m-2 s-1 (light source: INDY66 LED 60 W 4000 K 6000 lm). Half of the tanks ($n = 8$) had flow-through filtered (0.2 µm + UV-treated) deep-sea (40 m) seawater (33 PSU), while the other half of the tanks ($n = 8$) were filled to 40 L using filtered deep-sea seawater (45 m) with the following difference from the first half: every third day the seawater was manually renewed and the tanks received HPPWs diluted to 25 µM ammonium (NH4+). The HPPWs came from in-house storage of whole herring in tubs from a primary industrial processor - a detailed explanation of the water and its processing can be found in (Stedt, Trigo, et al., 2022). The total NH4+ content of the water, analyzed using a commercial enzymatic kit as described earlier (Stedt, Trigo, et al., 2022), was determined to 3140±285 µM ($n = 3$).

2.2. *Post-harvest processing of seaweed biomasses*

Upon harvesting, the biomasses were transported in plastic bags with seawater on the same day to a restaurant in Gothenburg (Sweden) for post-harvest treatment according to a protocol followed by the company Nordic Seafarm; the protocol involved HWT at 80 °C for 120 s in tap water, followed by cooling down the biomass in cold tap water. Then, the biomass was drained and placed in heat-sealed polystyrene bags (~500 g each) to be flash-frozen (Blastchiller BCB/0520, GEMM). The untreated tank-cultivated *U. fenstrata* biomass was packed in the same way before flash-freezing. The reason for using flash-freezing was to avoid the formation of large ice crystals, which could otherwise lead to cell disruption and likely result in undesirable sensory changes. The flash-frozen biomasses were then stored at −80 °C at Chalmers University of Technology (Gothenburg, Sweden) and minced in a frozen state using a meat grinder (Model C-E22N, la Minerva) with a 4.5 mm hole plate (Fig. 1). The minced frozen biomasses were then transported to Uppsala University (Sweden) for the sensory analysis, where they remained stored at −20 °C for 3 weeks before sensory evaluation.

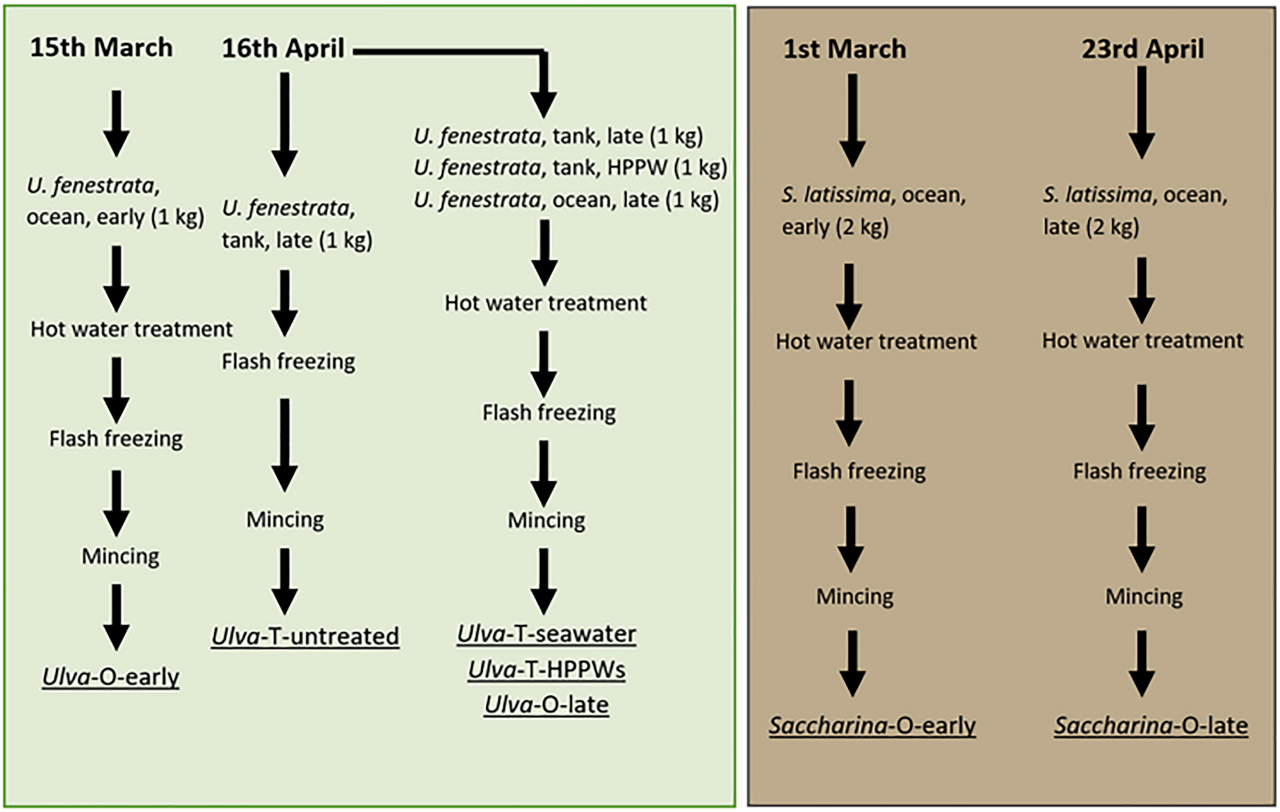


Fig. 1. Flow-chart including harvest times and post-harvest processing steps of *U. fenestrata* and *S. latissima. Ulva* = *Ulva fenestrata; Saccharina* = *Saccharina latissima; O* = ocean; *T* = tank; HPPWs = Herring production process waters.

2.3. Quantitative descriptive analysis with trained adult panel

The sensory profiling was conducted by a trained adult panel at Uppsala University using Quantitative Descriptive Analysis (ISO 13,299:2016). The panel's objective was to generate standardized descriptive data on seaweed appearance, odor, flavor, and texture, with assessors ensuring consistent identification and scaling of sensory attributes in accordance with established quantitative descriptive analysis methodology. Ten assessors with prior experience from descriptive analysis of seaweeds were selected according to the ISO standard 8586:2012 and trained for a total of 9.5 h during 6 sessions. The panel agreed upon and defined 25 sensory attributes to describe the samples (Table 2). The intensities of sensory attributes were scored on a continuous unstructured 15 cm line scale, anchored at 0 and 15 cm. The panelists also defined and agreed upon the tasting procedure (Appendix 1).

