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Sensory profiles of three Nordic seaweeds following industrially relevant post-harvest processing

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ABSTRACT

Seaweed has potential to be a sustainable food ingredient, yet its sensory properties are poorly understood, and previous research has focused on species differences, with less attention given different post-harvest processing formats. To characterize sensory properties across different post-harvest processing formats, 15 seaweed ingredients were profiled by Quantitative Descriptive Analysis. These encompassed three Nordic-relevant species (*Saccharina latissima*, *Palmaria palmata*, and *Ulva fenestrata)* treated with different combinations of blanching, stabilization (flash-freezing, drying), and disintegration (re-hydrated flakes and powder as well as wet mince and paste). Data were analysed using ANOVA and Principal Component Analysis.

Two previously unreported sensory attributes were consistently perceived across all *P. palmata* samples: a salmiac-like flavour and a tingling, carbonation-like mouthfeel. The blanched *U. fenestrata* samples differed from the non-blanched counterparts, with higher sulphurous odour and flour-like flavour notes and lower marine flavour, saltiness, sourness, and bitterness. No differences were detected between samples that were flash-frozen before drying and those that were dried directly after harvest, suggesting that intermediate frozen storage may be feasible in an industrial context. Samples differing in tissue disintegration (flaking/milling, mincing, and pasting to powder/paste) showed differences in texture- and structure-related attributes, with limited effects on flavour., the findings demonstrate that different processing formats are associated with differences in the sensory characteristics of seaweed ingredients, while flash-freezing before drying resulted in no detectable sensory differences in *P. palmata* and *U. fenestrata*, facilitating for more even feeding volumes into industry scale dryers.

1. Introduction

Seaweeds are photosynthetic multicellular marine organisms with rapid growth rates, and no need for soil, fertilizers, or fresh-water irrigation. Like most other plants, they absorb and sequester carbon dioxide from the atmosphere, making them resource-efficient and environmentally sustainable crops [1,2]. There are around 10,000 different seaweed species [3], of which 200 are commercially utilized worldwide [4]. However, only eight edible seaweed species, mainly red and brown, account for 96.8% of the seaweed consumed globally. China and Indonesia are the dominating producers of seaweed as food [5], with 99.5% of the global seaweed market share [6]. In the Nordic countries and most of Europe, seaweed is mainly consumed as a condiment alongside sushi [7] and other Asian dishes [8].

However, there is a growing interest in seaweed as sustainable food among consumers in Europe and globally [5,9,10], which in turn has fuelled several business opportunities for seaweed farming and distribution in Europe and other Western countries [9,11,12]. In Asia, seaweed has already been identified as a major aquaculture product based on produced biomass volume [13]. Yet most of the biomass is used for hydrocolloid extraction while a small proportion enters the food supply chain directly as raw material [5]. From a global perspective, only negligible quantities of seaweed biomass are produced in Europe [14,15].

Since seaweeds may absorb potentially harmful elements such as heavy metals from their surroundings, regular consumption of unprocessed seaweed can entail a health risk [13,16]. Furthermore, high water activity in freshly harvested seaweed stimulates fast deterioration

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through microbial and enzymatic activities [17,18]. Post-harvest processing, such as blanching combined with e.g., drying or freezing, is therefore often necessary to stabilize the biomass and turn it into a safer product [17]. Blanching reduces microbial load, enzymatic activity, and the content of specific undesired elements [19,20]. Drying and freezing decrease the biomass's water activity, making it less prone to microbial growth [21], as well as enzymatic processes [17]. However, it is widely known that slow freezing of food matrices, including seaweed biomass, can cause large ice crystals that damage cellular integrity [22]. On the contrary, flash-freezing usually results in the forming of smaller ice crystals [23] and might therefore be a better option to minimize cell damage. Thus, the choice of processing method also affects sensory quality.

However, there is a scarcity in studies exploring sensory properties of seaweed produced with different post-harvest processing regimes [24]. Blanching *S. latissima* biomass at 80 °C for 120 s has been found to reduce significant amounts of iodine, making it safer for human consumption [25]. At the same time, blanching seaweed biomass in fresh water often reduces its taste of salt and umami [13], which has also recently been demonstrated after blanching *U. fenestrata* [26].

Processing large volumes of fresh, wet seaweed as quickly and cost-efficiently as possible is industrially important for economically viable processes. Since drying operations are identified as logistical bottlenecks in the biomass-stabilization procedures [27–29], we hypothesized that freezing could serve as an intermediate pre-drying storage. However, to date it is not known how this affects the sensory properties of seaweed. Similarly, and to our knowledge, the role of tissue disintegration, translating into the degree of particle-size reduction, has not been studied with respect to the sensory properties of frozen seaweed. For other food items, e.g. vegetables, it has been described how extreme mechanical grinding can intensify flavour attributes, including bitterness [30–32]. Overall, exploring sensory characteristics of seaweeds processed with different industry-relevant methods is key in understanding the potential and challenges as a possible ingredient in food. Furthermore, sensory knowledge can support post-harvest quality control, biomass classification, and guide its allocation to relevant processing steps and ultimately suitable food applications.

Previous sensory studies of seaweed have primarily evaluated dried biomasses served either dry or rehydrated prior to assessment [33,34]. To our knowledge, the present study is the first to compare frozen-thawed seaweed biomass with dried-rehydrated seaweed biomass.

This study aimed to characterize the sensory properties of samples from three edible seaweed species that are industrially cultivated in Sweden; *U. fenestrata*, *S. latissima*, and *P. palmata*, following industry-relevant post-harvest stabilization techniques (blanching, flash-freezing, and drying) and different forms of tissue disintegration, including mincing, pasting, flaking, and milling it into powder.

2. Methods and materials

2.1. Cultivation of P. palmata, U. fenestrata, and S. latissima

A total of 15 samples from three seaweed species were included in the study: *P. palmata* (5 samples), *U. fenestrata* (6 samples), and *S. latissima* (4 samples). The cultivation and post-harvest processing methods were selected in collaboration with industrial partners to reflect feasible ingredient formats currently used in seaweed product development.

