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Sensory and consumer aspects of sea lettuce (*Ulva fenestrata)* – impact of harvest time, cultivation conditions and protein level

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ABSTRACT

The green seaweed *Ulva fenestrata* is a future food candidate, however, both compositional, e.g. protein content, and sensory qualities depend on cultivation and harvest conditions. The aim was to explore sensory qualities of, and consumer attitudes to, *U. fenestrata* derived from three different cultivation conditions and three harvest times. *U. fenestrata* was cultivated at sea and in two different land-based tank settings, one mimicking seawater and one with added process water from fishing industry to increase protein content. The seaweed was subjected to sensory analysis performed by an analytical sensory panel and a focus group consisting of consumers. The former assessed the seaweed as dried whole blades (9 samples) and as emulsions (9 samples). Consumers assessed whole blades and a vegan spread enriched with powdered *U. fenstrata*. All seaweed samples were intensely green; had tastes of umami, salt, bitter, and sour; odours and flavours of grass and fresh seaweed; and had a crispy texture. Cultivation in tanks resulted in a crispier texture than sea cultivation ($p<0.001$). Protein content increased from 14.4% to 21.6% in tank cultivation with process waters, which increased green colour intensity ($p<0.007$) and decreased intensity of bitterness ($p<0.001$). Overall, consumers were positive towards seaweeds as foods.

1. Introduction

Seaweeds are promising sources of nutritious and sustainable future food ingredients (Gephart et al., 2021; Jönsson et al., 2020; Hasselstrom et al., 2018). Based on their attractive tastes and flavours (Mouritsen et al., 2019), as well as their valuable nutrients, such as dietary fibre, micronutrients, and high-quality protein (Jacobsen et al., 2023), they have been used as human food for centuries. Factors such as health, sustainability, taste, and naturalness are strong driving forces for consumption of seaweed, and thus there is an increased demand for this raw material (Palmieri and Forleo, 2020; Govaerts and Olsen, 2022 and 2023; Wendin and Undeland, 2020; Birch et al., 2019). Seaweed is often described as useful, healthy (Fredriksson and Säwe, 2020; Merkel et al., 2021) and sometimes also as unique and a luxury food (Govaerts and Olesen, 2023). The ways through which seaweed may be consumed are highly diverse, examples are fresh, blanched or cooked (boiled or salted), dried, fermented, or brined in salt or with other ingredients, such as oil (Palmieri, et al., 2023). Consumers have further shown great interest in seaweed both as an ingredient in a variety of food applications and dishes and as a snack served as dried blades (Wendin and Undeland, 2020). Given its vegan nature, there is currently a great interest from both food manufacturers and consumers to incorporate seaweed into plant-based formulations (Safdar et al., 2022).

From a sustainability perspective, marine seaweeds are a highly interesting complement to crop cultivation on arable land, circumventing the negative environmental consequences associated with the use of fertilizers, pesticides, and freshwater irrigation. Seaweed farming has been shown to contribute to increased biodiversity and has been argued to be effective as a carbon sink that may slow down the process of ocean acidification and global warming (Forbes et al., 2022; Hasselström et al., 2018; Troell et al., 2023). Seaweed, therefore, may meet both future sustainability goals and offer solutions to issues of terrestrial agriculture, such as the need for fresh water, fertilizers, and land (Froehlich et al., 2019; Walls et al., 2016).

In the development of tasty and flavourful products based on seaweed, it is essential to investigate their sensory characteristics. It is

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well known that these characteristics vary between different seaweed species and cultivation conditions, due to differences e.g. in the contents of aldehydes, ketones, carboxylic acids, esters and sulfur containing molecules as dimethyl sulfide (Sugisawa et al., 1990; Sanchez-García et al., 2019, Van Alstyne et al., 2023). Aromas such as marine, crustacean, and green notes along with tastes of umami (glutamic acid, aspartic acid, some organic acids, e.g. lactic, succinic, and propionic acids, and many short peptides) and salt (sodium chloride) are however always pronounced (Figueroa et al., 2022; Sanchez-García et al., 2019; Mouritsen et al., 2019; Chaudhari et al., 2009). Differences between species or differences stemming from different harvest seasons may be used when including seaweeds in the development of unique products with high potential for becoming gastronomic delicacies (Ferraces-Casais, et al., 2013; Rioux et al., 2017; Mouritsen et al., 2019; Pérez Lloréns, 2020). For development of every-day meal products, an even sensory quality is on the other hand favourable. To further increase the understanding and recognition of seaweed's gastronomic potential; both as a healthy ingredient and a potential protein source for the broad public, its sensory attributes need to be further investigated (Pérez Lloréns et al., 2020).

Although the amino acid profiles differ between seaweed species, they most often meet the levels for complete proteins (Jönsson et al., 2020; Jönsson et al., 2023). At the same time, seaweeds are rich in dietary fibres (Jönsson et al., 2023), and despite a low lipid content (0.4% to 4.5% of dry seaweed biomass); n-3 and n-6 polyunsaturated fatty acids (PUFAs) account for a significant proportion of the total seaweed lipids, which adds to their health-beneficial potential (Mišurcová, et al., 2011). A recent review showed that the *Ulva* species may provide a meaningful contribution of some micronutrients that are often limited in plant-based foods; one portion of *Ulva,* for example, may contribute to $\geq$15% of the recommended daily intake of vitamin B12 (Jacobsen et al., 2023). Seaweeds, thus, have the potential as ingredients to formulate healthy, nutritious, and flavourful products.