For assessment, the biomass was thawed in room temperature in ceramic bowls for 3 h before evaluation and 5 g of thawed samples were served at room temperature (21 °C) in clear plastic 30 mL-medicine cups (Fig. 2) covered with lids and labelled with 3-digit random codes. For palate cleansing, room-tempered tap water and unsalted wafers (Smörgåsrån Göteborgskex, Sweden) were provided. Each assessor was also provided with a list of all the attributes, including definitions as well as the instructions for tasting to aid them during the sample evaluation (Appendix 1). Seven samples were assessed in triplicate over three sessions on two consecutive days. Between the two evaluations performed on the same day, the panelists had a 15-minute break. The samples were presented according to William Latin Square design to balance the effect of serving order. The assessment was carried out in a sensory laboratory designed according to ISO standard 8589:2007 and in individual booths, using white light and the FIZZ software (Biosystems, Counternon, France). The study was approved by the Swedish Ethical Research Council, reference no 2023–05,508-01. All participants consumed a sample amount always below the weekly ULs established by the Swedish Food Agency and EFSA for I, Pb, Cd, and iAs.

Table 2
Definition and references of the sensory attributes used in this study.

Attribute	Definition	Reference
Appearance		
Color	Intensity of bright green and emerald green	Military green – emerald green
Structure	Visual particle size	Baby porridge/ smoothie/purée - chopped parsley
Gloss	Surface gloss	Uncooked lasagna sheet/ blackcurrant jelly
Sliminess	Slime/gel formation ability	Slimy - crumbly crushed grass
Odor		
Marine	Scent of sea/fish (e.g., oysters, mussels, raw fish)	Mussels, cliffs, wet seaweed, oysters
Sulfur	Swamp, boiled egg, lake bottom, sewer, boiled cabbage, sauerkraut	Boiled egg, boiled cabbage
Berries	Red berries/sweet-sour scent reminiscent of dried fruit	Dried cranberries
Grass	Freshly cut grass	Grass
Cucumber/ melon	Freshness in newly cut cucumber, melon	Cucumber, melon
Odor intensity	How intense does the sample smell?	
Flavor		
Green leaves	Fresh taste of green leaves and plants, e.g., baby spinach or kale	Kale, spinach
Flour/pantry	Bland taste of dried grain or cardboard/paper	Unsalted oatmeal, wheat flour
Nutty	Taste of nuts, nutty flavor	Raw cashew nuts, hazelnuts, sunflower seeds
Umami	Intensity of umami taste	MSG + H_2O
Salt	Intensity of salty taste	NaCl + H_2O
Sweet	Intensity of sweet taste	$C_{12}H_{22}O_{11}$ + H_2O
Sour	Intensity of sour taste	$C_6H_8O_7$ + H_2O
Bitter	Intensity of bitter taste	$C_8H_{10}N_4O_2$ + H_2O
Marine	Sea, oysters, raw fish, gulp of seawater, seaweed	Fish liver oil, raw fish, oysters, seaweed
Perfumed	Perfume/flowery	Soap, violet pastilles
Flavor Intensity	Overall flavor intensity of the sample	
Texture		
Adhesiveness	Sticks in the mouth (needs to be rinsed down with water)	Corn husk, Nutella, coarsely chopped seaweed
Chewiness	Chewing resistance/hardness	Raw kale - baby porridge (purée)
Grittiness	Gives a gritty and floury feeling in the mouth (undissolved particles in liquid)	Whole grain flour/sand in water/suspension
Structure	Particle size	Smooth purée, smoothie - chopped parsley

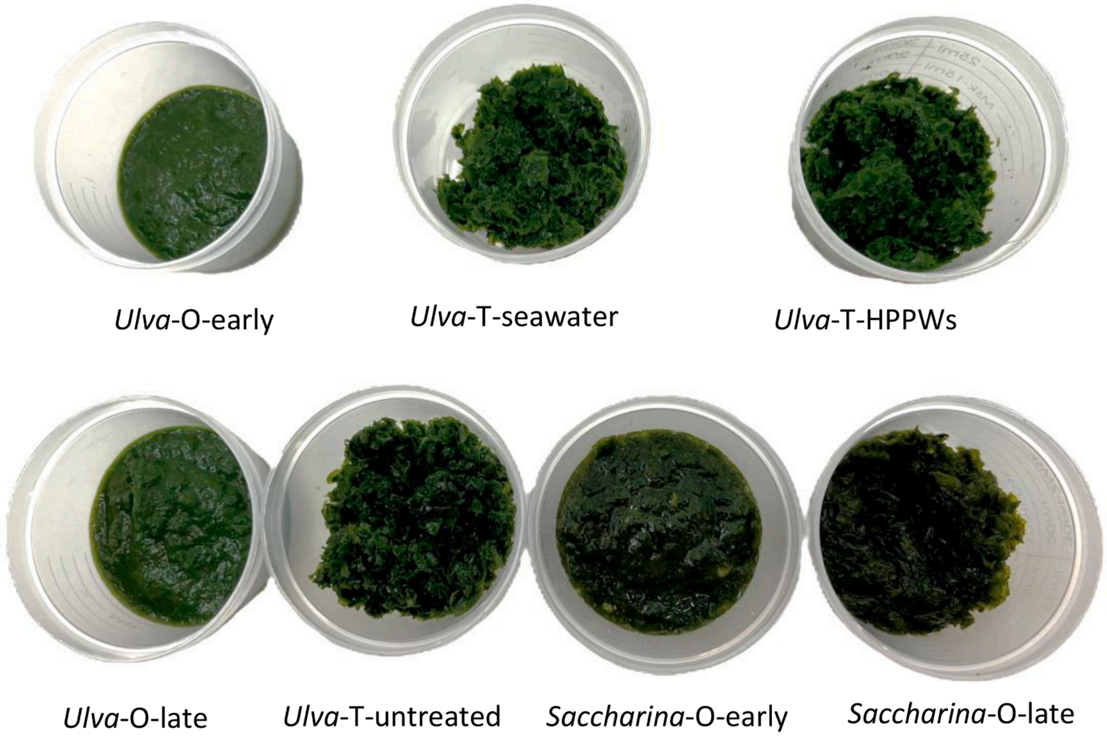
2.4. Element and true vitamin B12 analysis

All samples were freeze-dried and milled (Retsch ZM 200) to a powder with ≤0.5 mm particle size before being shipped to ALS Scandinavia AB (Luleå, Sweden) for microelement-composition analysis by HR-ICP-MS (ELEMENT XR, Thermo Scientific) using accredited protocols as described in Trigo et al. (2023). Analysis included elements calcium (Ca), copper (Cu), Fe, magnesium (Mg), molybdenum (Mo), manganese (Mn), zinc (Zn), Cd, iAs, Pb, and I. Although Hydrofluoric (HF) acid is commonly used to obtain complete dissolution when analyzing mineral concentrations in plant matrices, it was not considered relevant for the current study as the concentrations of elements in refractory phases were not likely to significantly affect the bioavailable concentration of elements in our samples. The recovery of the elements in the current matrix was within the range of 80–120%, which is the accepted range for analysis without HF acid. A sample consisting of *Spirulina* sp with concentrations validated against matrix-matched CRMs served as control. The analysis was performed on a single replicate and the results were expressed as µg element per kg biomass wet weight (ww).