Palmaria palmata was cultivated in land-based tanks and harvested on the 22nd of May 2024 as described by Stedt et al. [35]. Commercially cultivated *U. fenestrata* and *S. latissima* were harvested from the Swedish West coast (Skagerrak, Sweden; N 58.64271, E11.216433), on the 16th and 23rd of April 2024, respectively. To minimize post-harvest degradation, the biomass was drained and placed in expanded polystyrene containers with cold packs which kept a temperature between 4 °C and 8 °C during the immediate two-hour transport from the seaweed farm to a food-grade facility in central Gothenburg (Sweden). Upon arrival, the biomass was transferred to a refrigerator (4 °C) and stored overnight, pending further processing the following morning.

2.2. Post-harvest treatments: stabilization and disintegration

Due to the typical high iodine content in *S. latissima*, its entire biomass was subject to blanching. Since *P. palmata* has relatively low levels of iodine compared to both *S. latissima* and *U. fenestrata*, blanching is not critical for the reduction of iodine. Furthermore, blanching of *P. palmata* transforms its colour from vivid purple/red to grey [36], thus, to avoid a colour shift the entire *P. palmata* biomass was left unblanched. Subsequently, *U. fenestrata* was the only species that was partially blanched. *P. palmata* was either frozen or oven-dried immediately upon arrival to the facility.

For the blanching, biomasses were placed in tap water at 80 °C for 120 s, thereafter, cooled in potable water, drained, and packed in heat-sealed polystyrene bags. The blanched biomass was then either oven-dried at 40 °C for 24 h (V-series rack oven, Sveba Dahlen) or flash frozen (Blastchiller BCB/0520 5xGN1/1, GEMM). Following flash-freezing, the biomasses were either left frozen or oven-dried (Fig. 1). The frozen biomasses were subsequently processed into mince (PP-mince, UF-mince, and SL-mince) using a grinder (C-E22N, La Minerva) equipped with a 4.5 mm hole plate, whereas the oven-dried biomasses were milled into flakes of <4 mm particle size (PP-flakes, PP-fr-flakes, UF-flakes, UF-NoBl-flakes, UF-fr-flakes, and SL-fr-flakes) and powder of <1 mm particle size (PP-powder, UF-fr-powder, and SL-fr-powder) using a Centrifugal mill (ZM200, Retsch) (Fig. 1).

All biomasses (frozen and dried) were stored in −80 °C for 4 months (*P. palmata*) and 5 months (*U. fenestrata* and *S. latissima*) before being transferred in a cooler box to Uppsala, Sweden and stored at −20 °C for 2 weeks until the sensory evaluations.

2.3. Sensory evaluation

The method used for the sensory evaluation of the 15 different samples was Quantitative Descriptive Analysis (QDA®) [37]. The evaluation was performed by a trained panel in a sensory laboratory (ISO 8589:2007) where each panel member was separated in an individual booth with white lighting according to ISO 13299:2016. The panel consisted of eight individuals (ages: 33–64 years) with previous experience from QDA with seaweed [26]. The panellists were recruited and screened following ISO 8586:2012 and provided their written consent for participation in the study.

2.4. Sample preparation

For sensory assessment, the samples were prepared to obtain cohesive samples suitable for evaluation. Nine different samples containing dried biomass were rehydrated to obtain homogeneous paste-like samples which would not separate into a solid and liquid phase, at the same time as they would provide similar bolus. Following trials with rehydration experiments with different ratios including consistent samples after one hour in room temperature, the optimal and final seaweed (dry weight) to water ratios were used: 1:15 (*S. latissima*), 1:10 (*U. fenestrata*), and 1:3 (*P. palmata*). The frozen biomasses (6 samples) were thawed for 3 h at room temperature (21 °C). To compensate for drip loss during freezing and thawing, water was added to the thawed biomasses. The following seaweed-water ratios (wet weight basis) were applied: 5:1 (*S. latissima*) and 10:1 (*U. fenestrata*). Water was not added to *P. palmata* since no drip loss was empirically observed, consequently, the seaweed-to-water ratios were adjusted based on visual assessment to obtain paste-like samples (Fig. 2). The paste samples (PP-paste, UF-paste, and SL-paste) were mixed with a stand mixer (Philips ProMix, 650 W) 20 min before the evaluation. All samples were served as 5 g portions in lidded 30 ml clear plastic medicine cups labelled with randomized 3-digit codes

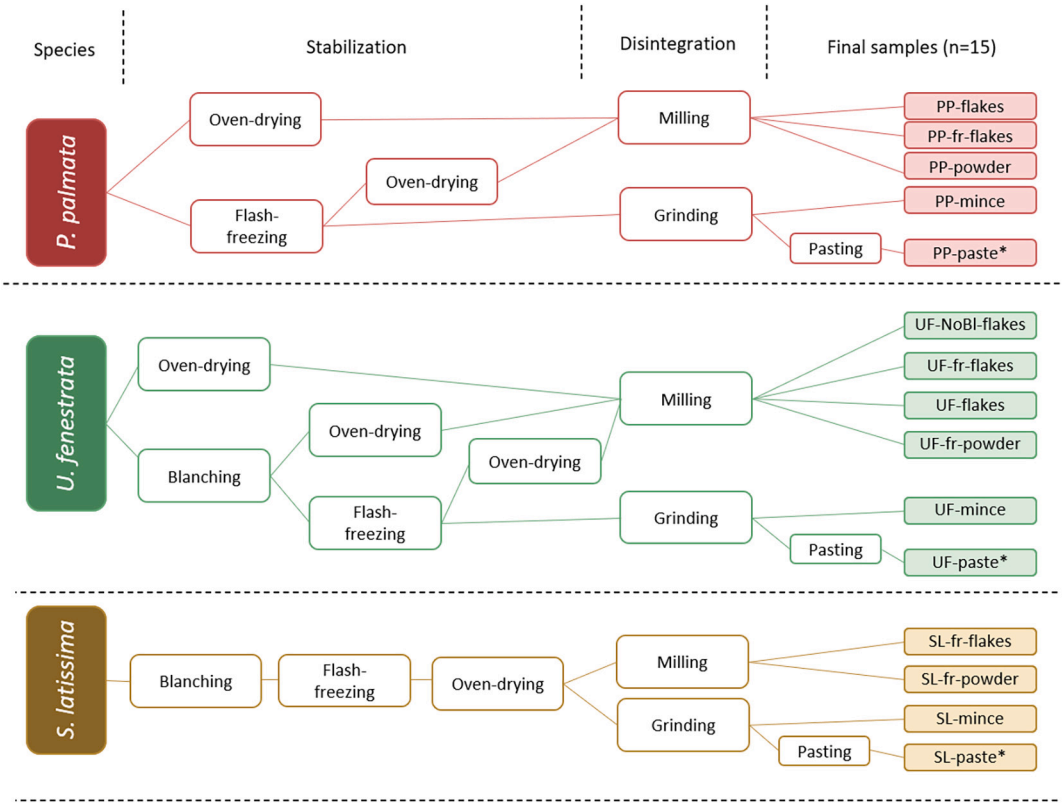


Fig. 1. Flow chart displaying the different steps of post-harvest processing. The three species were not subjected to identical processing procedures. PP = *Palmaria palmata*, UF = *Ulva fenestrata*, SL = *Saccharina latissima*, fr = frozen before drying, NoBl = non-blanched. *Samples in paste form were prepared by mixing minced biomass 20 min before sensory evaluation.