Cultivation conditions have an impact on taste and nutritional qualities of seaweed. Regarding the latter, for example the protein content and colour of the specie sea lettuce (*Ulva fenestrata)* have been shown to be highly dependent on seasonal conditions, cultivation conditions and time of harvest (Steinhagen et al., 2022). However, as sea lettuce is suitable for cultivation both on land in tanks, and in the ocean (Steinhagen et al., 2022; Stedt et al., 2022b), there are possibilities to control its compositional properties. An example is to add nutrients to the cultivation media to increase the nutritional value of the resulting biomass. Studies have shown that addition of process waters from industrial food production, for example herring production process waters (HPPWs), results in significant increased growth and elevated crude protein content of the sea lettuce (Stedt et al., 2022a,b,c). When cultivation was carried out in presence of HPPWs and was compared to cultivation in seawater, the growth rate was over four times higher, and the crude protein content was three times higher (30% vs 10% on a dry matter basis) (Stedt et al 2022b). Seaweed cultivation can therefore contribute significantly to the remediation of nutrient rich waters (Kang et al., 2021) at the same time as a new marine protein source is being produced. To the best of our knowledge, nothing is however known on the link between protein content of sea lettuce and its sensory properties.

This study contributes to the identified knowledge gaps, and to increase the understanding of how to use seaweed as a food ingredient in different dishes and food applications. The aim was to explore the sensory qualities of, and consumer attitudes towards, sea lettuce (*Ulva fenestrata)* derived from different cultivation conditions and harvest times, which both affect the protein content. Dried biomass was in focus since it allowed comparison of seaweed samples harvested at different dates. Further, drying is still the most common method to stabilize seaweed towards microbial growth. For a deeper understanding of how to use the dried *U. fenestrata* as an ingredient to be used alone or in a food application, the dried blades were used as are, or milled into powder and mixed into emulsions analysed by an analytical sensory panel. As a real-life example of how to use and consume seaweed, milled seaweed was mixed with spread and served on wafers to be evaluated by consumers.

2. Material and Methods

2.1. Samples

Gametophytes of the Northern Hemisphere sea lettuce *U. fenestrata* Postels & Ruprecht were collected from a long-term indoor tank cultivation of gametophytes at Tjärnö Marine Laboratory (TML, 58°52′33.7″ N, 11° 08′44.9″ E) for treatments *i-ii* (see explanation below). The biomass for treatment *iii* was collected from a sea-based seaweed farm (2 ha, 100×200 m) located in the Koster archipelago (Skagerrak), Sweden (58°51'34.0"N, 11°04'06.2"E). After collection, the *U. fenestrata* was cultivated in three different settings: *i)* land-based tanks with sea water enriched with Provasoli Enriched Seawater (1:100 dilution) (containing nitrate and phosphate, further TRIS base buffer, trace metals, and vitamins in place of soil water extract) (PES) (Provasoli, 1968), *ii)* land-based tanks with salt brine from a fish processing industry (SAL; a detailed explanation can be found in Stedt et al (2022c), while the characteristics for the SAL used in this experiment can be found in Stedt et al (2022a)), and *iii)* sea-based farm (SF) (for details on the sea-based farm, see Steinhagen et al. 2021). Out of food safety reasons it should be noted that the added salt brine was in food grade state when collected at the fish company. The production of the seaweed in this project was following European and National Regulations on Seaweed Cultivation and Harvesting.

Three replicate samples were gathered at each time point (n=3). The different harvesting dates were chosen to give indications of how different stages of growth have an impact on the quality. Since the growth rate is 3-4 times faster in tanks compared to in the sea, the harvest dates differed between these two cultivation settings. It also is known that higher temperature and more light have negative impact on the seaweed quality, thus the seaweed grown at sea should be harvested during early spring. In the case of tank cultivations, replicates were obtained from three distinct tanks, whereas for the sea-based farm, the replicates were obtained from three separate ropes. The conditions at sea increased from 6°C in January to 10°C in May, while the sun hours increased from 57 to 284 h/month during the same period. The seaweeds were collected at three different time points and stored in a freezer (-80°C) before being dried in an oven (40°C) as whole blades.

The harvest at three different harvest times from the three cultivation settings resulted in 9 samples of oven dried seaweed blades for analytical sensory analysis, Table 1**.** Parts of the dried seaweed were also

Table 1
Overview of samples, sample abbreviations, harvest dates, and protein contents for *Ulva fenestrata* (mean±SD, n=3). Letters show significant differences between means (p<0.05).

Sample name*	Sample No	Growing media	Harvest no	Harvest date**	Crude protein g/100g***
PES1	1	PES	1	220120	17.3 ± 2.7^{ab}
PES2	2	PES	2	220126	14.2 ± 7.9^{ab}
PES3	3	PES	3	220202	14.4 ± 6.5^{ab}
SAL1	4	SAL	1	220120	20.6 ± 9.3^{a}
SAL2	5	SAL	2	220126	13.2 ± 3.4^{ab}
SAL3	6	SAL	3	220202	21.6 ± 4.5^{a}
SF1	7	sea water	1	220221	22.5 ± 1.2^{a}
SF2	8	sea water	2	220407	20.6 ± 0.8^{a}
SF3	9	sea water	3	220509	4.5 ± 0.2^{b}

* Seaweed samples were analysed both as dried samples and as emulsions.
** It can be noted that PES and SAL samples were harvested on day 1 (PES1 and SAL1), day 7 (PES2 and SAL2), and day 14 (PES3 and SAL3), while SF samples were harvested on day 1 (SF1), day 45 (SF2), and day 77 (SF3).
*** Analysis of crude protein is described in Appendix A.

milled into a fine powder (particle size < 20 μm) and then mixed into 5% oil/water emulsions forming another 9 samples. A total of 18 samples were therefore obtained.