The extraction of true vitamin B12 as cyanocobalamin from the milled freeze-dried biomasses followed the protocol reported in (Chamlagain et al., 2025), and recently applied for analyzing vitamin B12 in seaweed biomass (Trigo et al., 2025). The extracted fraction was purified with an immunoaffinity column ("Easi-Extract", R-Biopharma), Ultra-high performance liquid chromatography (UHPLC) with PDA detection (Waters Acquity) was then used to separate cyanocobalamin chromatographically from pseudovitamin B12 (Chamlagain et al., 2018), ensuring quantification of human-active cobalamin. This workflow allowed selective quantification and confirmation of biologically active cobalamin, avoiding interference from inactive corrinoid analogues. The analysis was performed in triplicates and the contents of true vitamin B12 are expressed as µg per kg biomass ww. The B12 contents and its forms qualifies HWT, frozen and thawed *U. fenestrata* for the B12 nutritional EU claim "source of vitamin B12" (European Regulation 1169/2011, 2011; European Regulation 1924/2006, 2006).

2.5. Calculation of reference amounts for consumption

As maximum levels (MLs) for potentially toxic elements in seaweeds have not been determined yet, we calculated the amount of each biomass required to reach the tolerable upper intake level (UL) of the potentially toxic elements by dividing it with the content of the biomass (Table 4). Likewise, the amount of each biomass required to reach 15% of recommended dietary intake (RDI) or adequate intake (AI) in grams was determined for each essential element (Table 5). Since this study aimed to explore the potential of an increased seaweed consumption targeting all aged, including children, the selected age range was 7–10



Ulva-O-early *Ulva*-T-seawater *Ulva*-T-HPPWs

Ulva-O-late *Ulva*-T-untreated *Saccharina*-O-early *Saccharina*-O-late

Fig. 2. Samples of *U. fenestrata* and *S. latissima* presented as served to the sensory panel *Ulva* = *Ulva fenestrata; Saccharina* = *Saccharina latissima; O* = ocean; *T* = tank; HPPWs = Herring production process waters.

years. The RDI, AI, and UL for 7 to 10-year-old children were obtained from the Swedish Food Agency and EFSA and the reference body weight was obtained from the Nordic Nutrition Recommendations 2023 (Appendix, NNR, n.d.).

Results for Na, P, and Se are provided in the supplementary material. For these elements, the amount of biomass required to reach 15% of each adequate intake (AI) would surpass the threshold amount at which the tolerable upper intake level (UL) of I for 7–10-year-old children is exceeded (Table 4).

2.6. Statistical analysis

The results of the descriptive sensory analysis were analyzed according to Lawless & Heymann (2010) by first using a mixed model 3-way multivariate analysis of variance (MANOVA) assessing the effects of samples (fixed effect), assessors (random effect), and replicate (random effect) all with 2-way interaction. After that, a mixed-model analysis of variance (ANOVA) with homogeneity testing was applied to each attribute with the same structure as the MANOVA. The sample was not tested for normality as ANOVA is considered a robust method if sample size ≥30 (Ghasemi and Zahediasl, 2012). Significant differences between samples were evaluated using the Least Significant Difference (LSD) test. Principal Component Analysis (PCA) was performed on the mean value for each sample and attribute significant in the ANOVA. A p-value of <0.05 was considered significant. PCA was performed in Jamovi software (version 2.6.26.0, 2025), while ANOVA and MANOVA in SPSS (version 28.0.1.0, 2021).

3. Results

3.1. Quantitative descriptive analysis with trained adult panel

The 3-way model MANOVA was significant for the main effects sample ($p < 0.01$) and assessor ($p < 0.01$), as well as the 2-way interactions sample*assessor ($p < 0.01$), but not for the main factor replicate ($p = 0.378$) (Appendix 1). The results from the mixed model ANOVA indicated that all except two descriptive attributes (sweet taste and grainy texture) differed significantly among the samples ($p < 0.05$). The mean scores for each of the 25 sensory attributes and the 7 seaweed samples are shown in Table 3. The PCA shows how the seven samples cluster into four groups (Fig. 3). The first principal component (PC1) represents 53.7% of the data variation, while the second principal component (PC2) represents 35.3%.

As seen in Table 3, both *S. latissima* samples – *Saccharina*-O-early and *Saccharina*-O-late – were characterized by a more marine odor and a higher degree of sliminess compared to all of the *U. fenestrata* samples. With regards to early vs. late harvest, *Saccharina*-O-early and *Saccharina*-O-late differed significantly in structure and particle size (Table 3), whereas *Ulva*-O-early and *Ulva*-O-late did not show any significant differences. When comparing *Ulva*-O-early and *Ulva*-O-late with *Ulva*-T-seawater and *Ulva*-T-HPPWs, there were several significant differences in their sensory profiles; the ocean-cultivated samples had a smoother and softer texture with low adhesiveness, appeared glossier and slimier, with a lower overall odor intensity. With regards to texture, both *Ulva*-T-seawater and *Ulva*-T-HPPWs exhibited higher adhesiveness, chewiness, and larger perceived particle sizes than the two ocean-cultivated samples. As hypothesized, adding HPPWs to tank-cultivated *U. fenestrata* only had minor effects on the overall sensory profile of the sample, although resulting in significantly lower levels of grassy odor compared to *Ulva*-T-seawater (Table 3).

The only sample which was not subject to HWT, the tank-cultivated *U. fenestrata* (*Ulva*-T-untreated), displayed a distinct profile compared to the other samples, characterized by overall higher flavor intensity as well as a tougher texture (Table 3). Thus, the HWT significantly impacted the sensory profile of the tank-cultivated *U. fenestrata*. It resulted in a more emerald green color and a smoother yet slimier texture. HWT also reduced berry odors and increased sulfurous odors, with the net effect of lowering the overall odor intensity. Flavor profiles also changed, with increased notes of green leaves, flour, and nuttiness, while salty, sour, bitter, and perfume-like flavors, along with overall

Table 3
Mean values (M) and Standard Error (SE) for each sample and sensory attribute.

