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Savouring the sea: Production and consumption of future seaweed foods

Savouring the sea: Production and consumption of future seaweed foods

Madeleine Jönsson

DOCTORAL DISSERTATION

Doctoral dissertation for the degree of Doctor of Philosophy (PhD) at the Faculty of Engineering at Lund University to be publicly defended on the 19th of April 2024 at 10.00 in lecture hall A at Kemicentrum, Lund

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Abstract: Current food systems pose one of the greatest health and environmental challenges of the 21st century. A systemic shift in the food sector can be accelerated by technologies and innovations, such as seaweed food applications. However, introducing and expanding seaweed as a food resource into Western markets comes with several challenges.

These challenges include its microbial, chemical, and sensory quality, which constitute the main focus areas of this thesis. Microbial stability was assessed by two alternative methods: fermentation and high-pressure processing. It was found that fermentation of seaweed by means of lactic acid bacteria is possible and can exert a promising preservation effect that is able to decrease the pH to out-conquer spoiling bacteria. The effect of treatment with high pressure was more difficult to evaluate but showed that the algal texture was altered by up to an 87.7% reduction in hardness and a 60.0% reduction in compression (chewiness). Processing can enhance the chemical and sensory characteristics, which is important for increasing food safety and consumer acceptance.

It was further found that the chemical composition of seaweed differs depending on species and harvest site, and between its different parts. This was observed for both nutrients and potentially toxic elements. Our studies further showed that while treatment with scalable methods was able to decrease the levels of total arsenic by 61.1%, inorganic arsenic by 92.4%, lead by 49.4%, and iodine by 72.8%, some elements, such as mercury and cadmium, were difficult to remove. Considering current regulations, iodine and cadmium exert the greatest challenges for chemical seaweed quality. Therefore, the species and cultivation sites should be selected carefully to produce seaweed that is safe for consumption.

To evaluate consumers' perceptions, descriptive and hedonic analyses were performed. In the descriptive study, the sensory profiles of four common northern European seaweed species were mapped. Generally, they had high levels of saltiness, medium umami, low bitterness and sourness, and no perceived sweetness. Variations between the species' sensory attributes were moreover observed, with green and red seaweed associated with grassiness and the sea, respectively. Brown kelps did not stand out considerably and were similar overall. In the hedonic study, 53.1–77.6% of the respondents gave positive scores for seaweed bread and 50.0–67.3% liked the seaweed spread. Inclusion of seaweed into familiar food products could be a successful strategy for increasing its consumption. However, the sensory attributes of different species should be considered. Nutritional and sensory profiles of seaweeds can serve as indicators for how to use seaweeds in everyday life.

Overall, the findings in the thesis can be useful as knowledge for the development and improvement of future seaweed products and their availability, by industrial stakeholders, the academic community and/or indirectly by consumers.

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To Mother Nature

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Abstract

Current food systems pose one of the greatest health and environmental challenges of the 21st century. A systemic shift in the food sector can be accelerated by technologies and innovations, such as seaweed food applications. However, introducing and expanding seaweed as a food resource into Western markets comes with several challenges.

These challenges include its microbial, chemical, and sensory quality, which constitute the main focus areas of this thesis. Microbial stability was assessed by two alternative methods: fermentation and high-pressure processing. It was found that fermentation of seaweed by means of lactic acid bacteria is possible and can exert a promising preservation effect that is able to decrease the pH to out-conquer spoiling bacteria. The effect of treatment with high pressure was more difficult to evaluate but showed that the algal texture was altered by up to an 87.7% reduction in hardness and a 60.0% reduction in compression (chewiness). Processing can enhance the chemical and sensory characteristics, which is important for increasing food safety and consumer acceptance.

It was further found that the chemical composition of seaweed differs depending on species and harvest site, and between its different parts. This was observed for both nutrients and potentially toxic elements. Our studies further showed that while treatment with scalable methods was able to decrease the levels of total arsenic by 61.1%, inorganic arsenic by 92.4%, lead by 49.4%, and iodine by 72.8%, some elements, such as mercury and cadmium, were difficult to remove. Considering current regulations, iodine and cadmium exert the greatest challenges for chemical seaweed quality. Therefore, the species and cultivation sites should be selected carefully to produce seaweed that is safe for consumption.

To evaluate consumers' perceptions, descriptive and hedonic analyses were performed. In the descriptive study, the sensory profiles of four common northern European seaweed species were mapped. Generally, they had high levels of saltiness, medium umami, low bitterness and sourness, and no perceived sweetness. Variations between the species' sensory attributes were moreover observed, with green and red seaweed associated with grassiness and the sea, respectively. Brown kelps did not stand out considerably and were similar overall. In the hedonic study, 53.1–77.6% of the respondents gave positive scores for seaweed bread and 50.0–67.3% liked the seaweed spread. Inclusion of seaweed into familiar food products could be a successful strategy for increasing its consumption. However, the sensory attributes of different species should be considered. Nutritional and sensory profiles of seaweeds can serve as indicators for how to use seaweeds in everyday life.

Overall, the findings in the thesis can be useful as knowledge for the development and improvement of future seaweed products and their availability, by industrial stakeholders, the academic community and/or indirectly by consumers.

Popular science summary

The current food system is a major villain in the climate change drama. While it has a vast potential to nurture a healthy population and planet, it is currently threatening both. Today's excess of greenhouse gas emissions from human activities, including our dietary practices, threatens the climate and not least the welfare of the world's oceans. The habitat of seaweed. Meanwhile, malnutrition is a problem that lurks in all corners of the world. This calls for a systemic shift – an effort beyond any individual person.

A systemic shift in the food sector can be accelerated by technologies and innovations, such as seaweed food applications. It is proposed that seaweed cultivation could help restore balance in oceans by absorbing nutrients, capturing carbon dioxide, and creating secure places for aquatic life. Achieving this requires no fresh water, land space, fertilizers, herbicides, and pesticides. Still, seaweeds grow at rates exceeding those of land-based crops, while also having the potential to bring several health benefits upon consumption. Although seaweed is on many people's lips today, in Western settings it is rarely found on people's plates. Therefore, introducing seaweed as a food in Western markets comes with several challenges.

These challenges include the microbial, chemical, and sensory quality of seaweed.

Firstly, adapted to life underwater, seaweed is exposed to various microorganisms, such as bacteria and fungi, which do not hesitate to feast on these delicate sea vegetables. In this thesis, microbial stability was explored by two alternative methods: fermentation and high-pressure processing. It was found that fermentation of seaweed by lactic acid bacteria, similar to kimchi and sauerkraut, was possible and can become a successful preservation method. Fermentation decreases the pH of the product to out-conquer spoiling microbes. The effect of high-pressure treatment was more difficult to evaluate, but showed that the algal texture was altered drastically. Accordingly, processing can enhance the chemical and sensory characteristics, which is important for increasing food safety and consumer acceptance.

Secondly, as commonly known, seaweeds take up nutrients and elements from their surrounding waters. This includes the potentially toxic elements arsenic, cadmium, iodine, lead, and mercury, which may become a problem when placed on people's plates. It was found that the chemical composition of seaweed differs depending on species and harvest site, and between its different parts. This was seen for both nutrients and potentially toxic elements. The amount of arsenic in sugar kelp can be slightly higher than in rice, but mild treatment reduced the levels of arsenic, iodine, and lead. Considering current regulations, iodine, and cadmium are the greatest challenges for chemical seaweed quality today.

Thirdly, people may say: ‘Ugh, disgusting!’ or ‘It is the food of the future!’. Seaweed is a fascinating phenomenon, a watershed that can bring out feelings of both disgust and wonder. Slimy, yet satisfying. But how is seaweed actually perceived? And will people in Western settings eat it? To evaluate consumers’ perceptions, descriptive and liking tests were performed. In the descriptive study, the sensory profiles of four common northern European seaweed species were mapped. Generally, they had high levels of saltiness, medium umami, low bitterness and sourness, and no perceived sweetness. Variations between the species’ sensory attributes were moreover observed, with green and red seaweeds associated with grassiness and the sea, respectively. Brown kelps did not stand out considerably and were similar overall. In the consumer liking study, a majority of the respondents liked the provided seaweed bread and spreads. The inclusion of seaweed in familiar food products could be a successful strategy for increasing its consumption. However, the sensory attributes of different seaweed types should be considered, as green colours can be associated with mould and sea flavours are not appreciated in some products. Nutritional and sensory profiles of seaweeds can serve as indicators for how to use seaweeds in everyday life.