For the consumer analysis the seaweed was included in two forms: i) as whole blades and ii) as an example of how to use and consumer seaweed, a commercial oat-based spread containing 5% *U. fenestrata* powder (Creamy Oat Spread Plain, Oatly, Sweden). Three samples (the third harvest time from each of the three cultivation settings) were used. In all, six samples were assessed: three whole blade samples and three seaweed/spread samples. The spread was served to the consumers on neutral wafers.

2.2. Analyses

2.2.1. Analytical Sensory Analysis

All samples (9 whole blade samples and 9 emulsions) were evaluated by a trained analytical sensory panel (Kristianstad University, Sweden) in two separate trials using quantitative descriptive analysis. The assessors were selected and trained according to ISO 8586-2012 and the evaluations were performed in a sensory laboratory equipped according to ISO 8589-2007. Water and neutral wafers were used to rinse and clean the mouth and palate between each sample. Samples were served randomly using a Latin square design and evaluated in triplicate. The software EyeQuestion (Version 5.4, Netherlands) was used to collect the data.

The descriptive sensory analysis was following the procedure of Quantitative Descriptive Analysis, described by Lawless and Heymann (2010). The analysis was preceded by two training sessions using the same samples as used in the trial. An attribute list was developed and the attributes were defined during the training. The assessors were trained in how to evaluate samples using the attribute list and how to use the 100-unit line-scale, anchored at a low intensity (labelled ''low'') at 10 units and a high intensity (labelled ''high'') at 90 units. The anchor points worked as guides for the assessors when evaluating the samples. Sensory terms and their definitions are given in Table 2. The whole blades and the emulsions were served at room temperature. The whole blades were served as one or two pieces on small paper plates and the emulsions were served as 10 ml portions in transparent plastic cups (30 ml).

Table 2
Sensory attributes, their abbreviations, and definitions

Sensory Attribute	Abbreviation	Definition
Appearance		
White spots (whole leaves only)	AWhite spots	Area covered with white spots
Green colour	Agreen	Intensity of green colour
Yellow colour	Ayellow	Intensity of yellow colour
Odour		
Odour of sea	OSea	Fresh sea breeze
Odour of grass	OGrass	Grassy odour
Odour of wet seaweed	OWet Seaweed	Odour of stale, old and wet seaweed
Taste		
Saltiness	TSaltiness	Basic taste salt
Sourness	TSourness	Basic taste sour
Umami	TUmami	Basic taste umami
Bitterness	TBitterness	Basic taste bitter
Flavour		
Flavour of seafood	FSeafood	Fresh seafood
Flavour of grass	FGrass	Grassy flavour
Flavour of wet seaweed	FWet Seaweed	Flavour of stale, old and wet seaweed
Texture		
Crispiness (whole leaves only)	TexCrispy	Crispy texture, thin crisps
Toughness (whole leaves only)	TexTough	Tough chewy texture
Roughness (Emulsions only)	TexRoughness	Perceived roughness on the tongue
Particles (Emulsions only)	TexParticles	Amount of perceived particles

2.2.2. Consumer analysis

A focus group discussion was performed to investigate views, experiences and perception of the seaweed, *U. fenestrata*, included in this study. The focus group discussion was performed in accordance with Morgan (1996) and included nine participating consumers, six women and three men, aged between 36 and 68 years. The session was held in a conference room at Kristianstad University and lasted for 1.5 hours. Before starting the discussion, the panel leader informed the participants about the products to be tested, informed consent and GDPR. The discussions were recorded using a mobile phone (Apple iPhone) and notes were taken by the panel leader.

The products were served to the participants together with a glass of water. To guide the discussion a semi-structured questionnaire was used which included the following questions:

Part 1:

- Taste and differences between samples?
- How to eat seaweed? Whole or in a product?
- Is this the first time you have eaten seaweed? How have you eaten seaweed before?
- Positive and negative associations to seaweed as food?

The panel leader presented the cultivation methods to the panellists and the discussion continued.

Part 2:

- Thoughts about the cultivation methods? Are any of them more preferable than others?
- Is it possible to consider seaweed as a vegan product when cultivated in salt brine from the fish processing industry?

2.3. Ethics

The Swedish Ethics Review Act applies to research carried out in Sweden if the research includes the processing of sensitive personal data. This study includes questions about food perception and food opinions which, according to the Data Protection Ordinance, are not classified as sensitive personal data. According to GDPR, none of the responses to any of the analyses used in this study include information that can be traced to, or used to identify, any individual. All participants received written and verbal information about the sensory analyses, the focus group discussion, and the ingredients in the included products, and all gave informed consent to participate.