	Ulva fenestrata		Ulva fenestrata			Saccharina latissima		
	Ocean cultivation		Tank cultivation			Ocean cultivation		
	Ulva-O-early	Ulva-O-late	Ulva-T-seawater	Ulva-T-HPPWs	Ulva-T-untreated	Saccharina-O-early	Saccharina-O-late	p-value
Appearance								
Color	12.7 ± 0.5^{a}	12.2 ± 0.5^{a}	12.1 ± 0.5^{a}	12.0 ± 0.5^{a}	9.7 ± 0.6^{b}	2.3 ± 0.4^{c}	1.5 ± 0.3^{c}	<0.001
Structure	0.8 ± 0.1^{a}	1.1 ± 0.2^{a}	8.7 ± 0.6^{b}	9.2 ± 0.6^{b}	13.6 ± 0.2^{c}	4.3 ± 0.4^{d}	7.4 ± 0.6^{e}	<0.001
Gloss	11.7 ± 0.4^{bc}	11.3 ± 0.5^{b}	8.2 ± 0.5^{a}	9.0 ± 0.5^{a}	10.7 ± 0.3^{b}	13.0 ± 0.2^{d}	12.5 ± 0.3^{cd}	<0.001
Sliminess	5.8 ± 0.8^{a}	5.9 ± 0.8^{a}	2.6 ± 0.4^{b}	2.0 ± 0.3^{b}	0.5 ± 0.1^{c}	12.9 ± 0.3^{d}	13.1 ± 0.3^{d}	<0.001
Odor								
Marine	6.6 ± 0.7^{a}	7.3 ± 0.6^{ab}	8.2 ± 0.6^{abc}	8.5 ± 0.7^{bc}	9.3 ± 0.5^{c}	12.1 ± 0.4^{d}	11.7 ± 0.5^{d}	<0.001
Sulfur	6.4 ± 0.7^{b}	5.9 ± 0.8^{b}	6.6 ± 0.8^{b}	6.1 ± 0.7^{b}	2.5 ± 0.4^{a}	2.1 ± 0.3^{a}	2.5 ± 0.5^{a}	<0.001
Berry	1.7 ± 0.3^{a}	2.0 ± 0.4^{a}	2.5 ± 0.4^{a}	2.2 ± 0.4^{a}	5.3 ± 0.7^{b}	2.6 ± 0.5^{a}	2.5 ± 0.4^{ab}	<0.001
Grass	4.4 ± 0.6^{bc}	4.3 ± 0.5^{abc}	5.2 ± 0.5^{cd}	3.8 ± 0.5^{ab}	5.6 ± 0.6^{d}	3.2 ± 0.5^{a}	3.5 ± 0.5^{a}	0.005
Cucumber	2.7 ± 0.3^{abc}	2.6 ± 0.3^{abc}	2.3 ± 0.3^{ab}	2.3 ± 0.3^{ab}	1.9 ± 0.3^{a}	3.3 ± 0.5^{c}	3.1 ± 0.4^{bc}	0.027
O-intensity	5.0 ± 0.5^{a}	4.9 ± 0.5^{a}	7.5 ± 0.5^{b}	6.9 ± 0.5^{b}	12.8 ± 0.4^{c}	7.4 ± 0.5^{b}	7.3 ± 0.6^{b}	<0.001
Flavor								
Green leaves	7.9 ± 0.6^{b}	7.6 ± 0.6^{b}	8.1 ± 0.5^{b}	7.3 ± 0.6^{b}	5.9 ± 0.8^{a}	5.1 ± 0.6^{a}	5.5 ± 0.6^{a}	0.002
Flour	6.1 ± 0.6^{c}	6.0 ± 0.7^{c}	6.0 ± 0.6^{c}	5.8 ± 0.7^{c}	1.5 ± 0.3^{a}	2.4 ± 0.4^{ab}	3.1 ± 0.5^{b}	<0.001
Nutty	3.2 ± 0.4^{b}	3.2 ± 0.3^{b}	3.1 ± 0.4^{b}	3.3 ± 0.4^{b}	1.8 ± 0.2^{a}	2.0 ± 0.2^{a}	2.2 ± 0.2^{a}	0.007
Umami	3.4 ± 0.5^{a}	3.8 ± 0.5^{a}	3.4 ± 0.5^{a}	3.6 ± 0.5^{a}	6.6 ± 0.7^{b}	3.8 ± 0.5^{a}	4.2 ± 0.5^{a}	<0.001
Salt	0.7 ± 0.2^{a}	0.9 ± 0.2^{a}	0.9 ± 0.2^{a}	0.8 ± 0.2^{a}	9.9 ± 0.8^{b}	0.8 ± 0.2^{a}	0.8 ± 0.2^{a}	<0.001
Sour	0.8 ± 0.1^{a}	0.9 ± 0.2^{a}	0.8 ± 0.2^{a}	0.9 ± 0.2^{a}	5.0 ± 0.6^{b}	1.0 ± 0.2^{a}	1.0 ± 0.2^{a}	<0.001
Sweet	2.3 ± 0.3	2.2 ± 0.3	2.4 ± 0.5	1.8 ± 0.3	2.0 ± 0.5	1.7 ± 0.3	1.8 ± 0.3	0.900
Bitter	1.1 ± 0.2^{a}	1.7 ± 0.4^{ab}	1.4 ± 0.3^{ab}	1.6 ± 0.3^{ab}	7.9 ± 0.6^{c}	2.2 ± 0.5^{ab}	2.3 ± 0.5^{b}	<0.001
Marine	4.9 ± 0.5^{a}	6.2 ± 0.4^{ab}	6.0 ± 0.5^{ab}	6.7 ± 0.5^{ab}	7.6 ± 0.5^{bc}	10.6 ± 0.5^{d}	9.5 ± 0.6^{cd}	<0.001
Perfume	1.2 ± 0.2^{a}	1.2 ± 0.2^{a}	1.5 ± 0.3^{a}	1.5 ± 0.3^{a}	6.3 ± 0.8^{b}	1.9 ± 0.3^{a}	1.7 ± 0.3^{a}	<0.001
F-intensity	4.6 ± 0.4^{a}	4.7 ± 0.4^{a}	5.2 ± 0.4^{a}	5.2 ± 0.5^{a}	12.9 ± 0.4^{b}	6.7 ± 0.6^{a}	6.3 ± 0.5^{a}	<0.001
Texture								
Adhesiveness	4.4 ± 0.7^{b}	4.3 ± 0.7^{b}	11.3 ± 0.4^{c}	11.7 ± 0.4^{c}	12.0 ± 0.3^{c}	2.3 ± 0.5^{a}	3.3 ± 0.6^{ab}	<0.001
Chewiness	1.0 ± 0.1^{a}	1.8 ± 0.3^{a}	9.0 ± 0.7^{b}	8.8 ± 0.7^{b}	10.9 ± 0.5^{c}	9.0 ± 0.5^{b}	10.7 ± 0.4^{c}	<0.001
Grainy	5.7 ± 0.7	5.6 ± 0.7	8.8 ± 0.7	8.3 ± 0.8	6.4 ± 0.9	5.2 ± 0.7	5.8 ± 0.8	0.157
Particle size	0.7 ± 0.1^{a}	1.0 ± 0.2^{a}	8.8 ± 0.6^{c}	9.4 ± 0.6^{c}	13.3 ± 0.2^{d}	6.4 ± 0.5^{b}	8.8 ± 0.5^{c}	<0.001

Different superscript letters within a row indicate significant differences ($p < 0.05$) between samples.
The p-value represents the main factor sample in the three-way ANOVA.
Ulva = *U. fenestrata; Saccharina* = *S. latissima; O* = ocean; *T* = tank; HPPWs = Herring production process waters.

flavor intensity, decreased. HWT samples were further perceived as smoother with somewhat lower chewiness, and smaller particle sizes (Table 3).