With enhanced knowledge and understanding, a future where seaweed not only mitigates climate change but also nourishes communities can be envisioned, creating a sustainable and delicious legacy for generations to come. Resilience and innovation continue to pave the way for a seaweed-powered revolution, transforming the narrative of our food system and the health of our planet. Would you eat seaweed?

Populärvetenskaplig sammanfattning

Vårt nuvarande livsmedelssystem är en stor skurk i klimatförändringsdramat. Medan det har en enorm potential att värna om en hälsosam planet och population, hotar det för närvarande båda. Dagens överskott av växthusgasutsläpp från mänskliga aktiviteter, inklusive från våra kostvanor, hotar klimatet och inte minst välfärden hos världens hav. Tångens habitat. Samtidigt är felnäring ett problem som lurar i alla världens hörn. Detta kräver ett systemskifte – en insats bortom varje enskild individ.

Detta systemskifte inom livsmedelssektorn kan accelereras av teknologier och innovationer, såsom livsmedelstillämpningar av tång. Det förutspås att odling av dessa havsgrönsaker kan hjälpa till att återställa balansen i haven genom att ta upp näringsämnen, fånga koldioxid och skapa säkra platser för vattenliv. Allt detta är möjligt utan användning av färskvatten, markutrymme, gödningsmedel, och bekämpningsmedel. Dessutom växer tången snabbare än landbaserade grödor och har potential att frambringa flera hälsofördelar vid konsumtion. Men även om tång är på mångas läppar idag, finns den sällan på våra västerländska tallrikar. Att introducera denna livsmedelsresurs på västerländska marknader kommer därför med flera utmaningar.

Dessa utmaningar inkluderar mikrobiell-, kemisk- och sensorisk kvalitet hos tång.

För det första, anpassade till ett liv under vatten exponeras tång för olika mikroorganismer, såsom bakterier och svampar, vilka inte tvekar att festa på dessa delikata havsgrönsaker. I denna avhandling utvärderades mikrobiell stabilitet med två olika metoder: fermentering och högtrycksbehandling. Det visade sig att fermentering av tång med mjölksyrabakterier, liknande kimchi och surkål, var möjlig och kan bli en framgångsrik konserveringsmetod som sänker pH-värdet för att besegra nedbrytande mikrober. Effekten av högtrycksbehandling var svårare att utvärdera men visade att tångens textur ändrades drastiskt. Behandling av tång kan förbättra de kemiska och sensoriska egenskaperna, vilket är viktigt för att öka livsmedelssäkerheten och konsumentacceptansen.

För det andra, som allmänt känt tar tång upp näringsämnen och element från sin omgivande miljö. Detta inkluderar potentiellt giftiga ämnen, såsom arsenik, kadmium, jod, bly och kvicksilver, vilket kan bli ett problem när det serveras på människors tallrikar. Det visades att den kemiska sammansättningen av tång skiljer sig beroende på art, skördeplats och mellan olika delar av tången. Detta gällde både näringsämnen och potentiellt giftiga ämnen. Mängden arsenik i sockertång kan vara något högre än i ris, men med mild behandling kunde arsenik, jod och bly drastiskt minskas. I relation till nuvarande livsmedelslagar är jod och kadmium de största utmaningarna för den kemiska kvaliteten hos den undersökta tången.

För det tredje, så kan det ofta låta, ”usch, vad äckligt!” eller ”det är framtidens mat!”. Tång är ett fascinerande fenomen, en vattendelare som kan framkalla känslor av både avsky och förundran. Slemmigt, men mättande! Men hur uppfattas egentligen tång? Och kommer människor i västerländska miljöer äta det? För att utvärdera konsumenternas uppfattningar genomfördes beskrivnings- och gillandetester. I den beskrivande studien kartlades de sensoriska profilerna för fyra vanliga nordeuropeiska tångarter. Generellt hade de höga nivåer av sälta, medium umami, låg bitterhet och surhet samt ingen upplevd sötma. Variationer mellan arternas sensoriska egenskaper noterades också, där grön och röd tång associerades med gräsighet respektive havssmaker. De bruna tångsorterna stack inte ut betydligt och var övergripande likartade. I studien om konsumenters gillande tyckte majoriteten av deltagarna om de serverade tångbröden och tångpåläggen. Att inkludera tång i bekanta livsmedelsprodukter kan vara en framgångsfaktor för att öka dess konsumtion. Dock bör de sensoriska egenskaperna hos olika tångarter beaktas, eftersom gröna färger kan associeras med mögel och havssmaker inte uppskattas i vissa produkter. Näringsmässiga och sensoriska profiler hos tång kan fungera som indikatorer för användning av tång i vardagen.

Med förbättrad kunskap och förståelse kan en framtid skönjas där tång inte bara mildrar klimatförändringar utan också där samhällen skapar ett hållbart och välsmakande arv för kommande generationer. Ihärdighet och innovation fortsätter att bana väg för en tångdriven revolution som förändrar berättelsen om vårt livsmedelssystem för planetens och personers hälsa. Skulle du vilja äta tång?

List of papers

This thesis is based on the following papers, referred to by their Roman numerals and provided at the end of the thesis. All papers are either open source or reprinted with the permission of their respective publishers.

I. **Exploration of high-pressure processing (HPP) for preservation of the Swedish grown brown macroalgae *Saccharina latissima***
Jönsson, M., Allahgholi, L., Rayner, M., and Nordberg Karlsson, E.
Front. Food. Sci. Technol., 2023, 3:1150482
https://doi.org/10.3389/frfst.2023.1150482

II. **Fermentation of the brown Seaweed *Alaria esculenta* by a lactic acid bacteria consortium able to utilize mannitol and laminari-oligosaccharides**
Allahgholi, L., Jönsson, M., Christensen, M. D., Jasilionis, A., Nouri, M., Lavasani, S., Linares-Pastén, J. A., Hreggviðsson, G. Ó., and Nordberg Karlsson, E.
Fermentation, 2023, 9(6):499
https://doi.org/10.3390/fermentation9060499

III. **Chemical food safety of seaweed: Species, spatial and thallus dependent variation of potentially toxic elements (PTEs) and techniques for their removal**
Jönsson, M., and Nordberg Karlsson, E.
J. Appl. Phycol., 2023
https://doi.org/10.1007/s10811-023-03131-8

IV. **Nutritional, physicochemical, and sensory characterization of four common Northern European seaweed species intended for food**
Jönsson, M., Merkel, A., Fredriksson, C., Nordberg Karlsson, E., and Wendin, K.
Alg. Res., 2023, 75:103258
https://doi.org/10.1016/j.algal.2023.103258

V. **A sense of seaweed: Consumer liking of breads and spreads with the addition of four different species of northern European seaweeds. A pilot study among Swedish consumers.**
Jönsson, M., Maubert, E., Merkel, A., Fredriksson, C., Nordberg Karlsson, E., and Wendin, K.
Future Foods, 2024, 4:100292
https://doi.org/10.1016/j.fufo.2023.100292

Author’s contribution to the papers

I. MJ, ENK, and MR conceptualized and designed the study. MJ further coordinated the project and carried out the laboratory investigation with help from LA. MJ performed the data interpretation, statistical analysis and visualization. MJ wrote the first draft of the manuscript, which was revised by all authors, and submitted it as the corresponding author.

II. This study was coordinated by LA, who performed most of the investigation and data analysis. MJ contributed to laboratory investigation and data interpretation of the sub-study described in 2.3 (fermentation of seaweed), as well as reviewing and editing of the manuscript.

III. MJ and ENK carried out the conceptualization and design of the study. MJ coordinated the project and carried out the laboratory investigation and sent samples for external analysis. MJ performed the data interpretation, statistical analysis, visualization, and wrote the first draft of the manuscript, and submitted it as the corresponding author.

IV. All authors contributed to the conceptualization and study design. MJ and AM coordinated the study. Investigation was performed by MJ, KW, and the sensory laboratory technician. Data interpretation and statistical analysis were carried out by MJ and KW. MJ created the visualizations and wrote the first draft of the manuscript, with contributions from the co-authors. Reviewing and editing were performed by all authors. MJ submitted the paper as the corresponding author.