2.4. Sensory Data Analysis

Descriptive statistics were used, mean values and standard deviations were calculated for all quantitative data. Continuous data from the sensory analysis were further subjected to two-way analysis of variance (ANOVA) with samples and assessors as fixed effects (IBM SPSS version 27). Significant differences ($p < 0.05$) between samples were evaluated using the Tukey's Post Hoc pairwise comparison test. Sensory results were correlated by Pearson correlation. Regression analysis was performed where the design variables were independent, and the measurements were dependent factors (IBM SPSS, version 27). Finally, principal component analysis (PCA; Panel Check V 1.4.2, Nofima, Norway) was performed to give an overview of the results.

The recordings from the focus group discussions (N=9) were transcribed verbatim and the analysis of the qualitative data was based on content analysis with pre-defined main themes. The evaluation involved systematically sorting the outcomes from the focus groups into the different themes.

3. Results

An overview of samples, their abbreviations, harvest dates and the content of crude protein in *U. fenestrata* is given in Table 1. A significantly lower protein content was found for *U. fenestrata* harvested at the third harvest time in sea water compared to the first and second harvest. The protein content was also significantly lower at the third harvest time in sea water compared to harvest numbers 1, and 3 in herring process water (SAL). When cultivating *U. fenestrata* in seawater, the protein content had decreased significantly at the last harvest time.

There was a significant interaction between cultivation type and harvest time due to protein content.

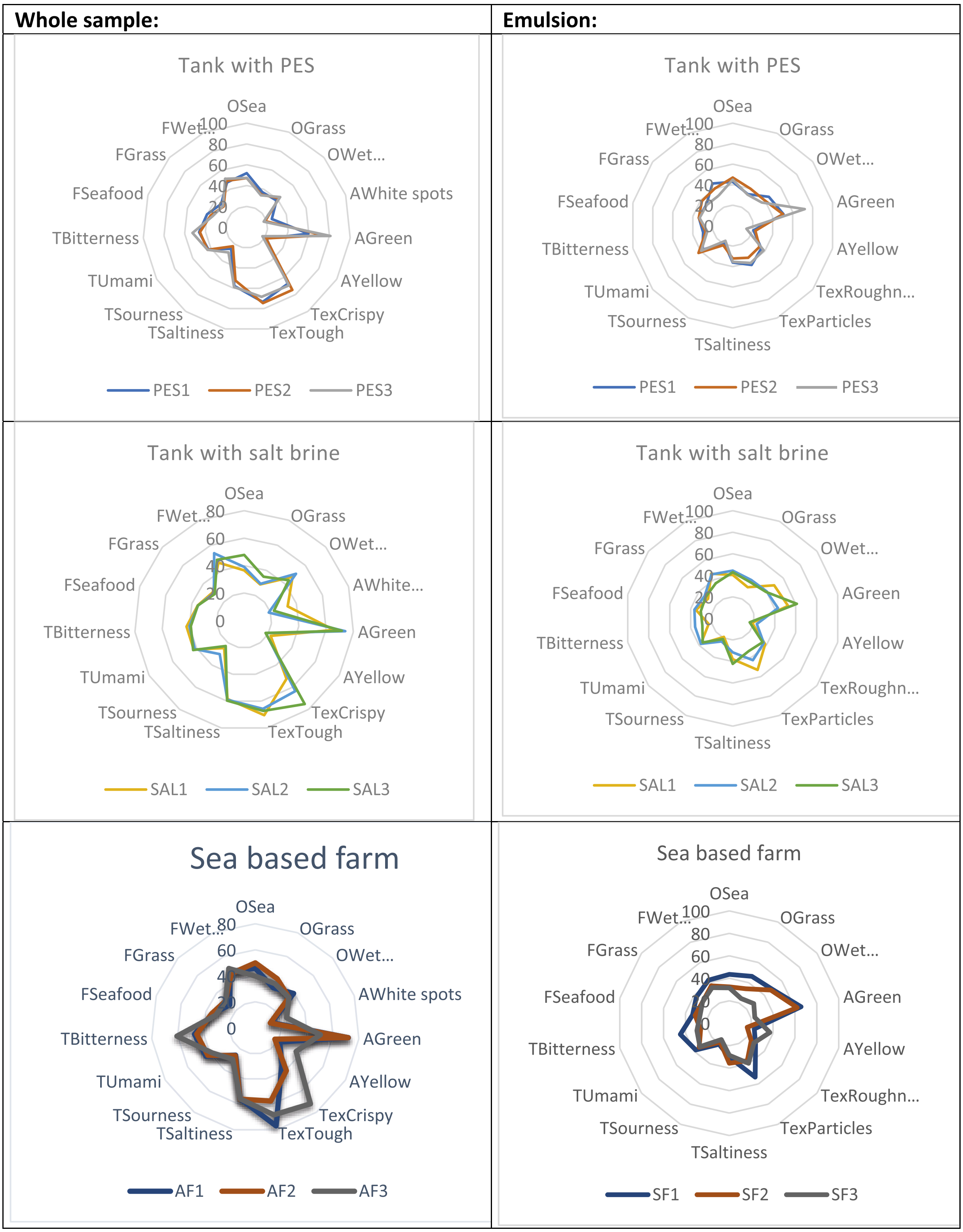

Fig. 1. Sensory profiles of the included samples of seaweed as whole samples and emulsions.