3.2. Potentially toxic elements and iodine

As shown in Table 4, *Ulva*-T-untreated had the highest concentrations of I (3 447±689 μg/100 g ww) and Cd (1.21±0.24 μg/100 g ww); *Saccharina*-O-late had the highest levels of iAs (15.4 ± 3.1 μg/100 g ww). Both *Ulva*-O-early and *Ulva*-O-late had significantly lower I concentrations compared to all other samples (Table 4). *Ulva*-T-seawater and *Ulva*-T-HPPWs had significantly higher concentrations of Pb compared to the ocean-cultivated *U. fenestrata* and *S. latissima* samples, with the highest concentration (5.01 μg/100 g ww) in *Ulva*-T-HPPWs. The main element limiting the consumption of the analyzed biomasses was I, surpassing the UL (250 μg/day) in all samples, except in *Ulva*-O-early and *Ulva*-O-late. the levels of iAs and I were significantly higher in *Saccharina*-O-late than in *Saccharina*-O-early, whereas *Saccharina*-O-early had significantly higher levels of Pb than *Saccharina*-O-late. (Table 4).

3.3. Essential elements and vitamin B12

As presented in Table 5, *Ulva*-T-untreated had higher levels of the selected micronutrients compared to the other *U. fenestrata* samples, except Fe, which was more abundant in *Ulva*-O-early and *Ulva*-O-late. *Ulva*-T-untreated had significantly higher levels of vitamin B12 than all other samples (up to 10 - 70 times), while it had a significantly lower concentration of Fe than all other samples. *Saccharina*-O-early was significantly more abundant in Fe than *Saccharina*-O-late, as opposed to the *U. fenestrata* samples, of which *Ulva*-O-late had more Fe than *Ulva*-O-early. Moreover, *Ulva*-T-HPPWs had significantly ($p < 0.05$) higher concentrations of Fe and molybdenum compared to *Ulva*-T-seawater. Meanwhile, both *Ulva*-O-early and *Ulva*-O-late had significantly lower I levels compared to the other samples. Notably, both *Ulva*-T-seawater and *Ulva*-T-HPPWs had significantly higher levels of I compared to both *Ulva*-O-early and *Ulva*-O-late, i.e., regardless of early or late harvest (Table 5).

3.4. Calculation of reference amounts for consumption by 7–10-year-old children

Table 6 shows the calculated amounts of biomass required to reach the UL of potentially toxic elements and limiting components (i.e., I), and 15% of RDI for the essential elements (including I). For example, 80.5 g ww of *Ulva*-O-late/day is the required amount of biomass to reach 15% of the RDI for vitamin B12; 1.3 g ww to reach 15% of RDI for Fe; and 3.0 g ww to reach 15% of the RDI for Mg, whereas the corresponding amounts of *Ulva*-T-untreated was 5.1 g ww for vitamin B12, 3.3 g ww for Fe, and 2.2 g for Mg (Table 6).

4. Discussion

4.1. Sensory characteristics of the samples

The principal component analysis showed that *Ulva*-T-untreated differs the most from the other samples particularly in terms of texture, flavor, and odor. This sample had the highest overall odor- and flavor intensity (Fig. 3). The exceptions were marine flavor and odor, which were perceived as significantly stronger in the *Saccharina*-O-early and *Saccharina*-O-late. Furthermore, the sulfurous odor, likely due to the presence of dimethyl sulfide (DMS) (Carrión et al., 2023) was higher in

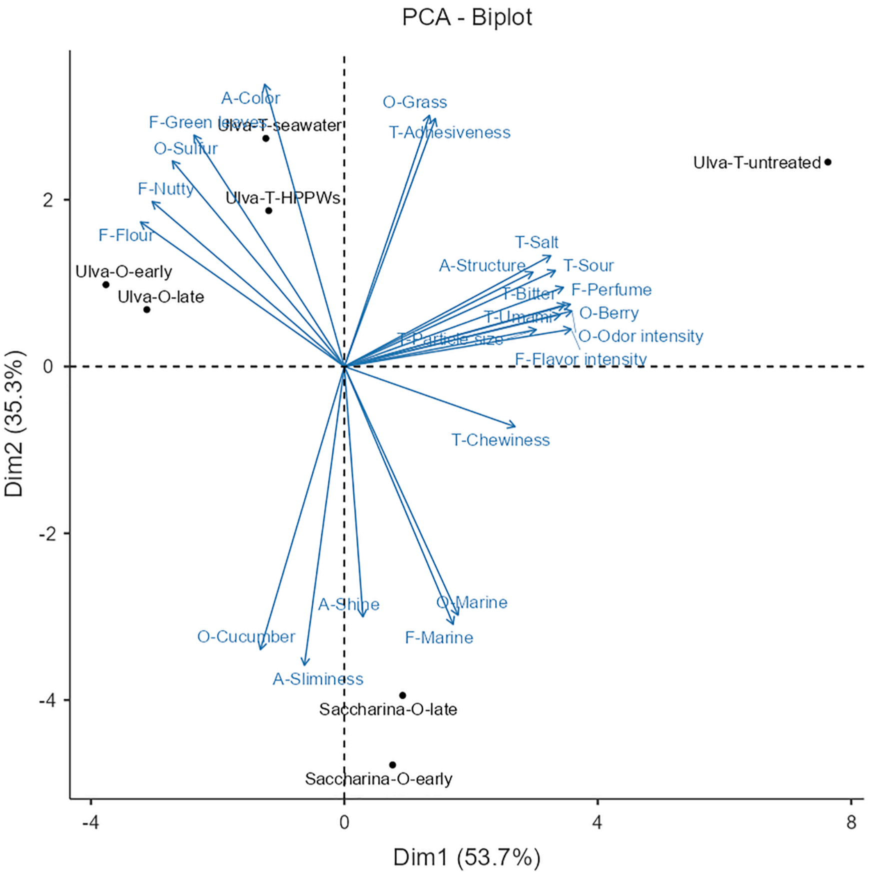


Fig. 3. Principal component analysis of the significant sensory attributes of the different samples: Ulva = *Ulva fenestrata*; Saccharina = *Saccharina latissima; O* = ocean; *T* = tank; HPPWs = Herring production process waters.