V. KW and EM carried out the conceptualization and study design, with contribution from the co-authors. EM performed the investigation. Data interpretation and statistical analysis were carried out by EM and MJ. Also, MJ created the visualizations and wrote the first draft of the manuscript, which was reviewed and edited by all authors. MJ submitted the paper as the corresponding author.

List of papers not included in the thesis

VI. **Extraction and modification of macroalgal polysaccharides for current and next-generation applications**
Jönsson, M., Allahgholi, L., Sardari, R.R., Hreggviðsson, G.O., and Nordberg Karlsson, E.
Molecules, 2020, 25(4):930
https://doi.org/10.3390/molecules25040930

VII. **Sensing seaweed settings: Making sense of a mixed-method design for sensory analysis**
Fredriksson, C., Jönsson, M., Merkel, A., Nordberg Karlsson, E., and Wendin, K.
Int. J. Gastron. Food Sci., 2023, 33:100762
https://doi.org/10.1016/j.ijgfs.2023.100762

VIII. **Extractability, selectivity, and comprehensiveness in supercritical fluid extraction of seaweed using ternary mixtures of carbon dioxide, ethanol, and water**
Freedom Gondo, T., Jönsson, M., Nordberg Karlsson, E., Sandahl, M., and Turner, C.
J. Chromatogr. A, 2023, 1706:464267
https://doi.org/10.1016/j.chroma.2023.464267

Abbreviations

AE	*Alaria esculenta* (synonym: winged kelp)
AOAC	Association of Official Agricultural Chemists
ASTM	American Society for Testing and Materials
b.w.	Body weight
CE	Circular economy
CEN	Comité Européen de Normalisation
CFU	Colony forming units
DM	Dry matter
EDTA	Ethylenediaminetetraacetic acid
EMP	Embden-Meyerhof-Parnas
GC	Gas chromatography
GHG	Greenhouse gas
HAE	Heat-assisted extraction
HPAEC	High-performance anion exchange chromatography
HPLC	High-performance liquid chromatography
HPP	High-pressure processing
HR-ICP-MS	High resolution inductively coupled plasma mass spectrometry
ISO	International Organization for Standardization
LAB	Lactic acid bacteria
LCA	Life cycle assessment
LC-PUFAs	Long-chain polyunsaturated fatty acids
MAE	Microwave-assisted extraction
PCR	Polymerase chain reaction
PEF	Pulsed electric field
PP	*Palmaria palmata* (synonym: dulse)
PTE	Potentially toxic elements
QDA	Quantitative descriptive analysis
SDGs	Sustainable development goals
SEM	Scanning electron microscopy
SL	*Saccharina latissima* (synonym: sugar kelp)
U [1]	*Ulva* sp. (tubular morphology)
UAE	Ultrasound-assisted extraction
UL [1]	*Ulva lactuca* (bladed morphology. Synonyms: *Ulva fenestrata*, sea lettuce)
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
WHO	World Health Organization

[1] Note: While *Ulva* with bladed and tubular morphology is differentiated by UL and U, respectively, in the thesis kappa, both seaweed types are referred to as UL in the articles. The species used in the respective articles are always specified under the paper's material and method section.

Introduction

Present food systems pose one of the greatest challenges of the 21st century to human and planetary health [1,2]. Therefore, a transition towards more sustainable food systems is argued to be imperative for compliance with the global goals outlined in the Paris Agreement and Agenda 2030. The wind of change carries new technologies and innovations with potential to accelerate the shift in the food sector towards sustainability [3]. How do you imagine our future foods? In this thesis, brown, red, and green seaweeds were sourced from the blue fields of northern Europe as part of the green transition to end up on the white plates of Swedish consumers.

On a global level, the Paris Agreement (United Nations Framework Convention on Climate Change) and the United Nations' Agenda 2030 represent two internationally agreed global visions for a more sustainable future. Launched in 2015, the two visions act in favour of sustainable development and reduced climate impact from anthropological activities [4,5]. All member states have taken on the responsibility of creating a better, more just and sustainable world. Among the 17 sustainable development goals (SDGs) put forward in the Agenda 2030, this thesis primarily relates to two, namely Goal 12: Responsible Production and Consumption and Goal 14: Life Below Water.

In addition to the member states' pledges to act in pursuit of a sustainable future, other initiatives have more specifically addressed our diets. When the Nordic nutrition recommendations were revised in June 2023, environmental impacts of our diet were for the first time integrated into the recommendations. Hence, upon the release of the new Nordic nutrition recommendations, the directive was evident: prioritizing a predominantly plant-based diet is crucial for healthier people and a healthier planet [6].

Seaweed consumption is postulated to meet both requirements. Therefore, the main motivators for the consumption of seaweed are linked to their posited benefits for both human health and the environment [7]. Firstly, the health benefits are linked to diverse algal nutritional components, particularly certain compounds showcasing potential functional properties. Edible seaweed presents a promising source of dietary fibre, proteins, and minerals, while also harbouring bioactive elements such as polyphenols, certain polysaccharides, and sterols, contributing to the functional properties associated with seaweed consumption [8]. Secondly, the ecological sustainability associated with seaweed has previously been reported to arise from their ability to grow without fertilizers, pesticides, herbicides, land space, and fresh water irrigation, while also proliferating at growth rates exceeding terrestrial plants, utilizing carbon dioxide for their photosynthesis, and providing ecosystem services [9-11]. In the light of these aspects, there is a general positive attitude among Western consumers towards eating seaweed [7]. However, a gap between intention and behaviour is observed.

This gap may be explained by unaffordable pricing, limited accessibility, and poor product diversity. These factors may in turn depend on challenges including scattered regulations within the EU, inefficient post-harvest treatment for microbial and chemical safety, as well as the lack of culinary innovation and knowledge of the sensory quality of seaweed materials [12,13].

Among these challenges, this thesis focuses on several barriers across the value chain from production to consumption of future seaweed foods. These barriers include post-harvest treatment for microbial and chemical food safety, as well as consumer acceptance.

Species studied in this thesis represent common northern European seaweeds, including *Saccharina latissima* (L.) C.E. Lane, C. Mayes, Druehl, and G.W. Saunders 2006, *Alaria esculenta* (L.) Greville 1830, *Palmaria palmata* (L.) F. Weber & D. Mohr 1805, Ulva lactuca (L.) 1753 (bladed morphology), and Ulva sp. (tubular morphology).

Aim and research question

The overall aim of the thesis was to address selected urgent challenges for the introduction and expansion of seaweed into new markets, leading up to the following question: How can microbial, chemical, and sensory challenges associated with seaweed for food be overcome to facilitate its introduction and expansion into Western markets?

The specific aims for each paper include investigating post-harvest stabilisation of two kelps in **Papers I–II**, and investigating species-, spatial-, and thallus-dependent variation of potentially toxic elements in four species of seaweed and techniques for their removal in **Paper III**. The aim was to evaluate consumer acceptance in **Paper IV** by means of descriptive sensory analysis to map the sensory profiles of four seaweed species, and in **Paper V** using hedonic sensory analysis to understand the liking of two complementary food products with the inclusion of four species of seaweed. The papers cover aspects related to production and consumption of future seaweed foods, as reflected in the outline of the thesis.

Outline of the thesis

Just like the oceans stretch out worldwide, connecting countries and continents, so this interdisciplinary thesis project has interlinked the academic disciplines of biotechnology, food science and technology, social science, and analytical chemistry. This is reflected in the diverse topics it has touched upon, as it aims to bridge the gaps between various fields. This thesis is outlined to follow the value chain from seaweed production to consumption – from its natural habitat, via processing and production, to consumption and beyond.

In the chapter *Seaweed as a marine food resource*, we dive deep into the world-spanning oceans, as this thesis' journey commences in the habitat of the marine resource. The focus is on seaweed as a complex natural material, and it is through this lens that its nutritional content (**Papers I–IV**) and potential health benefits are discussed. Its role as food in historic and cultural respects is subsequently addressed, and Japan is used as a case study.

In *A sustainable food resource in the circular bioeconomy*, the role of seaweed is contextualized in the transition towards more sustainable food systems. It is presently argued that the food sector is contributing substantially to climate change and unhealthy lifestyles. The circular bioeconomy is a model with transition potential, and farming and utilization of seaweed can fit within the concept. However, introducing and expanding seaweed in new markets is associated with several challenges, including microbial, chemical, and sensory quality of seaweed.