3.1. Analytical sensory analysis

An overview of the resulting sensory profiles are shown in Fig. 1; the mean values, standard deviations, and significant differences can be found in **Appendix B**. Fig. 1 shows that tank cultivation gives the seaweed a crispier texture compared to sea-based cultivation. However, when looking into specific samples, the SF3 was considered a highly crispy sample. Generally, seaweed from the SF group differed significantly by having a higher intensity of bitterness than seaweed cultivated in tanks, especially when served as emulsion and harvested early. Whole blades from seaweed cultivated in tanks, harvested later had more intense green colour than sea cultivated *U. fenestrata* harvested early. Further, whole blades harvested early were perceived as slightly tougher compared to later harvest time, especially in the samples cultivated at sea.

In Fig. 2**a**, a Principal Component Analysis (PCA) plot shows an overview of all resulting data of whole blade samples, where PC1 explains 43.7% and PC2 explains 25.3%, i. e., a total explanation of 69% of the variation in data. In Fig. 2**b**, the PCA plot shows an overview of all resulting data of emulsions, where PC1 explains 52.5% and PC2 explains 19.7%, i. e., a total explanation of 72.2% of the variation in data. The sensory attributes AGreen, AYellow, TexCrispy (whole blades), and TBitterness differ the most between samples. Furthermore, for whole blades, a large variation between harvest time occurs in the seaweeds cultivated at sea. Seaweed cultivated in tanks, independent of cultivation method and harvest time, were more similar to each other than those cultivated at sea. It can be noted that SF3 differs considerably from the other SF samples. For samples served as emulsions, it is clear that samples from the third harvest time provided quite similar results in comparison to the samples harvested earlier. The difference in sample distribution between the PCA plots can be explained by the great differences among whole blade samples regarding the attribute TexCrispy, which was not assessed for emulsions.

The Pearson correlations showed that a major part of the sensory attributes developed for both whole blades and emulsions correlated significantly ($p<0,05$) with each other, except for bitterness. However, the emulsions seemed to enhance the perception of the sensory attributes.

Regression analysis showed that protein content and cultivation type have a significant ($p<0.009$) impact on the colour of the seaweed. A higher protein content and cultivation in tanks gave a more intense green colour and less intense yellow colour. Cultivation in tank also increased crispiness ($p<0.001$), the intensity of saltiness ($p<0.031$) and decreased the intensity of bitterness ($p<0.001$) significantly compared to cultivation in sea. Overall, bitterness was significantly ($p<0.001$) impacted by cultivation type, time for harvest and protein content, although mainly by harvest time where a late harvest increased the bitterness. Samples with low amounts of protein were perceived as more bitter ($p<0.02$) than those with high protein.

3.2. Consumer analysis

The consumers participating in the focus group had a positive attitude towards seaweeds as food and enjoyed the sea lettuce while tasting, especially highlighting the umami taste. They were all impressed by the high protein content. Five of the nine consumers had previous experience of eating seaweed.

The SF3-sample was considered the as the crispiest seaweed sample. However, some of the consumers thought that crispiness was only an initial perception of all samples, and after a short while in the mouth the