Table 4
Content (mean±SD) of potentially toxic elements and I in *U. fenestrata* and *S. latissima* biomasses.

		Ulva fenestrata		Ulva fenestrata			Saccharina latissima	
		Ocean cultivation		Tank cultivation			Ocean cultivation	
Element/100 g ww	UL/day (7 – 10 years)[2,3]	Ulva-O-early	Ulva-O-late	Ulva-T-seawater	Ulva-T-HPPWs	Ulva-T-untreated	Saccharina-O-early	Saccharina-O-late
Cd (μg)	12.32[1]	0.13±0.03^{a}	0.12 ±0.02^{ad}	0.41±0.08^{b}	0.41±0.08^{b}	1.21±0.24^{c}	0.07±0.01^{de}	0.06±0.01^{e}
iAs (μg)	9.24[1,5]	0.10±0.02^{a}	0.15 ±0.03^{ab}	0.15±0.03^{ab}	0.17±0.03^{b}	1.66±0.33^{c}	6.73±1.35^{d}	15.4 ± 3.1^{e}
I (μg)	250[1]	54.1 ± 10.8^{a}	164±33^{b}	1 521±304^{cd}	1 954±391^{c}	3 447±689^{e}	1 158±232^{d}	2 138±428^{c}
Pb (μg)	15.4[1]	0.55±0.11^{ab}	0.58 ±0.12^{ab}	1.04±0.21^{c}	5.01±1.00^{d}	2.59±0.52^{e}	0.68±0.14^{b}	0.39±0.08^{a}

Different lowercase letters (a-e) denote significant differences (95% confidence interval) within each row. The analysis was performed using accredited methods with a relative standard deviation (RSD) of ±20% as extended ($K = 2$), combined uncertainty.

Ulva = *U. fenestrata; Saccharina* = *S. latissima*; ww = wet weight; iAs = iAs; *O* = ocean; *T* = tank; HPPWs = Herring production process waters.

[1] Obtained from the Swedish Food Agency, https://www.livsmedelsverket.se. Cd: 0.4 μg/kg bw/day, iAS: 0.3–0.8 μg/kg bw/day, Pb: 0.5 μg/kg bw/day[2]UL = Tolerable upper intake level.

[3] Reference bodyweight of 30.8 kg for ages 7 – 10 years, obtained from Nordic nutrition recommendations 2023, https://pub.norden.org/nord2023-003/appendix.html.

[5] Calculated for the lower limit; 0.3 μg.

*Only *Ulva*-O-early and *Ulva*-O-late fall below UL for Cd, iAs, I, and Pb, and can be considered for consumption by children. All tank-cultivated *U. fenestrata* samples exceed the UL for I at low intakes. *Saccharina*-O-late exceeds UL for iAs.

the HWT *U. fenestrata* samples, cultivated in both the ocean and in tanks, compared to the *S. latissima* samples. However, HWT was not compared to cold water soaking, which was a limitation of the current study. DMS is enzymatically derived from DMSP, a molecule with numerous functions, e.g., as an osmolyte and an anti-stress compound that increases in response to oxidative stress, salinity, and thermal stress (e.g., high temperatures) (Carrión et al., 2023). Although DMS is expected to also be present in *Ulva*-T-untreated (Van Alstyne et al., 2023), it is possibly overpowered by the other attributes, and appears more distinctly when treating the biomass with hot water. The characteristic marine odors found in both of the *S. latissima* samples, come from a number of volatile compounds, such as unsaturated aldehydes, ketones (Wei et al., 2024)

Table 5

Content (mean ± SD) of selected essential elements (including I both as nutrient and limiting factor) and true vitamin B12 in *U. fenestrata* and *S. latissima* biomasses.

		Ulva fenestrata		Ulva fenestrata			Saccharina latissima	
		Ocean cultivation		Tank cultivation			Ocean cultivation	
Element/100 g ww	RDI –(7 – 10 years)[1]	Ulva-O-early	Ulva-O-late	Ulva-T-seawater	Ulva-T-HPPWs	Ulva-T-untreated	Saccharina-O-early	Saccharina-O-late
Ca (mg)	800	31 ± 6^{ab}	22 ± 4^{a}	34 ± 7^{ab}	45 ± 9^{b}	76 ± 15^{cd}	56 ± 11^{bc}	88 ± 18^{d}
Cu (µg)	570	85 ± 17^{a}	81 ± 16^{a}	103 ± 21^{a}	251 ± 50^{b}	185 ± 37^{b}	111 ± 22^{a}	75 ± 15^{a}
Fe (mg)	9	62 ± 12^{a}	106 ± 21^{b}	109 ± 22^{b}	50 ± 10^{a}	41 ± 8^{c}	148 ± 30^{b}	56 ± 11^{a}
Mg (mg)	230	951 ± 190^{ab}	$1\,140\pm228^{ac}$	990 ± 198^{ab}	986 ± 197^{ab}	$1\,564\pm313^{c}$	707 ± 141^{b}	753 ± 151^{b}
Mn (µg)	1 500	80 ± 16^{a}	79 ± 16^{a}	169 ± 34^{b}	140 ± 28^{b}	352 ± 70^{c}	76 ± 15^{a}	57 ± 11^{a}
Mo (µg)	30	9 ± 2^{ab}	14 ± 3^{bc}	21 ± 4^{c}	10 ± 2^{b}	20 ± 4^{cd}	13 ± 3^{bd}	6 ± 1^{e}
Zn (µg)	7 700	216 ± 43^{ab}	154 ± 31^{a}	248 ± 50^{b}	572 ± 114^{c}	583 ± 117^{c}	430 ± 86^{c}	635 ± 127^{c}
I (µg)	100[2]	54 ± 11^{a}	164 ± 33^{b}	$1\,521\pm304^{cd}$	$1\,954\pm391^{c}$	$3\,447\pm689^{e}$	$1\,158\pm232^{d}$	$2\,138\pm428^{c}$
vit B12 (ng)	2 500	362 ± 4^{ab}	466 ± 21^{ab}	772 ± 87^{a}	771 ± 70^{a}	$7\,284\pm744^{c}$	203 ± 31^{b}	107 ± 6^{b}
Moisture content (%)		93.2	94.5	89.5	89.8	73.3	96.5	95.8

The contents of Na, P, and Se are provided in the supplementary material. Different lowercase letters (a-e) denote significant differences (95% confidence interval for elements and $p < 0.05$ for vitamin B12) within each row; The elemental analysis was performed using accredited methods with a relative standard deviation (RSD) of ±20% as extended ($K = 2$), combined uncertainty.

Ulva = *U. fenestrata; Saccharina* = *S. latissima;* ww = wet weight; RDI = Recommended dietary intake; *O* = ocean; *T* = tank; HPPWs = Herring production process waters.

[1] Obtained from the Swedish Food Agency, https://www.livsmedelsverket.se.