Hence, the next chapter, *Microbial quality*, delves into the intricate interactions between seaweed and marine microorganisms. Two methods for stabilisation of the easily degradable biomass are presented: high-pressure processing (**Paper I**) and fermentation (**Paper II**). These methods can also act to enhance the chemical quality of seaweed, which leads to the next section.

In the chapter *Chemical quality*, the uptake of potentially toxic elements by seaweeds is explored (**Paper III**). Species-, spatial- and thallus-dependent variations of these elements are demonstrated and techniques for their removal are proposed to enhance the chemical food safety related to seaweed consumption.

In *Sensory quality*, this journey along the value chain reaches its final destination – the consumer. This section argues for the need for descriptive sensory analyses to map the sensory profile of different seaweeds (**Paper IV**) and hedonic sensory analyses, to investigate the consumers' liking of seaweed products (**Paper V**). This is imperative for gastronomic inventions and can serve as indicators for how to use seaweeds in everyday life.

Lastly, in the sixth and final chapter, *Conclusions and future perspectives*, the outcomes of the thesis are summarized, and we gaze out over the horizon into the future of seaweed production and consumption in Western markets.

Seaweed as a marine food resource

Macroalgae, microalgae. Seaweed, seagrass. Linguistically similar, but biologically different. Let us begin by unravelling the entangled terms: what are seaweeds? Synonymous with marine macroalgae, seaweeds are macroscopic multicellular algal organisms, not to be confused with microalgae (unicellular organisms) or seagrass (flowering marine plants). The sizes of the algal body can vary from a few millimetres up to around 70 metres, indicating large variations in structure and composition among different species [14].

The different species of seaweed are classified into three different phyla: green (Chlorophyta), brown (Heterokontophyta), and red (Rhodophyta) algae [15]. They have a complex phylogenetic history shaped by a series of endosymbiotic events, where brown algae appear to have emerged later in time than red algae, green algae, and terrestrial plants. This has resulted in the development of unique cell wall structures and components among the different seaweed types [16,17].

However, the variation in the composition depends not solely on species affiliation, but also on seasonal, environmental, and regional factors as well as subsequent post-harvest handling [14]. As with other natural materials, this variation makes it difficult to establish a uniform picture of seaweed composition, concerning both levels of nutrients and potentially toxic elements.

Nutritional composition

Acclimatized to underwater environments, seaweeds have evolved distinct chemical compositions to endure the changing conditions associated with tidal fluctuations and osmotic stress [16]. Overall, their main components include carbohydrates, minerals, and proteins, as well as small amounts of lipids, polyphenols, pigments, and vitamins [8,14]. **Papers I–IV** determined the nutritional content of two kelps, as well as a red and a green species, since the composition constitutes a cornerstone in the endeavour of further understanding their properties (Figure 1). In the following section, we figuratively place seaweed under the magnifying glass to explore the microscopic realm of the building blocks that collectively form the macroalgae.

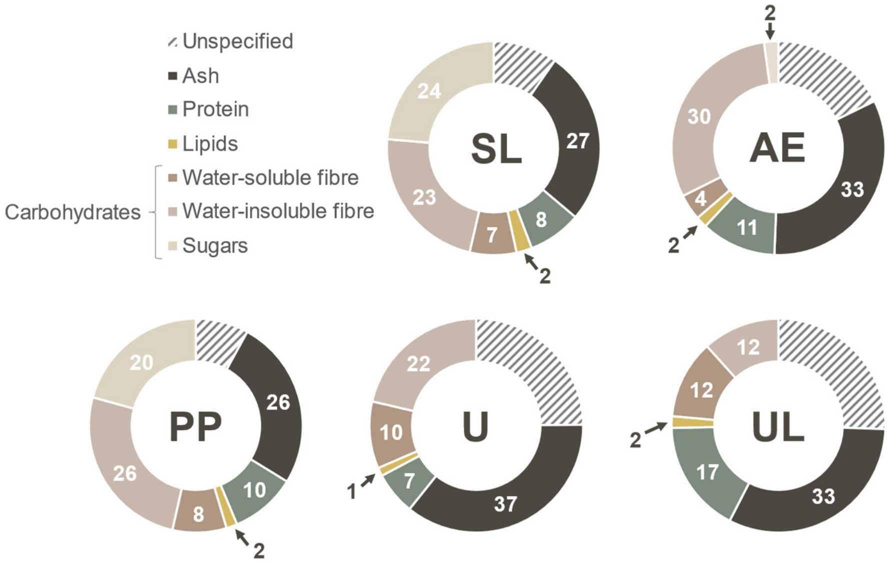


Figure 1. Example of composition for five species of seaweeds harvested in Ireland. SL: *Saccharina latissima*. AE: *Alaria esculenta*. PP: *Palmaria palmata*. U: *Ulva* sp. (tubular). UL: *Ulva lactuca* (bladed). The composition is given as g/100g dried seaweed.

Carbohydrates

The macroalgal cell wall is a complex, diverse, and dynamic structure rich in polysaccharides (Table 1), and these structures also contribute to the perceived texture of seaweed [14,16]. The carbohydrate fraction varies between species, seasons, and growth sites, but comprises around 4–76% of the algal dry weight (DW). The portion of dietary fibre represents 33–62% DW, which can potentially act as a prebiotic for the human gut microflora [8,14].

In **Papers I–IV**, the carbohydrate content was determined by analysing the neutral monosaccharides, uronic acids, and mannitol by high-performance anion exchange chromatography (HPAEC) after hydrolysis by sulphuric acid. Dietary fibre content was analysed by an external lab according to a modified version of the Association of Official Agricultural Chemists (AOAC) 991.43 method, which employs an enzymatic-gravimetric analysis.

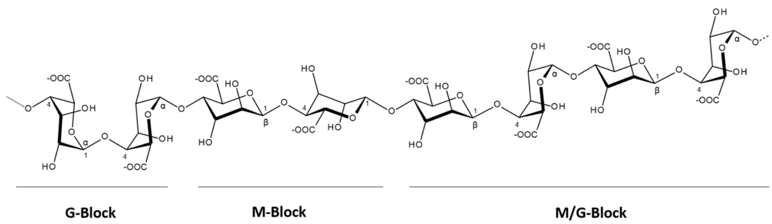
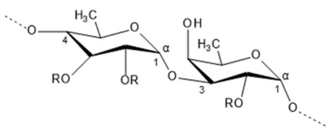
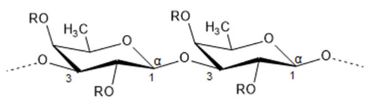
In brown seaweed, the cell wall polysaccharides consist primarily of alginate, but also of varying amounts of fucoidan, and laminarin, as well as minor amounts of cellulose. Alginates (salts of alginic acid) comprise varying ratios of mannuronic acid (M) and guluronic acid (G), which form M/G-blocks, rendering diverse structures and functions of the alginates. Fucoidan is a sulphated polymer of mainly fucose but also minor amounts of other monomers, and laminarin is a β-glucan, consisting mainly of glucose and serving as a storage carbohydrate. Brown seaweeds can also contain a substantial amount of the sugar alcohol mannitol (≤25% DW) [8,14,16], which becomes an important substrate in lactic acid fermentation, as explained in the section *Microbial quality*.

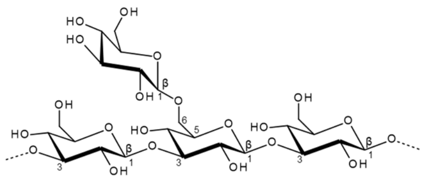
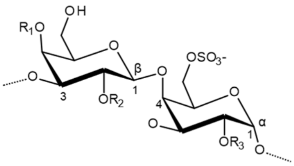
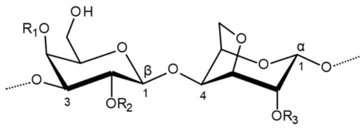
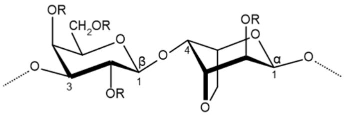
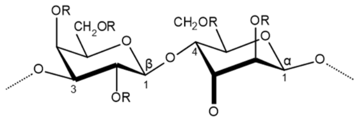
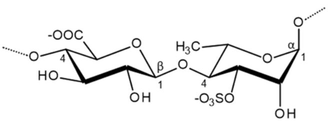
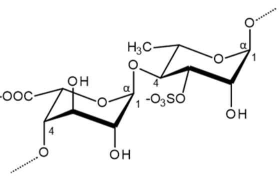
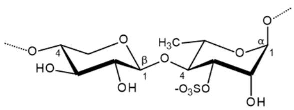
Red seaweed polysaccharides include carrageenan (a sulphated galactan), agar (a mixture of polysaccharides including agarose and agaropectin), xylans, and cellulose. Floridean starch, highly branched amylopectin, is a storage polysaccharide in red algae [8,14].