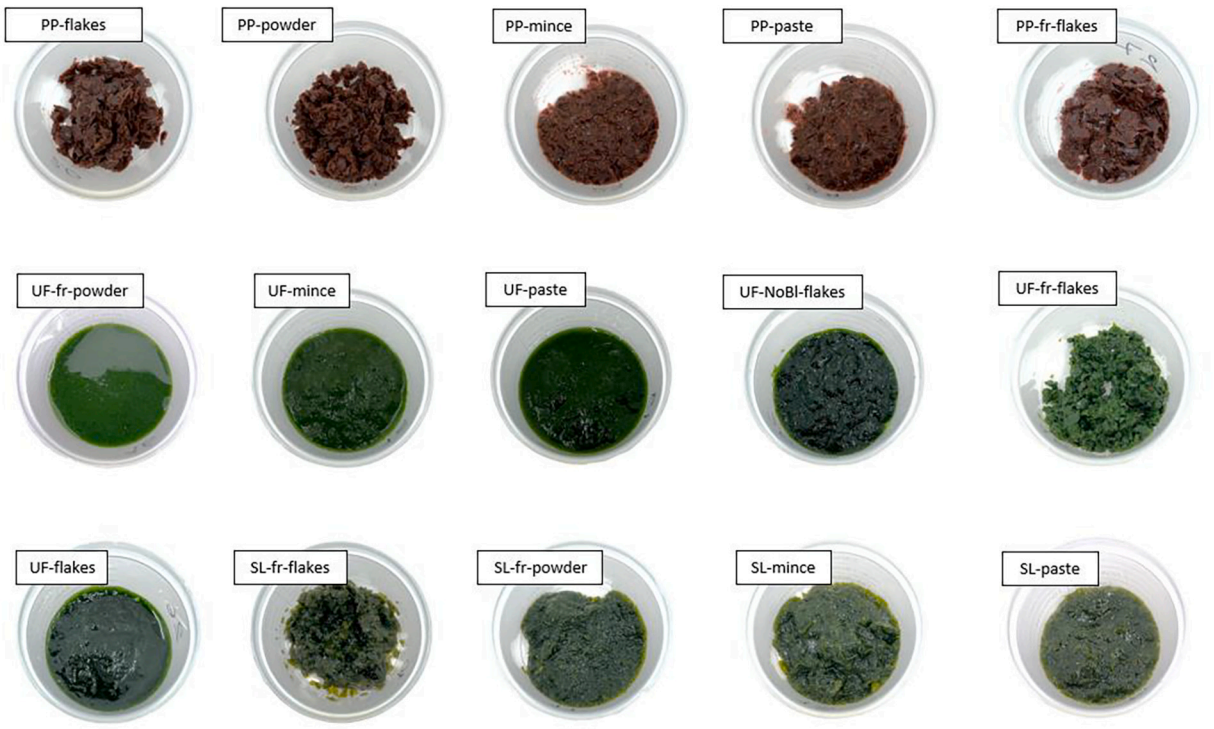


Fig. 2. Samples as served to the panellists. PP = *Palmaria palmata*, UF = *Ulva fenestrata*, SL = *Saccharina latissima*, fr = frozen, NoBl = non-blanched.

and plastic spoons.

2.5. Evaluation procedure

Six training sessions took place at the sensory laboratory and lasted for two hours each. During the first two sessions, the panel elicited 206 descriptors, followed by discussions, which resulted in a reduction to 26 attributes for the final vocabulary. During these discussions, the panel agreed on attribute definitions, references, and attribute anchors (Table 1). Four attributes were evaluated for appearance (colour intensity of emerald green and burgundy, visual structure and sliminess), 7 attributes were evaluated for odour (ocean, fish, sulfur, berry, cucumber, shellfish and odour intensity), 9 for taste/flavour (flour, umami, salty, sweet, bitter, fish, ocean, salmiac and flavour intensity) and 6 attributes were evaluated for texture/mouthfeel (adhesiveness, chewiness, particle size, tingling mouthfeel, sliminess and cartilaginous). The definitions of each attribute, the references, attribute anchors, and evaluation procedures are shown in Table 1. The final evaluation lasted over three consecutive days with five triplicate samples per day with 10-min breaks between each replicate session. The samples were served in a balanced Latin-square-design. The panellists were provided with a list of attributes, attribute definitions, and evaluation instructions. The samples were graded on 15-cm unstructured scales (0 = minimum intensity, 15 = maximum intensity) using the software FIZZ (Biosystems, Counternon, France). Due to the volatile nature of the different odour compounds in seaweed, the panel decided to utilize the headspace right after removing the lid from the cups and were therefore asked to start by evaluating the smell of each sample, followed by appearance, taste/flavour, and texture instructions (Table 1).

2.6. Statistical analysis

The results from the final evaluation were analysed using a mixed model 3-way multivariate analysis of variance (MANOVA) in SPSS (version 28.0.1.0, 2021) to assess sample effect (fixed), assessor effect (random), and replicate effect (random) on the results of the QDA. Each attribute was then analysed separately with a mixed model analysis of variance (ANOVA), with all 2-way interactions, including homogeneity testing in SPSS (version 28.0.1.0, 2021) with Least Significant Difference (LSD) to detect significant differences between the samples. XLSTAT (version 2025.1.1 (1429) was used for the table with means, Principal Component Analysis (PCA), and spider plots. Only the attributes that were significantly different (p-value <0.05) in the ANOVA's were plotted in the spider plots (Fig. 4).