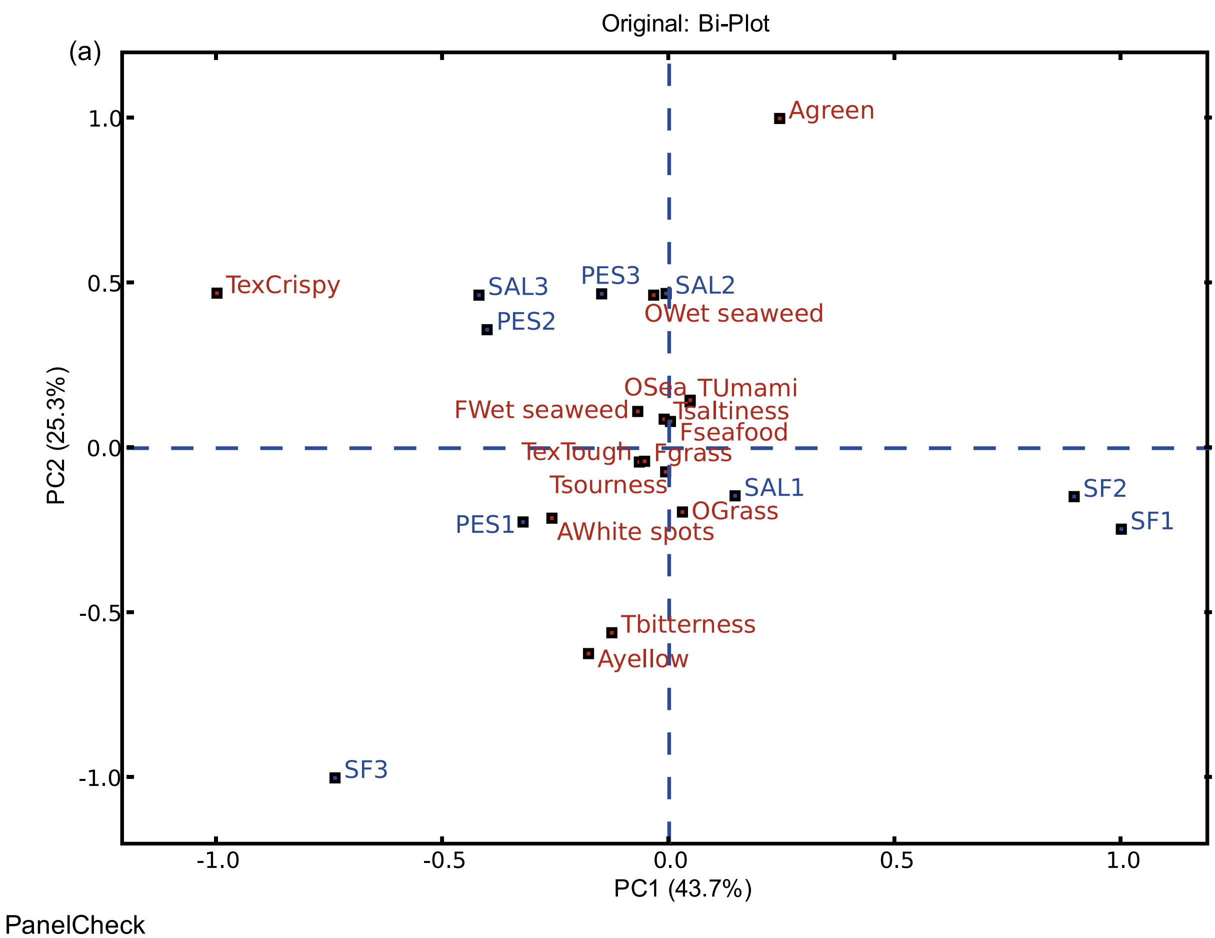

Fig. 2. a. PCA plot of the sensory results, whole blades. Fig. 2b. PCA plot of the sensory results, emulsions.

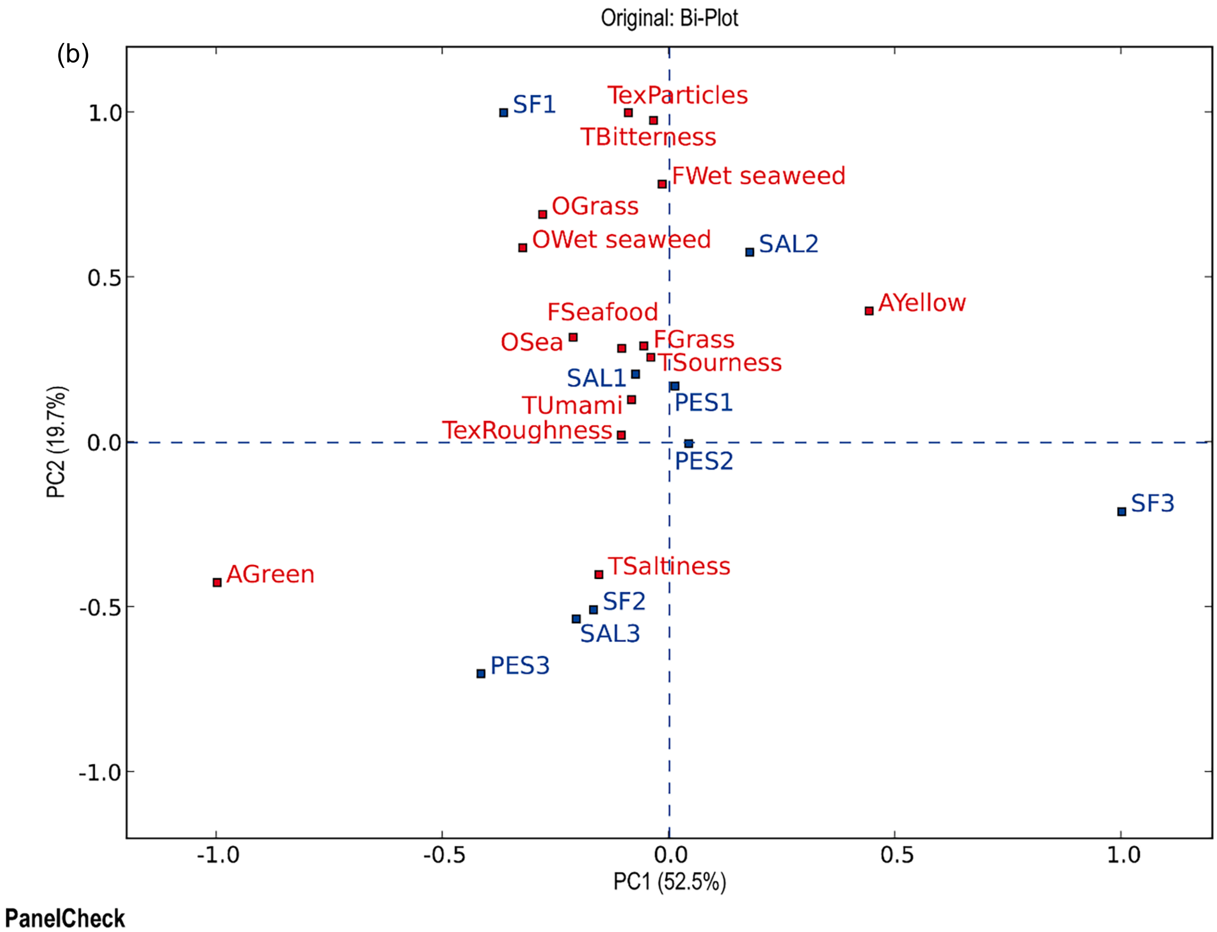

Fig. 2. (*continued*).

seaweed became tough and was difficult to swallow. During the discussion, the consumers agreed that seaweed can be eaten whole, but also used in processed products. The majority of the consumers preferred to include dried and milled seaweeds in food products in which they are considered easier to chew and swallow and may also contribute to the taste experience. The spread mixed with seaweed powder was highly appreciated and it was suggested that seaweed could be used instead of salt. Some of the consumers mentioned that when using seaweed in food it was of importance to avoid a slimy texture. Concerns regarding heavy metal content in the seaweed were also raised.