Green seaweed polysaccharides are less researched but are roughly divided into two major groups classified as uronic acid-rich (ulvans) or uronic acid-limited. Ulvans are highly sulphated structures composed of rhamnose, xylose, glucuronic acid, and iduronic acid, with repeating disaccharide units, including aldobiuronic acids [14,18].

Algal polysaccharides are reported to have bioactive properties, including antitumor, antibacterial, antidiabetes and anticoagulant, and could potentially serve as prebiotics. However, more clinical research must be performed to support these claims [8,14].

Table 1. Basic structures of polysaccharides in seaweed: **a)** alginate, **b–c)** fucoidan, **d)** laminarin, **e–f)** carrageenan, **g–h)** agar, and **i–k)** ulvan (where **i–j)** are ulvanobiuronic acids and **k)** is ulvanobiose). Adapted from Jönsson et al. [14], with structures [18-23] drawn in BIOVIA draw.

Polysaccharide	**Structure**	
Alginate	**a)**  β-1,4-D-mannuronic acid (M) and α-1,4-L-guluronic acid (G) residues forming GG, MM and M/G-blocks	
Fucoidan	**b)**  *R = SO_3^- or H* Alternating 1,3- and 1,4-linked α-L-fucose	**c)**  α-1,3-L-fucose

Laminarin	**d)**  β-1,3-D-glucose backbone with branching β-1,6-D-glucose unit	
Carrageenan	**e)**  *μ-carrageenan: $R_1 = SO_3^-$, $R_2 = R_3 = H$* *ν-carrageenan: $R_1 = R_3 = SO_3^-$, $R_2 = H$* *λ-carrageenan: $R_1 = H$, $R_2 = R_3 = SO_3^-$* Alternating α-1,4-D-galactose and β-1,3-D-galactose	**f)**  *κ-carrageenan: $R_1 = SO_3^-$, $R_2 = R_3 = H$* *ι-carrageenan: $R_1 = R_3 = SO_3^-$, $R_2 = H$* *θ-carrageenan: $R_1 = H$, $R_2 = R_3 = SO_3^-$* Alternating β-1,3-D-galactose and 3,6-anhydro-α-1,4-D-galactose
Agar	**g)**  *R = H or side chain substituents e.g. sulfate ester, methoxy ether or pyruvic acid* Alternating β-1,3-D-galactose and 3,6-anhydro-α-1,4-L-galactose (agarose)	**h)**  Alternating β-1,3-D-galactose and α-1,4-L-galactose (agaropectin)
Ulvan	**i)**  Alternating β-1,4-D-glucuronic acid and α-1,4-L-rhamnose	**j)**  Alternating α-1,4-L-iduronic acid and α-1,4-L-rhamnose
	k)  Alternating β-1,4-D-xylose and α-1,4-L-rhamnose	

Minerals

Many seaweed species contain a substantial amount of minerals (10–55% DW) [8,14]. In general, seaweeds have high levels of calcium, iron, potassium, magnesium, sodium, phosphorus, sulphur, iodine, and other various minerals (**Papers III–IV**). Different minerals, and their morphologies can result in different perceived levels of saltiness upon consumption [24]. In addition, while some minerals are essential for human health, excess intake of some non-essential (and essential) minerals can pose human health hazards. Hence, further investigation of the mineral fraction was performed in **Papers III–IV**, as covered in the chapter *Chemical quality*.

In **Papers I–IV**, the total content of ash (minerals) in seaweed was determined gravimetrically by weighing seaweed-filled crucibles before and after incineration for 3 hours at 575°C. Further specification of the mineral content was investigated in **Papers III–IV** by quantification of the elemental content using high resolution inductively coupled plasma mass spectrometry (HR-ICP-MS) at external labs.

Proteins

The protein content in seaweed varies between species, and whereas brown algae generally comprise low levels (up to 20% DW), the content in green and red algae is higher (up to 45% DW). In general, seaweeds can contain all the essential amino acids, and are particularly rich in aspartic acid and glutamic acid, giving them their characteristic umami taste [8]. In fact, the fifth taste, umami, was discovered from the seaweed kombu in the early 20th century by the Japanese researcher Kikunae Ikeda [25]. In **Paper IV**, the amino acid profile of *S. latissima*, *A. esculenta*, *P. palmata*, and *Ulva* sp., was determined. Overall, of all the essential amino acids, only histidine was below the recommended level in all species, and lysine in the *Ulva* sp. Tryptophan was not analysed. Different amino acids also contribute to the perceived taste of seaweed, enhancing for instance sweet, bitter, and salty notes [26,27]. The high levels of protein in certain species of seaweed make them attractive alternatives to current protein sources. However, more research on bioavailability is imperative.

In **Papers I**, **III–IV**, the total protein content was determined by the Dumas method for nitrogen analysis by conversion to protein content using a nitrogen-to-protein conversion factor [28]. The limitation of such conversion is its lack of accuracy across all materials. However, a factor of 5 has in general been shown to represent seaweed well [28,29]. In **Paper IV**, the amino acid composition was determined by an external lab using high-performance liquid chromatography (HPLC) with fluorescence detection.

Lipids and other minor compounds

Lipids are a broad group of hydrophobic compounds including free fatty acids, mono-, di-, and triglycerides, fat-soluble vitamins (e.g. vitamins A, D, E, and K), phospholipids, sterols, waxes, and others [8]. With a content of up to 4.5% DW, the lipid fraction in seaweed is not very extensive, but can contain substantial amounts of long-chain polyunsaturated fatty acids (LC-PUFAs). Pigments in seaweed include chlorophylls, and carotenoids, such as carotenes (e.g. β-carotene) and xanthophylls (e.g. fucoxanthin, lutein, and violaxanthin).

In **Paper IV**, the total lipid fraction was analysed gravimetrically after extraction using a chloroform:methanol solution, and the fatty acid profile was subsequently obtained by gas chromatography (GC).

Other minor constituents of seaweeds are phenolic compounds. Whereas green and red seaweed are reported to have low phenol concentrations (<1% DW), it is known to occur at higher levels in brown seaweed (<14% DW) [8], especially phlorotannin which is comprised of polymerised phloroglucinol units [30]. The antioxidative potential of phenolic compounds attracts interest for several applications and can, for instance, serve as a natural food stabilizer and act as a self-preservative [31]. In addition, a group of phenols synthesized in seaweed, bromophenols, are described as giving rise to their perceived agreeable smell of fresh sea [32].

As outlined in this section, the building blocks of seaweed form the nutritional content (biochemical composition) and influence how seaweed is physiologically perceived. Their unique, healthy, and sustainable associations fuel the trend of seaweed consumption in Western societies [7]. Although often described as novel foods in Wester settings, many cultures testify to early use of seaweeds.

Seaweed: then and now

Seaweed has possibly been consumed in coastal areas around the world since prehistoric times. Whereas some cultures, especially in Southeast Asia and Polynesia, have maintained the tradition of eating seaweed in modern times, Western societies have largely lost the tradition of using seaweed for food. In fact, in some coastal areas, such as in Ireland, the Faroe Islands, Scotland, and Brittany, seaweed is to some extent still associated with poor people and times of famine [33]. In recent years, seaweed has started climbing the social ladder and is now increasingly used by high-end restaurants and among sustainability-conscious consumers in Western settings [34,35]. Interestingly, seaweed graced the plates in the grandest of halls when the 2023 edition of the Nobel banquet celebrated exceptional scientific achievements. Seaweed is trending and is often marketed as a novel super-food.