3. Results

The MANOVA showed significant main effects of sample ($p < 0.001$) and assessor ($p < 0.001$), whereas no significant effect of replicate was observed ($p = 0.457$). Attribute-specific two-way ANOVAs with interaction effects further demonstrated significant sensory differences between several of the evaluated samples (Table 2 and Supplementary).

The PCA (Fig. 3) showed a clear separation of the samples according to seaweed species. Principal component (PC) 1 separated *P. palmata* samples from *S. latissima* and *U. fenestrata* samples, except the non-blanched *U. fenestrata* flakes (UF-NoBl-flakes), which were positioned closer to the centre of the score plot. Positive PC1-values were associated with ocean flavour, odour and flavour intensity, umami, saltiness, chewiness, cartilaginous texture, and structural roughness, attributes primarily associated with *P. palmata* samples. Negative PC1-values were instead associated with emerald-green appearance, flour-like flavour, sulphurous odour, and smooth structural characteristics, attributes mainly associated with blanched *U. fenestrata* samples. PC2 separated *S. latissima* samples from *U. fenestrata* samples and was mainly related to differences in sliminess, cucumber-like odour, particle size, and structural appearance. Positive PC2-values were associated with sliminess, cartilaginous texture, and larger particle size, whereas negative PC2-

Table 1
Definition and references of the sensory attributes elicited by the panel.

Attribute	Definition	Reference	Attribute anchors	Evaluation procedure
Appearance				
Emerald green	Intensity of green	Dark green, bright emerald green	No hint – High intensity	Look at the sample from above, stir it around, press it towards the edge, and pick up a little with the spoon.
Burgundy	Intensity of red	Brown, rusty red, burgundy, bright red		
Structure	Surface structure, smoothness, roughness	Fruit purée, porridge, coffee grounds, tapenade	Smooth – Rough	
Sliminess	Slimy, gel-like appearance	Slime	Not slimy – Very slimy	
Odour				
Ocean	Scent of ocean	Ocean breeze, wet rocks mussels, seaweed	No hint – High intensity	Open the lid and give the sample three light and quick sniffs. Repeat the procedure if necessary.
Hay	Scent of hay	Hay, hayloft		
Sulfur	Sulphurous smell	Boiled egg, sewer, marsh		
Grass	Scent of grass	Green grass, cut grass		
Cucumber	Freshly cut cucumber	Cucumber, melon		
Shellfish	Sweet smell of shellfish, i.e. crab	Surimi sticks		
Odour intensity	Intensity of overall odour	Odour intensity	Low – High	
Flavour/ Taste				
Flour	Bland flavour of flour and/ or cardboard	Wheat flour, rye flour, pantry	No hint – High intensity	Take a spoonful, chew, and let the sample cover the entire oral cavity to release as many flavours as possible – Do not repeat
Umami	Basic taste	Umami		
Salty	Basic taste	Salt		
Sweet	Basic taste	Sweet		
Sour	Basic taste	Sour		
Bitter	Basic taste	Bitter		
Ocean	Gulp of seawater	Seawater, seaweed, oysters		
Salmiac	Salmiac flavour	Salmiac, salt licorice,		
Flavour intensity	Intensity of overall flavour	Flavour intensity	Low – High	
Texture/ mouthfeel				
Adhesiveness	Tendency to stick to inside of mouth and surface of teeth	Vegetable peel, popcorn pericarp	Not adhesive – Very adhesive	Take a spoonful, chew, and assess the texture/ mouthfeel – Do not repeat
Chewiness	Mastication	Raw kale, porridge	Not chewy – Very chewy	
Particle size	Effect of the milling-, or grinding size on the texture	Smooth fruit purée, rough coffee grounds, olive tapenade	Smooth/ purée-like – Coarsely chopped	
Tingly	Tingling/ fuzzy sensation, e.	Sparkling water	Not tingly – Very tingly	

(*continued on next page*)

Table 1 (*continued*)

Attribute	Definition	Reference	Attribute anchors	Evaluation procedure
	g., carbonated drinks			
Sliminess	Slimy mouthfeel	Thin oatmeal with chia seeds	Not slimy – Very slimy	
Cartilaginous	Cartilage-like mouthfeel, ability to bounce back when chewed	Pickled vegetables	Not cartilaginous – Very cartilaginous	

values were associated with greener appearance and flour-like sensory notes.

3.1. Palmaria palmata

P. palmata samples exhibited a burgundy colour (10.9–13.5 on the 0–15 scale), coarse and cartilaginous structure, high chewiness (11.3–13.5), and pronounced flavour intensity. In addition, all *P. palmata* samples exhibited a tingling mouthfeel (2.9–6.2) and a pronounced salmiac flavour (8.4–9.7)- attributes that were not present in the other species. All the *P. palmata* samples were unblanched and exhibited high saltiness (11.0–11.4), pronounced umami taste (8.0–9.1), and intense ocean flavour notes together with high odour and flavour intensity. Differences between the evaluated *P. palmata* processing formats were observed mainly in texture-related attributes. Flaked samples (PP-flakes and PP-Fr-flakes) exhibited rougher structural appearance (13.4–14.0) and larger particle size (13.2–13.8), whereas powder (PP-powder), mince (PP-mince), and paste (PP-paste) samples showed significantly smoother structural appearance (9.5–10.0) and smaller particle size (10.2–11.3). The paste sample (PP-paste) also exhibited a significantly higher tingling mouthfeel (6.2) compared with the other *P. palmata* samples (2.9–4.2). No significant sensory differences were observed between samples that were flash frozen prior to drying and milling (PP-Fr-flakes) and those that were dried directly after harvest (PP-flakes) (Fig. 4a).

3.2. Ulva fenestrata

According to the PCA, samples of *U. fenestrata* were generally characterised by an emerald green appearance (11.7–14.0), sulphurous odour, and flour-like flavour notes. Overall, *U. fenestrata* samples exhibited a relatively mild sensory profile with smooth structural characteristics and low chewiness, particularly in the minced (UF-mince) and paste (UF-paste) samples. The blanched *U. fenestrata*

Table 2
Mean values (M) for each sample and sensory attribute.