[2] AI = Adequate intake.

Table 6

Amount of biomass (g ww) required to reach 100% of the UL of potentially toxic elements (including I) and 15% of the daily RDI or AI of selected essential elements.

	Ulva fenestrata		Ulva fenestrata			Saccharina latissima	
	Ocean cultivation		Tank cultivation			Ocean cultivated	
	Ulva-O-early	Ulva-O-late	Ulva-T- seawater	Ulva-T-HPPWs	Ulva-T-untreated	Saccharina-O-early	Saccharina-O-late
Element							
Cd[1]	9 476.9	10 266.7	3 004.9	3 004.9	1 018.2	17 600	20 533.3
iAs[1]	9 240	6 160	6 160	5 435.3	556.6	137.3	60
I[1]	462.1	152.4	16.4	12.8	7.3	21.6	11.7
Pb[1]	2 800	2 655.2	1 480.8	307.4	594.6	2 264.7	3 948.7
Ca[2]	389.6	540.5	357.1	269.1	157.5	215.1	135.9
Cu[2]	100.6	105.6	83.0	34.1	46.2	77.0	114
Fe[2]	2.2	1.3	1.2	2.7	3.3	0.8	2.4
Mg[2]	3.6	3.0	3.5	3.5	2.2	4.9	4.6
Mn[2]	281.3	284.8	133.1	160.7	63.9	296.1	394.7
Mo[2]	50.8	31.5	21.7	46.4	23.1	34.6	0.8
Zn[2]	534.7	750.0	465.7	201.9	198.1	268.6	181.9
I[2]	27.7	9.7	1.0	0.8	0.4	3.5	0.7
Vit B12[2]	103.6	80.5*	48.6	48.6	5.1*	184.7	350.5

Ulva = *U. fenestrata; Saccharina* = *S. latissima;* UL = Tolerable upper intake level; ww = wet weight; iAs = iAs; *O* = ocean; *T* = tank; HPPWs = Herring production process waters.

[1] amount of biomass required to reach 100% of the UL shown in Table 4.

[2] amount of biomass required to reach 15% of the RDI or AI shown in Table 5.

* exceeds AI for I, thus not safe to be consumed regularly.

and amines (Liu et al., 2024). There were no significant sensory differences between *Ulva*-O-early and *Ulva*-O-late with respect to appearance, texture and odor. In contrast, *Ulva*-T-HPPWs had a significantly lower intensity of grassy odor compared to *Ulva*-T-seawater. There are no previous studies to explain this finding, but it is well-known that grassy notes can be derived from numerous aldehydes, alcohols, esters and furans existing in algae (Urlass et al., 2023) Examples of the former are hexanal, nonanal, nonenal and 2,4-decadienal formed e.g., through lipoxygenase and/or fatty acid hydroperoxide lyase pathways from unsaturated fatty acids >C18 (Alsufyani et al., 2014; Boonprab et al., 2006). Considering the distinctive sensory properties of nutrient-rich herring brine (Szymczak and Kołakowski, 2012), which constitute HPPWs, odor effects are to be expected. Furthermore, the basic tastes, salt, sour, and umami were significantly more intense in *Ulva*-T-untreated compared to the *Ulva*-O-early and *Ulva*-O-late (Table 3). The leachability of water-soluble elements, such as free amino acids (specifically glutamic and aspartic acid), peptides, 5′-nucleotides and Na, compounds enhancing both umami and saltiness, can explain decreases in these basic tastes related to HWT of the biomass (Correia et al., 2021). As opposed to the thin and delicate leaves of *U. fenestrata*, fully-grown *S. latissima* has a coarse texture, likely explaining the significant effect of early vs. late harvest on its structure.

4.2. Nutritional and safety aspects

Although the I concentration on a wet weight basis in the *S. latissima* samples was significantly lower than in *Ulva*-T-untreated, it was well above the UL for I, despite the HWT. The I content in *Ulva*-O-late was significantly higher than in *Ulva*-O-early, yet lower compared to the *S. latissima* samples. Although HWT can reduce the iodine levels by ~90% in the *S. latissima* biomass (Nielsen et al., 2020), the initial levels can be very high, which would still result in a biomass with I as the limiting element (Trigo et al., 2023; Zava and Zava, 2011). Furthermore, both *S. latissima* samples had the highest concentrations of iAs with up to 100 times more than in *Ulva*-O-late, making iAs the second limiting element after I in *S. latissima*. Therefore, safe consumption levels should be regulated by iodine upper intake levels (UL) and iAs concentrations in seaweeds. Under these safety thresholds, *Ulva*-O-early and *Ulva*-O-late remain the only realistic candidates, whereas tank-grown *U. fenestrata* and *S. latissima* samples would exceed safety limits at relatively low intake levels and are therefore unsuitable except in minimal amounts.

HWT not only reduced the concentrations of I, Cd, and iAs, but it also reduced the levels of micronutrients, making it more difficult to reach 15% of RDI with a small portion of seaweed. In theory, to reach 15% of the RDI for vitamin B12, a 7–10-year-old child must consume 5.1 g of *Ulva*-T-untreated or 80.5 g of *Ulva*-O-late. At these levels, *Ulva*-O-early, *Ulva*-O, late, and *Ulva*-T-untreated, all have the potential of being sources of B12, covering 15% of RDI (EFSA Panel on Dietetic Products, Nutrition and Allergies (NDA), 2009) for B12 without surpassing the UL for the limiting elements. However, the modeled intake levels exceed the Adequate Intake (AI; 100 μg/day) for I, indicating a high iodine density of the seaweed biomass. For dietary planning and safety evaluation, UL for I should be used as the primary safety threshold, while AI values may be used to assess nutritional adequacy within these safety limits. In addition, other potential dietary sources of I were not considered in the intake modelling presented in Table 6.

An interesting exception to this was the Fe concentration, which was significantly higher in the hot water-treated tank-cultivated samples compared to *Ulva*-T-untreated. HWT of seaweed is a safety measure, which is beneficial both from a toxicological and microbiological point of view (Adams et al., 2021). Thus, treating ocean-cultivated *U. fenestrata* with hot water can be an important processing step for the industry, especially if the objective is to encourage the public to consume seaweed (Trigo et al., 2025). Since there was no comparison between HWT and soaking in cold water, it cannot be determined if temperature played a critical role in the significant differences reported between hot water treated samples and the untreated sample. Furthermore, the bioavailability of any of the micronutrients was not measured in this study.