In Europe, the categorization of novel foods is based on Regulation (EU) 2015/2283, which defines novel foods as foods "not been consumed to a significant degree by humans in the EU before 15 May 1997" [36]. In the EU Novel Food Catalogue [37], some species, including *S. latissima*, *A. esculenta*, *P. palmata*, and *U. lactuca*, have been recognized for their significant use before the specified date and are thus not covered by the novel food regulation, meaning they do not have to undergo extensive authorization procedures to ensure their safety for human consumption. However, certain specific regulations might yet limit market access in particular member states within the EU [37]. In fact, coordinated and standardized legislation for safe seaweed consumption is lacking within the EU, which may impede its introduction and expansion into European markets [38].

While some species might not be encompassed by the novel food regulation, consumers may yet perceive seaweed as a novel resource in their food practices [35]. However, extracts from seaweed are already widely used in several commercial food products, ranging from canned foods to ice cream and instant desserts [8]. Seaweed polysaccharides (as previously described) are widely employed for their technological attributes as phycocolloids, including alginates (stabilizer and thickening agent, E401 – E405), agar (vegetable gelatine, E406), and carrageenan (thickening agent, E407). Despite their prevalence in various food products, many consumers remain unaware of their presence due to the use of technical language on packaging labels that might not be easily understood in everyday life (**Paper IV**).

While seaweed is a candidate for an emerging type of *superfood* in Western settings, it has become an abundant *staple food* in other cultures. The following section predominantly draws from personal experiences during a research visit to Japan in 2022, positioning myself at the intersection of these perspectives.

Japan as a case study

In Japan – like elsewhere – food is not solely seen as the body's source of energy and nutrition. It can also be recognized as nutrition for one's thoughts and feelings [39], and was already mentioned by the famous poet Fujiwara no Teika (1162–1241) some eight hundred years ago [40].

Today, centuries later, the packed grocery store shelves in Japan, where one seaweed-containing product is displayed after another, testify to how embedded the seaweed tradition is in Japanese culture. Moreover, seaweed can also be found at bazars and local markets as seen in Figure 2.

Not only does the availability of seaweed differ between the food cultures, but also how they are popularly termed. In Japanese food culture, edible seaweeds are commonly considered "sea vegetables" – each suitable for different dishes and purposes. Below the sea surface, a whole buffet of seaweed species appears, and the many species also come with different tastes, shapes, and textures. Nori, wakame, mekabu, kombu, mozuku, umi-budou, and hijiki, being some of the most important types, are sold in many different forms: canned (kandzume), fresh (shinsen'na), fried (ageta), roasted (yaki), dried (hoshi) as whole pieces or in sheets of various sizes and forms. They are included in salads, dressings, pastes, and soups to name but a few uses. This variety in the supply and division of species testifies to the maturity of the Japanese seaweed market in contrast to the yet-young Swedish settings.

Distinguishing various seaweed types seemingly also entails the refinement of their usability in Japanese cuisine. Each species has its own context and purpose. For instance, the nori sheet comes in many forms – zenkei (whole square piece, e.g. for sushi making), which can be cut in two, four, or eight pieces, shredded (kizami), or made into flakes (momi). These are used for sushi rolls (sushi maki), rice balls (onigiri), sushi cones (sushi temaki), garnish, or simply to eat as a snack. Kelp (kombu or konbu) is commonly used for soup broth (dashi), but can also be found in other settings, such as a rice ball filling seasoned with soy sauce.

In addition to the immense variety of seaweed foods available in Japan, products also come in a wide quality range. The little nori specialist shop, Koike Nori Ten, in Nagasaki accommodates a range of different varieties and qualities. It is tangible how nori of lower quality is greener and chewier compared to the more brittle and blackish nori of higher quality. Evaluation of quality is based on the colour, odour, form, weight, and dryness of the nori. Dryness in particular is crucial for acceptance. Therefore, the humidity is monitored in the store and research on optimal packaging and preservation is ongoing. Seaweed farmers have recently also noticed a trend for increasing production of discoloured, light-green, nori, which is reportedly not accepted by Japanese consumers. Consequently, researchers are trying to find alternative uses for it as they seek to understand the mechanisms behind the discolouration. In summary, consumer acceptance seems to be manifested differently in a new and an established market.

The next chapter looks closer at seaweed as a sustainable food resource contextualized in the concept of a circular bioeconomy.

Figure 2. A stall with seaweed at the Arita ceramics fair 2022.

A sustainable food resource in the circular bioeconomy

The global food system is often portrayed as a major villain in the climate change drama and poses one of the greatest health and environmental challenges of the 21st century [1,2,41]. Hence, a systemic shift in the food sector represents one of the most impactful actions in the transition towards sustainability [42] (Def: sustainability[2] [43,44]). This proposed shift can be accelerated by technologies and innovations throughout the whole value chain, including sourcing new foods, such as seaweeds in Western settings, and implementing a circular approach. Before delving into possible solutions, let us have a look at some of the challenges within the current system.

Effects of current food systems

The food's journey from producer to consumer involves a value chain that includes farming, harvesting, or catching, transportation, processing, packaging, distribution, storage, cooking, and the handling of resulting waste. Each of these steps contributes to the total greenhouse gas (GHG) emissions from the global food system [41].

Recent estimates of worldwide emissions from anthropological activities indicate that 21–37% of the emissions can be attributed to the food sector [41,45]. The main contribution comes from agriculture and land use/land use change activities, with emissions from animal-based sources coming in at twice those of plant-based foods [46,47]. Modern agriculture alone is a dominant contributor to methane (CH_4) and nitrous oxide (N_2O) emissions, which are attributed to livestock farming and the extensive use of nitrogenous fertilizers [46]. In the light of this data, anthropological activities related to modern life practices and agriculture exert a negative impact on the environment, including the welfare of the world's oceans.

[2] Sustainability is often described according to the Brundtland report and Elkington's triple bottom line reporting. The Brundtland report defines sustainable development as "*Development that meets the needs of the present without compromising the ability of future generations to meet their own needs*". Elkington suggests that sustainable development should be described from three different dimensions: social, environmental, and economic (or people, planet, profit).

Acidified, eutrophicated, and overfished – a dystopian description of many oceans worldwide. Increasing GHG emissions since the Industrial Revolution have led to an annual 30% CO_2 uptake by the oceans, which is contributing to widespread ocean acidification, corresponding to a pH decrease from 8.2 to 8.1 [48]. The total production of fertilizers (N: nitrogen, P: phosphorus, and K: potassium) has increased drastically since the 1960s (N: 852%, P: 300%, and K: 380%). Looking at the nitrogen source applied globally, merely around 47% is used by crops, and the remaining half runs off as excess nitrogen into rivers, lakes, and natural environments [49,50]. This leads to overfertilized waters which are subjected to the development of "dead zones," loss of biodiversity, and an increase in toxic phytoplankton [51]. Moreover, the natural balance in the oceans is further disturbed when large parts of the fish stocks are depleted from their habitats (UN SDG 14.4.1 [48,52]).

While current food systems pose a threat to ecological environments, they also reportedly contribute to observed malnutrition among humans worldwide, including undernutrition, micronutrient deficiencies, and overnutrition [1,2]. While current eating habits can pose a threat to our public health, many people feel that dietary choices are personal, and that governmental interference might infringe upon their freedom of choice. This poses a significant challenge in implementing desired systemic changes [53].

Circular transition of food systems

The circular economy has been described as having the potential to implement sustainable development and change the food sector with three ambitions [42]. Firstly, by sourcing food grown regeneratively and locally where appropriate; secondly, by designing and marketing healthier food products; and thirdly, by making the most of food.

An activity that is postulated to fit well within this definition of the circular economy is seaweed farming, which has the potential to bring many positive environmental effects [9-11]. Firstly, local offshore cultivation of seaweed could help restore balance in oceans by absorbing nutrients and hence mitigating eutrophication, facilitating carbon capture, and provisioning of other ecosystem services such as increased biodiversity. The postulated potential is further linked to its beneficial cultivation conditions, where neither fresh water, land space, fertilizers, herbicides, nor pesticides are required, while its biomass productivity exceeds that of terrestrial plants. Secondly, seaweed is also often described as a food resource with potential health benefits, including potential bioactivities and advantageous nutritional profiles, as described in the previous chapter *Seaweed as a marine food resource*. Thirdly, making the most out of food involves recirculation of by-products into the bioeconomy or, simply speaking, utilizing any waste in secondary processes. For seaweed, this can be exemplified by the concept of biorefineries where high-value products are extracted in smaller volumes, and the remaining quantities can be repurposed as biomaterials, energy, and fertilizers [54].