	P.palmata					*U.fenestrata*						*S.latissima*			
Sample	PP-flakes	PP-powder	PP-mince	PP-paste	PP-Fr-flakes	UF-Fr-flakes	UF-Fr-powder	UF-mince	UF-paste	UF-NoBl-flakes	UF-flakes	SL-Fr-flakes	SL-Fr-powder	SL-mince	SL-paste
Appearance															
Emerald green	0.0^{a}	0.0^{a}	0.0^{a}	0.0^{a}	0.0^{a}	11.8^{d}	11.7^{d}	13.6^{ef}	14.0^{f}	12.3^{de}	13.3^{def}	5.5^{b}	5.7^{b}	6.8^{b}	8.6^{c}
Burgundy	13.1^{c}	12.2^{bc}	10.9^{b}	11.5^{b}	13.5^{c}	0.0^{a}	0.0^{a}	0.0^{a}	0.0^{a}	0.0^{a}	0.0^{a}	0.0^{a}	0.0^{a}	0.0^{a}	0.0^{a}
Structure	14.0^{g}	10.0^{f}	10.0^{f}	9.5^{f}	13.4^{g}	6.7^{de}	1.7^{ab}	0.6^{a}	0.4^{a}	3.1^{bc}	8.0^{ef}	9.4^{f}	3.0^{bc}	6.9^{de}	5.2^{cd}
Sliminess	0.2^{a}	0.3^{a}	0.5^{a}	0.6^{a}	0.2^{a}	1.2^{ab}	3.2^{b}	1.8^{ab}	1.9^{ab}	1.9^{ab}	1.0^{a}	12.4^{d}	12.1^{d}	12.7^{d}	8.45^{c}
Odour															
Ocean	7.2^{abc}	0.3^{a}	0.5^{a}	11.1^{d}	9.2^{bcd}	4.9^{a}	5.1^{a}	3.7^{a}	3.7^{a}	6.9^{abc}	4.0^{a}	6.4^{ab}	4.9^{a}	6.8^{abc}	5.9^{ab}
Hay	4.0^{ab}	10.0^{f}	10.0^{f}	2.6^{ab}	3.6^{ab}	1.6^{a}	2.9^{ab}	3.2^{ab}	2.9^{ab}	2.0^{a}	2.4^{ab}	1.4^{a}	1.2^{a}	1.5^{a}	1.2^{a}
Sulfur	4.7^{abcd}	0.3^{a}	0.5^{a}	2.7^{ab}	2.7^{ab}	6.4^{abcd}	6.8^{bcd}	8.4^{d}	7.9^{cd}	4.8^{abcd}	6.3^{abcd}	4.1^{abc}	3.6^{ab}	2.9^{ab}	3.7^{abc}
Grass	2.8^{a}	0.0^{a}	0.0^{a}	2.1^{a}	2.1^{a}	2.0^{a}	3.0^{a}	2.2^{a}	2.3^{a}	2.4^{a}	3.0^{a}	2.4^{a}	2.5^{a}	2.2^{a}	2.9^{a}
Cucumber	1.3^{a}	12.2^{bc}	10.9^{b}	1.3^{a}	1.2^{a}	2.0^{a}	1.8^{a}	1.4^{a}	1.3^{a}	1.3^{a}	1.5^{a}	2.3^{a}	2.8^{a}	2.5^{a}	3.0^{a}
Shellfish	4.7^{abc}	12.7^{bc}	10.9^{b}	2.6^{abc}	3.3^{ab}	3.9^{abc}	2.5^{abc}	4.1^{abc}	3.4^{ab}	5.8^{c}	5.2^{bc}	1.6^{a}	2.5^{abc}	1.9^{ab}	2.0^{ab}
Odour intensity	8.1^{cde}	0.0^{a}	0.0^{a}	8.3^{de}	8.2^{de}	5.6^{abcd}	5.2^{abc}	5.3^{abc}	4.4^{ab}	9.5^{e}	5.4^{abcd}	5.2^{ab}	4.6^{ab}	3.8^{a}	3.9^{a}
Flavour/taste															
Flour	0.6^{a}	0.6^{a}	0.3^{a}	0.5^{a}	0.5^{a}	8.0^{cde}	10.1^{e}	8.6^{cde}	8.5^{cde}	5.2^{bc}	9.8^{de}	5.0^{bc}	6.7^{bcde}	3.6^{ab}	6.1^{bcd}
Umami	8.9^{b}	8.1^{b}	9.1^{b}	9.1^{b}	8.0^{b}	1.4^{a}	2.0^{a}	1.4^{a}	1.8^{a}	3.1^{a}	1.8^{a}	1.6^{a}	2.0^{a}	1.6^{a}	1.7^{a}
Salty	11.3^{c}	11.4^{c}	11.4^{c}	11.0^{c}	11.0^{c}	0.4^{a}	0.5^{a}	0.5^{a}	0.5^{a}	5.4^{b}	0.4^{a}	0.7^{a}	0.5^{a}	0.6^{a}	0.5^{a}
Sweet	1.0^{a}	1.4^{a}	1.6^{a}	1.4^{a}	1.6^{a}	1.7^{a}	3.7^{b}	1.9^{a}	1.8^{a}	1.2^{a}	1.5^{a}	1.5^{a}	1.1^{a}	1.5^{a}	1.3^{a}
Sour	2.5^{bc}	3.0^{c}	2.9^{c}	3.1^{c}	2.7^{c}	0.4^{a}	0.5^{a}	0.4^{a}	0.5^{a}	3.3^{c}	0.6^{ab}	0.4^{a}	0.4^{a}	0.6^{ab}	0.5^{a}
Bitter	1.7^{a}	2.7^{a}	1.9^{a}	2.2^{a}	1.7^{a}	2.0^{a}	1.7^{a}	1.0^{a}	1.0^{a}	6.6^{b}	1.9^{a}	1.1^{a}	1.0^{a}	2.0^{a}	1.2^{a}
Ocean	10.3^{cd}	8.6^{cd}	11.0^{d}	11.2^{d}	7.5^{bc}	3.4^{a}	3.3^{a}	2.3^{a}	3.3^{a}	5.2^{ab}	2.8^{a}	3.6^{a}	2.1^{a}	3.1^{a}	4.1^{a}
Salmiac	9.7^{b}	8.5^{b}	8.8^{b}	8.5^{b}	8.4^{b}	0.5^{a}	0.4^{a}	0.4^{a}	0.4^{a}	0.6^{a}	0.4^{a}	0.4^{a}	0.5^{a}	0.4^{a}	0.4^{a}
Flavour intensity	11.1^{c}	10.8^{c}	11.5^{c}	10.9^{c}	10.4^{c}	3.4^{ab}	5.1^{ab}	2.5^{a}	2.6^{a}	10.7^{c}	3.8^{b}	3.2^{ab}	3.3^{ab}	3.1^{ab}	3.1^{ab}
Texture/ mouthfeel															
Adhesiveness	9.1^{ef}	8.9^{def}	8.5^{def}	8.7^{def}	9.6^{f}	8.8^{def}	7.0^{cdef}	2.9^{ab}	2.1^{a}	5.4^{acd}	9.5^{ef}	6.0^{bcde}	4.5^{abc}	3.6^{abc}	3.5^{abc}
Chewiness	13.5^{g}	11.3^{f}	11.5^{fg}	12.2^{fg}	12.4^{fg}	4.5^{cd}	1.8^{ab}	0.9^{ab}	0.3^{a}	2.7^{bc}	4.5^{cd}	10.9^{f}	4.2^{cd}	8.4^{e}	5.8^{d}
Particle size	13.8^{g}	10.2^{ef}	11.3^{f}	10.5^{ef}	13.2^{g}	6.5^{c}	2.7^{b}	0.6^{a}	0.4^{a}	2.9^{b}	7.1^{cd}	10.5^{ef}	2.9^{b}	8.7^{de}	6.0^{c}
Tingly	2.9^{b}	4.2^{b}	3.6^{b}	6.2^{c}	4.0^{b}	0.3^{a}	0.2^{a}	0.3^{a}	0.3^{a}	0.7^{a}	0.4^{a}	0.3^{a}	0.2^{a}	0.3^{a}	0.3^{a}
Sliminess	0.4^{a}	0.4^{a}	0.4^{a}	0.4^{a}	0.3^{a}	0.9^{a}	1.5^{a}	0.9^{a}	1.8^{a}	1.5^{a}	1.0^{a}	9.1^{bc}	9.7^{c}	10.3^{c}	7.0^{b}
Cartilaginous	10.0^{fg}	8.5^{defg}	8.4^{adefg}	9.5^{aefg}	8.1^{defg}	5.0^{bcd}	2.6^{abc}	0.5^{a}	0.4^{a}	2.2^{ab}	4.9^{bcd}	11.6^{g}	6.2^{cde}	8.9^{efg}	7.3^{def}