Although cultivation with HPPWs did not affect the sensory properties of *U. fenestrata* in the current study, further exploring this cultivation strategy (by e.g., analyzing potential effects on micronutrient levels) might be interesting from a nutritional perspective, as it has previously shown to raise the total crude protein in the biomass (Stedt, Steinhagen, et al., 2022, 2022). In this regard, *Ulva*-T-HPPWs was low in Fe, but significantly higher in Cd and Pb compared to *Ulva*-O-early and *Ulva*-O-late. This finding can possibly be explained by the similar structure of both Cd and Fe, leading the essential metal transporters in seaweeds to bind Cd instead of Fe, if there is an abundance of the aforementioned (Clemens, 2006). Studies on rice cultivation and other plants have shown that the presence of Cd ions can disturb the homeostasis of several essential elements by replacing Fe and Mn ions (Clemens, 2006; Zhang et al., 2023). Although the concentration of molybdenum was significantly lower in *Ulva*-T-HPPWs compared to *Ulva*-T-seawater, the effect of HPPWs on the microelements analyzed in this study may not be fully understood.

4.3. *Future perspectives*

Seafood is consumed less frequently in households with children compared to households consisting of only adults (Nystrand and Fjørtoft, 2015). Fishy flavor, a part of the “marine” flavor attribute in the current study, is often a driver of rejection, especially when it comes to children and adolescents (Hosseinkhani et al., 2022; Wu et al., 2022). In contrast, for older individuals, wanting to eat healthy can be a motivator for fish consumption. Similarly, certain adult consumer segments associate food choices with progressive self-identities (Al-Thawadi, 2018; Govaerts and Olsen, 2023). For these individuals, potential health-benefits can outweigh suboptimal sensory quality (Shepherd and Raats, 2006), although this is rarely true for children, whose food preferences are primarily driven by sensory attributes (Waddingham et al., 2018). Furthermore, studies show that increasing seaweed content in different food products – familiar or unfamiliar to the consumers – correlates with lower liking scores, especially when the seaweed has been dried without prior HWT, which tends to intensify fishy odors (Rauf Dahlstedt et al., 2025). Given that neophobic eating behavior is common among young children (Cooke, 2007; Jaeger et al., 2021; Krupa-Kotara et al., 2024), it is crucial that the sensory qualities of food products intended for children are not altered when incorporated with unfamiliar ingredients, such as seaweed. Familiarity plays a key role in acceptance and should be a guiding principle in the development of child-friendly food products (Jaeger et al., 2021). Although this study did not investigate children’s acceptance of seaweed-based food products, the QDA provided insight into the different sensory attributes of the analyzed biomasses as well as the attributes’ intensities. Consequently, *Ulva*-O-late, which exhibits mild sensory characteristics, including a subtle flavor, minimal marine odor and smooth texture, may be particularly well suited for integration into food products aimed at consumers across all ages without excessively altering the products’ sensory properties. However, as there are many edible seaweed species, this result might not be applicable to all other species. Future research should therefore include identification of volatile compounds and other aspects responsible for the elicited sensory characteristics of the seaweed in order to optimize post-harvest treatments of seaweed biomass.

Additionally, umami, the basic taste appreciated across age groups, has been suggested to have the potential to be a driver towards more sustainable eating. In a study from 2022, the authors explain that the lack of craving for plain vegetables can be attributed to the absence of umami taste (Schmidt and Mouritsen, 2022). While HWT of *U. fenestrata* reduces bitterness and marine odors, it also diminishes umami intensity, which may negatively affect its sensory appeal. Nonetheless, hot water treated and ground *U. fenestrata* has the best potential to serve as an ingredient in familiar and accepted food products.

From an industrial perspective, harvesting *U. fenestrata* at the normal stage, rather than early, yields a higher biomass, making it a more economically viable option (Steinhagen et al., 2022). In addition, such harvests of *U. fenestrata* can contribute positively to environmental sustainability by minimizing the competition for arable land and serving as a partial substitute for land-grown vegetables in future food products. However, if gastronomic sensations are prioritized, untreated *U. fenestrata* may be a more interesting alternative. Whether or not applying HWT, the levels of vitamin B12, Fe, and Mg are sufficient for qualifying *U. fenestrata* as a source of these micronutrients without surpassing the UL for the main limiting component, I. However, future research should include bioavailability testing of the micronutrients found in *U. fenestrata* to further substantiate the field. AI for I is exceeded at relatively low intake levels and caution should therefore be taken when consuming *U. fenestrata*.

5. Conclusion

The sensory profile of ocean-cultivated and HWT *Ulva fenestrata*, with its smooth texture and slightly sulfurous odor differed from its tank-cultivated counterparts, and even more so from the untreated *U. fenestrata*, which had high intensities of both odor and flavor as well as a coarse structure. In this study, the addition of HPPWs to tank-cultivated *U. fenestrata* only reduced its grassy odor while it did not affect its color or any other sensory attribute significantly. HWT *Saccharina latissima* was characterized by a slimy appearance and a more distinctive marine odor and flavor compared to *U. fenestrata*. High and varying initial concentrations of I limit the consumption of *S. latissima*, even after HWT. This is especially important to address when it comes to vulnerable consumer groups, such as children. Furthermore, the levels of both I and potentially toxic elements in the tank-cultivated

U. fenestrata samples were significantly higher than in the ocean-cultivated *U. fenestrata* samples, and strategies for keeping levels down should be investigated further. Based on the findings of this study, *S. latissima* and tank-grown *U. fenestrata* all exceed AI and UL for I and iAs even in small amounts, making them less suitable for regular human consumption. Thus, following measures to verify amounts below AI for I and UL for iAs, only *Ulva*-O-early and *Ulva*-O-late have potential to become ingredients in future food products. As the sensory evaluation showed no significant difference between the early-harvested *U. fenestrata* and normal-harvested *U. fenestrata*, there is no sensory incentive to apply the former. Instead, when considering the levels of essential elements, potentially toxic elements, and financial aspects of a larger biomass yield, harvesting later could be more beneficial, not least from an industrial perspective. However, based on the intense flavor- and odor profile in untreated *U. fenestrata*, this biomass might be an option for improving both the sensory and nutritional profile of other food products where marine or seafood flavors are desired, using less biomass.

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Ethical statement

This paper is the authors' own original work, and has not been previously published elsewhere. This study is part of the SensAlg project, which has received ethical approval from the Swedish Ethical Review Authority (Id number: 2022–06,258-01) for research involving humans.

CRediT authorship contribution statement

Sermin Rauf Dahlstedt: Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **João P. Trigo:** Writing – review & editing, Validation, Resources, Investigation. **Kristoffer Stedt:** Writing – review & editing, Validation, Resources, Investigation. **Pekka Varmanen:** Writing – review & editing, Resources, Investigation. **Bhawani Chamlagain:** Writing – review & editing, Resources, Investigation. **Fredrik Rosqvist:** Writing – review & editing. **Ingrid Undeland:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Henrik Pavia:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Pernilla Sandvik:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.fufo.2026.100995.

Data availability

Data will be made available on request.

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