However, as promising as it sounds, each ambition described is associated with challenges. For instance, the impact of upscaled seaweed farms on marine ecosystems and habitats should be further investigated. Also, the carbon capture potential of seaweed for food is presently questioned [55]. In addition, as previously described, the health benefits of seaweed need further clinical evidence, as well as the effect of accumulated potentially toxic elements. Infrastructures for efficient handling of seaweed in a biorefinery scenario need to be developed. Moreover, the circular economy concept itself has been criticised for issues such as conceptual ambiguity, uneven distribution of social and environmental effects, and for its potential to drive demand for new products without addressing the complex problems of overproduction and overconsumption in certain regions of the world today [56-58].

The transition towards a circular bioeconomy is an intrinsically interdisciplinary challenge, encompassing actors throughout the value chain between production and consumption [42]. In particular, contemporary food systems are complex and challenging, and the border between consumer and producer is becoming increasingly blurred [59]. Hence, facilitating the circular transition in food systems requires collaborative interdisciplinary mobilisations.

Interdisciplinary research

Global food systems are complex and span multisectoral functions, motivating collaborative work across disciplines [59,60]. The level of interaction between multiple disciplines follows the order: disciplinary < multidisciplinary < interdisciplinary < transdisciplinary collaboration. Disciplinary research unfolds within a delimited field, multidisciplinary research acts within its disciplinary boundaries but draws on knowledge from different fields, interdisciplinary research bridges various disciplines into a coordinated and coherent whole, and transdisciplinary research goes beyond any border and takes a holistic view of the work [61]. Hence, the collaborative constellation behind **Paper IV** and **Paper V** adopted an interdisciplinary approach that aimed to reach beyond the boundaries of each field [59].

Delving into the intricate and interlinked networks of seaweed production and consumption, a fundamental question emerged: how can we attain a more profound comprehension and foster greater cohesion in the research processes that span across diverse disciplines? In **Paper IV** and **Paper V**, a framework for interdisciplinary research in food systems (Figure 3), adapted from Grace et al. [60], was brought into practice to facilitate and balance the collaborative work across disciplines. In our example, sensory research within the field of food science figured as a disciplinary bridge between biotechnology and social science – between the perspectives of the producer and consumer.

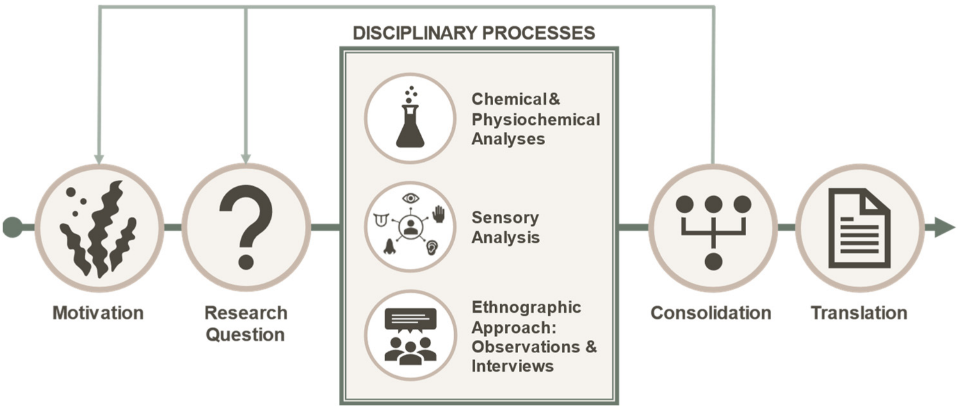


Figure 3. Design for interdisciplinary collaboration in food systems, adapted from Grace et al. [60] and Fredriksson et al. [59].

The interdisciplinary framework advocates an iterative approach to enunciate collaborative *motivation* and joint *research questions*, which are further developed and investigated within the separate *disciplinary processes*. The common motivation for **Paper IV** and **Paper V** relates to challenges in the introduction and expansion of seaweed food applications in Western markets. The iterative process prompted the questions: How can sensory perceptions and experiences be translated into nutritional content and physicochemical characteristics of the seaweed? And how does this resonate within consumers' everyday practices? In the *consolidation* step, the results were linked together to form a coherent output, which was disseminated in the *translation* phase.

The outcomes from the interdisciplinary collaboration and an expansion of the consumer perceptions of eating seaweed are further discussed in the chapter *Sensory quality*. But before placing seaweed on the plate, we take a closer look at seaweed's microbial and chemical qualities.

Microbial quality

Since time immemorial, humans have processed food and beverages for prolonged stability and improved palatability. This has been not only a survival strategy to save surplus from days of plenty to use in days of scarcity, but also a means to make the nutrition available upon ingestion, and make the foods tastier and safer [62]. Both in the past and the present, the foods we consume are not completely sterile but rather exhibit diverse microbial compositions [63]. The number and types of microorganisms associated with foods define its microbial quality. Prehistoric civilizations learned how to tame the fire for cooking, catch the sun for drying, and grow bacteria and yeast for turning grains into bread and beer. In fact, ancient settlements used mechanical, thermal, chemical, and biological processes in their early product development endeavours [62,64].

Thousands of years later, we still use the same techniques to process food. Whereas the use of some methods has ceased over the years, many new techniques have seen the light of the day. While consumers may not always view processing in a favourable light and may perceive it as conflicting with naturalness [65], these techniques have undeniably become embedded in our daily lives. We are cooking, smoking, drying, salting, fermenting, pickling, and jamming, all for the purpose of prolonging stability and/or improving the palatability of food [64].

When it comes to seaweed, many methods of preservation are available in the Japanese food culture and industry. As described in the chapter *Seaweed as a marine food resource*, the grocery stores in Japan are filled with fried, canned, freshly packed, frozen, pickled, dried, and roasted seaweed.

However, when it comes to the introduction and expansion of seaweed into new markets, post-harvest treatment has often been described as one of the most profound challenges [12,13]. Today, engineers are striving to make preservation methods more effective at an industrial scale, and less time-, energy-, and resource-consuming. These efficiency improvements are also an important step in the pursuit of introducing seaweed into new markets, where established techniques entail several challenges. To investigate what methods are suitable in a Nordic context, we must first understand the difference between food-spoiling microbes and pathogens, and which microorganisms colonize the seaweed.

Food spoilage and foodborne pathogens

Food-associated microflora mostly has no noticeable effect on either the product or on the consumer. However, in some cases, microbial presence is manifested as food spoilage or foodborne illness.

Food spoilage is a physical, chemical, or microbiological process rendering a food product undesirable or unacceptable for human consumption. I believe many of us at some points have instinctively recoiled from the smell of that old forgotten piece of food hiding in the back of the fridge. Spoilage is caused and accelerated by several factors associated with the three main categories: physical (water activity, pH, temperature, air, light, physical damage), chemical (available nutrients, enzymes), and microbial (bacteria, mould, yeast) [63,66]. Consequently, these factors should be managed and monitored when improving the foods' stability.

Food pathogens, unlike spoilage microbes, are bacteria, viruses or parasites that directly or indirectly can cause illness or disease in the consumer [67]. Among the bacteria naturally found in seaweed, *Bacillus* spp., *Vibrio* spp., and *Aeromonas* spp. have been identified as potential food safety hazards [68]. Of these species, only *Bacillus* spp. was observed in Swedish *S. latissima* in **Papers I-II**. Further studies on human pathogens in edible seaweeds are needed together with updated food safety guidelines for seaweeds in the EU.

In seaweed, the exalted water content and water activity (typically around 70–90% and 0.97–0.98%, respectively) favour the growth of microorganisms, suggesting a need to develop efficient methods for post-harvest processing. Hence, **Paper I** and **Paper II** investigate HPP and fermentation, respectively, as potential post-harvest treatment methods for increased microbial safety of seaweed.

Interactions between seaweed and microorganisms

The interaction between seaweed and microorganisms is an intricate system. The exchange of nutrients and substances between the microbial communities and seaweed is part of a vital symbiotic relationship that facilitates efficient metabolic processes within the macroalgae [69,70]. Nonetheless, the composition and abundance of microorganisms are contingent upon various factors, such as the seaweed growth site characteristics (e.g. sunlight exposure, tidal patterns, water currents, temperature, salinity, acidity, and nutrient availability), species, and the time of harvest [71]. These factors, together with several intrinsic (substrate-specific), extrinsic (environment-specific) and implicit (microbial-specific) factors, affect the development of microbial associations in food which can cause spoilage or illness.