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. Scale ranging from 0 to 15.
fr = frozen before drying, NoBl = non-blanched.
The table including standard errors can be found in the Supplementary.

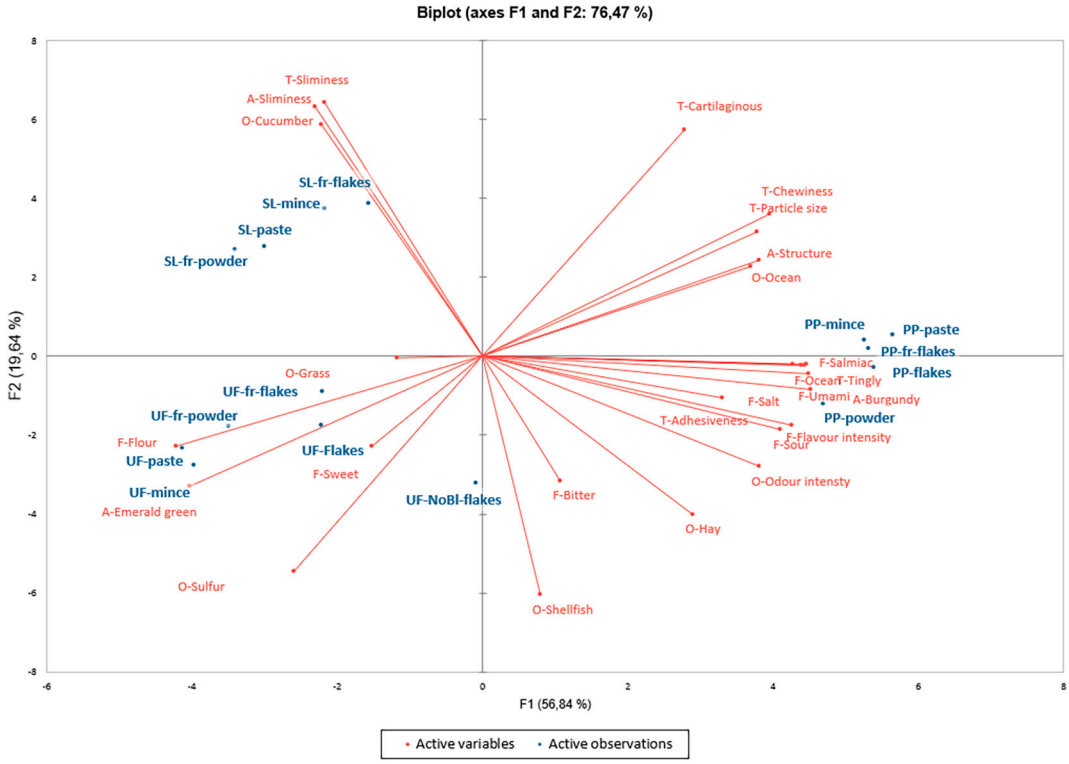


Fig. 3. Principal component analysis of the significant sensory attributes of the different samples. PP = *Palmaria palmata*, UF = *Ulva fenestrata*, SL = *Saccharina latissima*, fr = Frozen, NoBl = non-blanched.