When discussing the cultivation methods, the consumers preferred seaweed cultivated in the sea, an argument they based on the preferred taste. Furthermore, they were negative to cultivating seaweed in presence of salt brine and considered that such seaweed could not be regarded as vegan and probably not as vegetarian either.

4. Discussion

To deepen the knowledge within the area of phycogastronomy, differently cultivated *U. fenestrata* samples, were evaluated by an analytical sensory panel as dried, whole blades and as emulsions based on dried and milled blades using quantitative descriptive analysis. A selection of whole blade samples and milled blade samples blended into a spread were also presented to a focus group of consumers.

In line with Steinhagen et al. (2022), the *U. fenestrata* samples cultivated under different conditions, and harvested at different times varied in protein contents and sensory characteristics. In the seaweed grown at sea it was obvious that green colour and protein content decreased significantly ($p<0.05$) with a later harvest date. This can be explained by increased temperatures and irradiances, as well as lower levels of dissolved inorganic nutrients in the seawater later in the season (Toth et al., 2020; Steinhagen et al., 2022).

The significant differences ($p<0.05$) between the samples derived from the sensory analysis could be related to the type of cultivation, harvest time, and protein content. The identified sensory attributes for *U. fenstrata,* both as dried blades and emulsions, were similar to those found in previous studies (Jönsson et al., 2023; Figueroa et al., 2022; Sanchez-Garcia et al., 2021). The main characteristic sensory attributes were the green colour; tastes of salt, umami, sourness and bitterness; odours and flavours of grass and wet seaweed; and a crispy texture. The differences in tastes and flavours between the samples may be explained by varying amounts of for example aldehydes, ketones, carboxylic acids, esters, and sulfuric compounds (Sanchez-Garcia et al., 2019; Urlass et al., 2023). No significant differences between umami taste were obtained, although cultivation and harvesting conditions have been found to have an impact the umami taste (Milinovic et al., 2021). However, the concentration of umami have been found to be relatively low in sea lettuce umami is considered as a characteristic taste of all types of seaweed and is caused by free glutamatic and asparctic acids (Gao et al, 2021; Milinovic et al., 2021), 5'-nucleotides (Moerdijk-Poortvliet, et al. 2022) and organic acids such as lactic, succinic, and propionic acids (Chaudhari et al., 2009). The sensory attributes green colour and saltiness became significantly more intense with a higher protein content, while bitterness decreased in intensity. In plants, bitter taste is commonly described as a result of polyphenols (Li et al, 2023), and the same has been revealed for macroalgae (Mouritsen, 2021). Polyphenols are particularly abundant in brown seaweed such as bladderwrack (*Fucus vesiculosus*) (Ummat, et al., 2020), but are also enriched in green seaweed such as *U. Intestinalis* (Wekre et al, 2019) and *U. fenestrata* (Steinhagen et al., 2022). According to Breslin and Beauchamp (1997) as well as Delompré et al. (2019), the low bitterness and the high saltiness of *U. fenestrata* cultivated in tankcould be explained by high levels of sodium, calcium, and potassium, which may also affect other tastes and flavours.. As mentioned earlier, aspartic acid, glutamic acid, and 5′-nucleotides are responsible for the umami taste but may also contribute to a salty taste (Jönsson et al., 2023, Moerdijk-Poortvliet, et al. 2022). The lower bitterness at high crude protein levels could thus partly be explained by higher content of the amino acids aspartic acid and glutamic acid. Future studies should systematically evaluate the impact of different phenol/polyphenol levels in *U. fenestrata* and its perceived bitterness.

The intense green colour found in *U. fenstrata* aligns with earlier studies of many *Ulva* species (Sanchez-Garcia et al., 2021). Previous studies have also shown that the intensity of green colour of *U. fenestrata* can be efficiently used to estimate its protein content (Stedt et al., 2022b), which is explained by the co-existence of proteins and chlorophyll in the thylakoid membrane of chloroplasts, e.g. as chlorophyll-binding proteins (Wang and Grimm, 2015). A positive correlation between greenness and crude protein content was also documented in this study, as a significant and positive relation between protein content and cultivation conditions, both positively affecting green colour intensities.

The two sample types of *U. fenestrata* cultivated in tanks (SAL and PES) were more similar to each other compared to those cultivated at sea (SF). For example, tank cultivation resulted in a crispier texture than sea-based cultivation. However, the samples from sea-based cultivation harvested at the third time point had grown for a significantly longer time (77 days) compared to the tank cultivated samples (14 days) before harvesting, which may increase the differences between samples grown in tanks versus at sea. Crispiness and other textural properties can be related to the occurrence of certain monosaccharides, such as glucose, galactose, xylose, and uronic acids (Deniaud-Bouët et al., 2017). In an earlier study of *S. latissima*, samples harvested earlier (in June) were characterized by high contents of the monosaccharides fucose, galactose, mannitol, mannose and xylose while later harvest (August) gave high contents of glucose (Vilg et al., 2015), illustrating a link between monosaccharide content and biomass age. Compared to other species of seaweed, the texture of the *Ulva* species has in recent studies been described as less crispy, hard, and chewy (Jönsson et al., 2023). In addition to sensory analysis, Figuroa et al. (2022) performed texture profile analysis (TPA) on their seaweed samples, which may be recommended for future studies.

The correlation between the sensory results from whole blades and emulsions was significant, except for bitterness which were perceived as more intense in whole blades than in emulsions. However, for the other sensory attributes, emulsions seemed to enhance the perception, which may be an effect of the added oil. The amount of oil in seaweed emulsions is of importance and has been shown to impact perceived sensory attributes, mainly grassy odour and flavour (Trigo et al., 2024). Findings that may be of importance in the development of food products. The milling of *U. fenestrata* into a powder may have an impact and is also something to take into consideration in product development. Similar results were also demonstrated by Jönsson et al. (2023).

As described above, both type of cultivation and time of harvest affected the perceived sensory attributes of the seaweed. It was also clear that the impact of protein content was high. Regression analysis showed that the effect of these factors on the sensory attributes was significant. It has previously been shown that the cultivation of *U. fenestrata* in process water from the herring production industry does not influence the biomass in a way that can be conceived as negative (Stedt et al., 2022a).

Similar to other studies (Wendin and Undeland, 2020; Govaerts and Olsen, 2022 and 2023), the consumer panel was positive towards seaweeds as food. Further, they were also impressed by the high protein content. During tasting, they highlighted the umami taste and noted the crispiness in line with the results from the analytical sensory panel. However, crispiness was only experienced initially after which the whole blades of *U. fenestrata* became tough to chew. The toughness of whole seaweed has been described by Jönsson et al. (2023) who noted that the *Ulva* species were experienced as less tough compared to other species, such as the red seaweed *Palmaria Palmata*.

Nevertheless, due to toughness, the consumers preferred milled seaweed to be included as an ingredient in food products. In the study by Wendin and Undeland (2020) consumers were positive to seaweed as an ingredient in a variety of products, for example as a snack or as ingredient in a dish. In agreement with a review by Gullón et al. (2021), the consumer group suggested that seaweed could be used as a replacement for salt. Concerns regarding heavy metal content in seaweed were raised, which calls for the need of attention to the labelling of seaweed products on the market. It should, however, be mentioned that most European food products are labelled according to regulations (Davis et al., 2000).

From the focus group discussion, it was clear that the consumers were negative to cultivation of seaweed with herring salt brine. This is somewhat surprising since land-grown vegetables are often produced using animal-derived fertilizers, and the use of salt brine entails a more circular approach in the cultivation of seaweeds. By using high-nutrient process water from food industries as a cultivation media for seaweeds, the nutrients are removed from the waters while new food biomass is produced. Hence, nutrients from currently discarded process waters are circulated back into the food chain, creating a sustainable and circular food production system. This certainly highlights the importance of providing information about sustainability aspects of new cultivation regimes to consumers. A contrary result was obtained in a German consumer study, where cultivation system did not impact consumer acceptance of seaweed products (Weickert et al., 2021).

As limitations of this study the large difference in harvesting time between the samples from PES and SAL, and the samples from SF. Another limitation to mention is the relatively small size of the consumer study, where nine consumers were included in the focus group discussion. Although considering the qualitative character of this study, the results need to be confirmed by future studies.

5. Conclusion

The general sensory qualities of *U. fenestrata* could be described as being intensely green and having tastes of umami, salt, bitter and sour; odours and flavours of grass and fresh seaweed; and a crispy texture. It could be concluded that the design factors (cultivation conditions and harvest time) as well as the resulting protein content impacted the sensory properties of *U. fenestrata*, both when evaluated as whole dried blades and as a powder dispersed into emulsions. Tank cultivation seemed to give the seaweed a crispier texture than sea cultivation. Further, when the tank cultivation was done in presence of herring salt brine (SAL), a treatment which raised the protein content, the intensity of green colour increased while the intensity of bitter taste decreased. Increased bitterness was on the contrary experienced in samples from late harvest. The results implies that the sensory properties of green seaweed can be modulated by both cultivation conditions and harvest time. How, and if, for example a higher protein content is linked to less perceived bitterness remains to be confirmed by future studies. Results however clearly indicate that *U. fenestrata* may be used a future food ingredient in a variety of food applications and dishes, not least as a replacement for salt, but also as source of protein.

The consumers had a positive attitude towards, and a high liking for, seaweeds as foods. However, for a higher acceptance of the new production methods of healthy seaweed, information about sustainability advantages would be needed. It remains to be studied in what format such information should best be delivered.

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CRediT authorship contribution statement

Karin Wendin: Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Kristoffer Stedt:** Writing – review & editing, Validation, Resources, Conceptualization. **Sophie Steinhagen:** Writing – review & editing, Validation, Conceptualization. **Henrik Pavia:** Writing – review & editing, Project administration, Funding acquisition. **Ingrid Undeland:** Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

There are no conflicts of interest.

Data availability

Data will be made available on request.

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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.2024.100431.

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