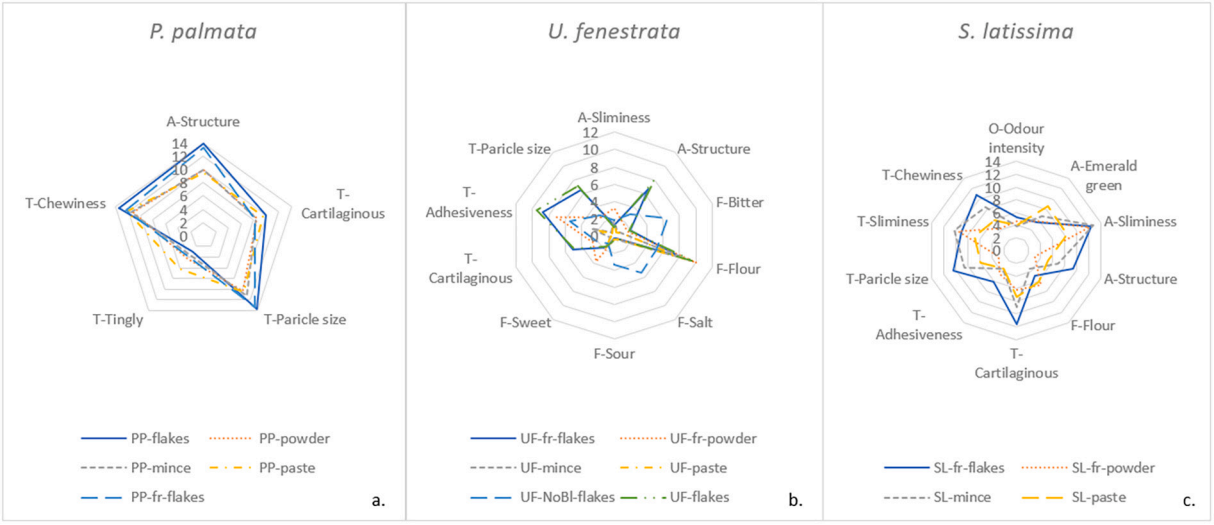


Fig. 4. Spider plots with intensities of the significant sensory attributes for *P. palmata* (a.), *U. fenestrata* (b.) and *S. latissima* (c.) PP = *Palmaria palmata*, UF = *Ulva fenestrata*, SL = *Saccharina latissima*, fr = Frozen, NoBl = non-blanched.

samples differed from the non-blanched in overall flavour intensity together with the perception of saltiness, umami, and bitterness. Compared with the non-blanched sample, UF-NoBl-flakes, the blanched samples exhibited higher sulphurous odour intensity (6.3–8.4 vs. 4.8) and more pronounced flour-like flavour (6.1–10.1 vs. 5.2), whereas the non-blanched sample were characterised by higher bitterness (Fig. 4). Samples differing in the degree of tissue disintegration showed differences in several texture-related attributes. UF-mince and UF-paste samples were characterised by comparatively very small particle size (0.4–0.6) and smooth structural appearance (0.4–0.6), whereas flaked samples (UF-flakes, UF-Fr-flakes, and UF-NoBl-flakes) exhibited larger particle size (3.1–8.0) and rougher structural appearance. Powdered samples (UF-Fr-powder) compared with flakes exhibited smaller particle size and stronger flour-like flavour and significantly higher perceived sweetness. Other odour and flavour attributes did not differ significantly between flakes and powder. No significant sensory differences were observed between *U. fenestrata* samples that were flash frozen prior to drying and flaking (UF-fr-flakes) and those that were dried directly after harvest (UF-flakes) (Table 2, Fig. 4b.).

3.3. Saccharina latissima

Samples containing *S. latissima* were primarily characterised by high sliminess (7.0–10.3) together with cartilaginous texture and intermediate chewiness. All *S. latissima* samples were blanched, thus they further exhibited a mild flavour profile with low flavour intensity and marine flavour notes. Differences among the evaluated *S. latissima* processing formats were observed mainly in texture-related attributes (both visually and in mouth feel). Flakes (SL-flakes), powder (SL-powder), and mince (SL-mince) were perceived as the slimiest samples (9.1–10.3), whereas the paste sample (SL-paste) exhibited significantly lower sliminess (7.0). Flakes (SL-flakes) and mince (SL-mince) were further characterised by larger particle size (8.7–10.5) and more cartilaginous texture (8.9–11.6), whereas the powder sample (SL-powder) exhibited substantially smaller particle size (2.9) (Fig. 4c.).

4. Discussion

The present study demonstrates that samples representing different processing formats differed mainly in texture- and structure-related properties within species, while differences between blanched and non-blanched *U. fenestrata* samples were observed primarily in flavour-related characteristics. The findings highlight that post-harvest processing strategy are important when developing seaweed ingredients for different food applications.

P. palmata has previously been described as a deep red or magenta-coloured seaweed with chewy texture, pronounced saltiness and umami, and fish-like odour notes [7,8,38,39]. The present study identified two additional sensory attributes that have received little attention in previous literature for *P. palmata*, “salmiac” (flavour) and “tingly” (mouthfeel). The salmiac-like flavour was consistently perceived across all *P. palmata* samples. Although this specific descriptor has not previously been explicitly reported in the literature, liquorice-like notes have been mentioned for *P. palmata* [39]. Salmiac, derived from the chemical compound ammonium chloride, (NH_4Cl) is a common flavour in Swedish and Nordic candy varieties and often known as “salty liquorice”. The second novel attribute perceived in this study was “tingly”, described by the panel as a fuzzy sensation like the one evoked by carbonated drinks (Table 1). It is unclear where this attribute originates from as there is no specific chemical compound associated with it. However, there are theories suggesting that sour and/or salty food and beverages can induce trigeminal sensations such as tingly or prickling mouthfeel [40]. The consistent perception of tingling mouthfeel across *P. palmata* samples indicates that this attribute may represent a characteristic sensory feature of the species and warrants further investigation. The salmiac-like flavour and tingling mouthfeel identified in *P. palmata* could potentially contribute to flavour complexity in innovative culinary applications. Individuals with impaired taste and smell could benefit from trigeminal sensations such as a tingling sensation, when flavour is not enough. However, the cultural familiarity of salmiac flavour should also be considered, as this sensory reference may primarily be meaningful in Nordic contexts.

The blanched *U. fenestrata* samples had lower odour intensity, flavour intensity, and perceived saltiness, sourness, and bitterness than the non-blanched sample (Table 2). These findings are consistent with previous results [26], suggesting that differences associated with blanching may persist across different stabilization forms, including drying and freezing. The blanched samples also exhibited higher sulphurous odour and flour-like flavour notes. From a food application perspective, blanched *U. fenestrata*, particularly in frozen and finely disintegrated forms, may therefore be suitable for incorporation into semi-manufactured foods where low flavour intensity and homogeneous texture are desirable, such as patties or breaded products. Furthermore, blanching has previously been shown to reduce levels of iodine, inorganic arsenic, and cadmium in *S. latissima* and *U. fenestrata* [13,26,41], potentially enabling higher inclusion levels in food products without markedly affecting flavour characteristics. However, blanching may simultaneously reduce the nutritional value of the biomass, highlighting the importance of balancing sensory, safety, and nutritional considerations during product development.

Sensory attributes previously associated with fresh and unblanched *S. latissima* include light brown colour, coarse texture, marine scent, and sliminess [42–44]. Given the high iodine content of unblanched *S. latissima*, the present study focused exclusively on blanched samples. Despite blanching, *S. latissima* samples still exhibited a slimy texture, suggesting that blanching has a more limited effect on these textural properties than on colour, consistent with previous reports in the literature [42]. Brown seaweeds, including *S. latissima* are rich in alginate, a polysaccharide with high water-binding capacity and gel-like properties, which contributes to slimy and viscous textures when hydrated [45]. Interestingly, although the *S. latissima* mince and paste samples differed primarily in the degree of tissue disintegration, the paste sample exhibited significantly lower sliminess than the mince sample, both visually and during oral processing. However, previous studies have shown that heat-treatment (95 °C for 15 min) can significantly reduce sliminess [43], due to thermal hydrolysis of the glucoside bonds holding the alginic acid polymers together. This degradation of alginic acid results in light-weight compounds, such as unsaturated oligo- and monosaccharides, ultimately leading to a less viscous structure of the wet *S. latissima* samples [46,47]. In the present study, the preparation of paste samples exposed the biomass to both mechanical load and a moderate thermal impact (+3.6 °C), caused by friction from the mixer blades. These processing conditions may have contributed to the lower sliminess observed in the paste samples. The pronounced water-binding and gel-forming properties of *S. latissima* may nevertheless be advantageous in food applications where increased juiciness and modified texture is desirable, as previously suggested by Gullón et al. and Maulida et al. [48,49].

No significant sensory differences were detected between *P. palmata* and *U. fenestrata* samples that were flash-frozen prior to drying and those that were dried directly after harvest. From an industrial perspective, this finding is important since drying operations often delay seaweed stabilization processes [27–29]. The results therefore suggest that freezing may serve as a practical intermediate storage step when immediate drying of freshly harvested *U. fenestrata* and *P. palmata* biomasses is not feasible, without substantially altering the sensory quality of the final ingredient. This could help increase processing flexibility and improve logistical handling for large-scale seaweed production.

Variation in tissue disintegration was associated primarily with differences in texture- and structure-related sensory attributes, whereas flavour attributes showed only limited variation among samples. Finely disintegrated samples generally exhibited smoother structural appearance, smaller particle size, and lower chewiness compared with flakes and coarse samples. Unlike previous findings suggesting that extreme grinding of land-grown vegetables and plants intensifies bitterness and overall flavour [30–32], the flavour-related differences in seaweed samples due to disintegration in this study were limited.

4.1. Strengths, limitations, and future perspectives

This study investigated sensory characterization of relevant seaweed ingredient formats. Chemical and physical characterization was therefore not included, although such measurements represent a natural direction for follow-up studies. Rather than applying highly standardized laboratory processing, the study aimed to reflect realistic processing chains currently considered feasible for commercial seaweed handling and food production. However, this approach also presented methodological considerations: three seaweed species were not subjected to identical processing regimes, thereby limiting strict inter-species comparisons of processing effects. Since the biomasses differed substantially in water-binding properties, texture, and dry matter content following processing, species-specific seaweed-to-water ratios were adjusted

empirically to obtain cohesive and sensory-evaluable samples with visually comparable consistencies. This pragmatic approach increased the practical relevance of the study, as seaweed ingredients are rarely consumed under standardized moisture conditions. Consequently, the results primarily provide information about sensory properties of the prepared ingredient formats rather than as direct intrinsic comparisons of the untreated biomasses. Additionally, the effect of freezing prior to drying was evaluated only for flaked *P. palmata* and *U. fenestrata*, as these were the only post-harvest chains in which freezing constituted an experimental factor. Furthermore, this study focused exclusively on descriptive sensory profiling and therefore does not address consumer acceptance or preference.

Future research should therefore combine descriptive analysis with consumer-oriented evaluation, understand how chemical and physical parameters are influenced by post-harvest processing, and explore how different ingredient formats perform in specific food applications.

5. Conclusion

This study suggests that sensory characteristics differed significantly among the evaluated post-harvest processing formats within the three evaluated species. Differences among processing formats were observed in texture-, mouthfeel-, and flavour-related attributes.

For *U. fenestrata*, the blanched samples differed from the non-blanched sample in several flavour-related attributes and showed a generally milder flavour profile. In contrast, no significant sensory differences were detected between samples that underwent flash-freezing prior to drying and those that were dried directly after harvest, suggesting that freezing may represent a feasible intermediate storage strategy in industrial seaweed processing chains. Degree of tissue disintegration was associated with differences in structural and mouthfeel-related attributes, whereas flavour-related differences were limited.

The samples from each individual species exhibited distinct sensory characteristics. Samples containing *P. palmata* were associated with marine, umami-rich, and trigeminal sensory properties, samples containing *S. latissima* with sliminess and cartilaginous texture, and samples of *U. fenestrata* with green appearance together with sulphurous and flour-like sensory notes. The study additionally identified a tingling mouthfeel and salmiac-like flavour notes in *P. palmata* samples, sensory characteristics that have received limited attention in previous seaweed sensory literature.

The sensory profiles observed for the different processing formats may help inform the selection of seaweed ingredients for specific food applications. Based on their sensory characteristics, blanched *U. fenestrata* samples may be promising for food applications requiring mild flavours and homogeneous textures, although consumer acceptance remains to be explored. In contrast, the water-binding and textural properties of *S. latissima* may be advantageous in products targeting increased viscosity, juiciness, or structural stability. Overall, this study contributes applicable sensory knowledge on the differences associated with industry-relevant post-harvest processing formats of seaweed. However, future consumer studies are needed to fully understand the level of potential for seaweed-based food-products.

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, Methodology, Investigation, Conceptualization. **Kristoffer Stedt:** Writing – review & editing, Validation, Resources, Conceptualization. **Henrik Pavia:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **Ingrid Undeland:** 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.

Ethical statement

This study received ethical approval (reg no. 2023–05508-01) from the Swedish Ethical Review Authority on 10/10/2023.

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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 data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.algal.2026.104988.

Data availability

Data will be made available on request.

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