In **Paper I**, the overall initial microbial load on *S. latissima,* harvested in April 2021 at Koster Sea, proved to be low. The lack of amplification of microbial DNA by PCR (performed at Eurofins Genomics GmbH, Ebersberg, Germany) indicated that the seaweed contained too low levels of microorganisms for detection, which was also confirmed by subsequent analyses of microbial colonization, by colony counting and spectrophotometric analysis. The study further suggested that the algal frond was unevenly subjected to colonizing microbes. This relates to findings from **Paper III**, demonstrating that the nutritional content also varies between algal parts.

However, the intrinsic microbial load on seaweeds can vary considerably. For instance, Lytou et al. [71] discovered significant variations in the abundance of colonizing microorganisms across different harvesting years and species. The range of microbial counts varied widely, spanning from nearly the enumeration limit of 1.0 log CFU/g to as high as 6.7 log CFU/g. Additionally, they observed a diverse array of microbial species that were associated with various seaweed species.

Although some symbiotic relationships are beneficial for the seaweed, other interactions may instead be of a detrimental nature. The susceptibility of seaweeds to unwanted interactions with microbes has prompted them to develop an antimicrobial defence. These compounds, such as polysaccharides, polyunsaturated fatty acids, carotenoids, phlorotannins and other phenolic compounds [23], can – in addition to increasing the resilience of seaweed – also contribute to a longer shelf-life for seaweed food products. However, addressing the overgrowth of spoilage bacteria and potential pathogens on seaweed material is acknowledged as a significant challenge, and preservation is, therefore, necessary for seaweed to become more widely used as a food source [13].

The call for enhanced post-harvest treatment of seaweed

So far in this chapter, we have seen that the intrinsic microbial load on seaweed can be at a negligible level and that numerous methods for the preservation of seaweed are already commercially available. Why then is the enhancement of processing methods regarded as a crucial stride in the general discourse on introducing and expanding seaweed into Western markets?

To answer this question, it must be recognized that the emerging seaweed industry outside of Eastern Asia is as yet fragmented, safety data is scattered, and a lack of aligned standards and regulations prevails [12]. New markets come with new challenges. In the next chapter, *Chemical quality*, the status of regulations is further communicated. Although **Paper I** showed low intrinsic levels of microorganisms associated with the investigated *S. latissima*, the call for enhanced post-harvest processing arises from the variation in microbial colonization previously mentioned, favourable conditions for growth on seaweed (water activity, available nutrients), and demand for efficient processes in new markets in other climates.

Various preservation techniques have traditionally been employed to extend the shelf-life of seaweed, including sun-drying, oven-drying, freeze-drying, freezing, salting, and fermentation/ensiling. Among these methods, sun-drying is the least energy and cost intensive; however, its suitability is limited in Nordic climates due to its weather dependence [72,73]. Both oven-drying and freeze-drying require substantial energy during the dehydration process, while freezing necessitates energy consumption throughout the entire shelf-life period. As a result, alternative or streamlined approaches to these traditional preservation methods are being sought to enhance profitability and minimize waste within the seaweed industry. Importantly, the pursuit of more sustainable processing methods should be accompanied by thorough economic and environmental impact assessments, such as life cycle assessments (LCAs).

Nilsson et al. [74] showed that post-harvest treatment represents a significant environmental hotspot in the value chain of seaweed for food, material, and energy. Thomas et al. [75] conducted a comparative analysis of four preservation methods (post-harvest treatments) for seaweed. Hang-drying was found to be the most energy-efficient method, followed by ensiling, air cabinet drying, and freezing (which involves continuous energy consumption). The selection of a specific preservation method should take account of the desired final product. It is important to consider the entire supply chain when deciding on the processing method. For example, transportation of a dried product is likely to have less of a negative impact than the distribution of ensiled and frozen seaweed, which have high water content and require cooling during transportation in the case of freezing. An ambition in the circular economy, as described previously, is to design sustainable processes that render healthy products. Moreover, efficient preservation is important to avoid and minimize waste, hence complying with the circularity of food systems.

The following sections in this chapter focus on two methods for the preservation of seaweed investigated in the scope of this thesis. While fermentation is a promising *traditional* preservation method, high-pressure processing represents a more *modern* approach to treating food products.

Fermentation: a traditional technique for food preservation

The discovery of fermentation as a preservation method dates to prehistoric times, and since then, it has had some 12 000 years to be refined into what it is today [62]. What would a late August in Sweden be without "surströmming"? Or the Icelandic midwinter festival, Þorrablót, without "Hákarl"? Well, I will deliberately refrain from judging the tastiness of these fermented products, and instead focus on what it can do for seaweed.

Up to this point, the emphasis of this chapter has been on elucidating the detrimental functions attributed to microorganisms in food. However, the proliferation of desired microorganisms can render a positive effect on the food [63]. Hence, the capability of lactic acid bacteria (LAB) to ferment carbohydrates available in the brown seaweed *A. esculenta* was investigated in **Paper II**.

LAB are a group of Gram-positive, non-spore-forming rods or cocci, of which most are aerotolerant anaerobes [63]. The metabolic processes depend on one or both of two pathways: homo- and heterofermentation, the former of which results in the formation of lactate, while the latter produces lactate, acetate (ethanol), and carbon dioxide. LAB contribute to microbial inhibition in several ways, including lowering pH by organic acid metabolites, producing ethanol, diacetyl, hydrogen peroxide, and bacteriocins, and outcompeting other bacteria through nutrition depleting. LAB are postulated to bring about benign effects on food, such as enhancing the nutritional values [63].

In **Paper II** a LAB consortium comprising three strains of *Lactiplantibacillus plantarum* (relative abundance 94%) and a minor amount of a *Levilactobacillus brevis* strain (relative abundance 6%) was used in the pursuit of fermenting the brown seaweed *A. esculenta*. At first, the ability of the LAB consortium to utilize carbohydrates in brown seaweed was proven in single-substrate cultivations. Thereafter, a seaweed slurry was used as the substrate for the fermentation process.

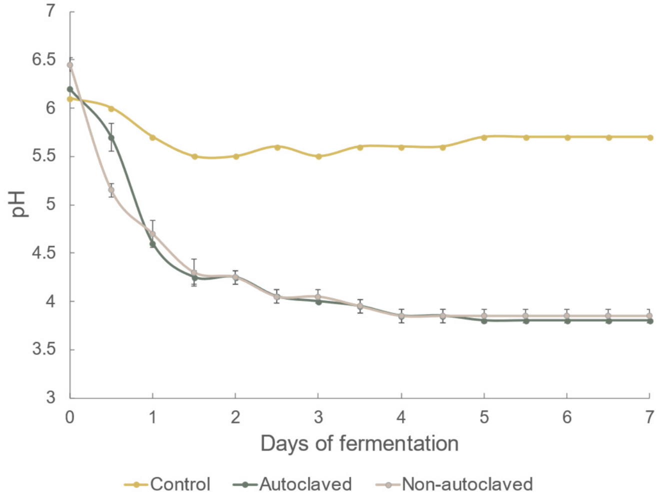
The consortium exhibited proficiency in fermenting glucose, mannitol, galactose, mannose, and xylose, with glucose and mannitol being the preferred substrates. Conversely, no growth was observed when fucose, mannuronic acid, and guluronic acid were provided as substrates. Both glucose and mannitol fermentation yielded lactic acid as the main final product. Based on the product profiles, it appears that the bacterial consortium metabolites glucose and mannitol through the Embden-Meyerhof-Parnas (EMP) pathway. In this homofermentative pathway, one unit of substrate is converted to two pyruvate units which is further reduced by lactate dehydrogenase to lactate [76]. However, mannitol utilization resulted in the co-production of small levels of ethanol and succinate (below level of quantification) which is expected as an outcome of utilizing acetate and ammonium citrate from the MRS media. Co-conversion of acetate to ethanol, and citrate to succinate and ethanol, have been reported for *L. plantarum* [77] when using mannitol as substrate, which can explain the observed results.

Given the consortium's capability to utilize free monosaccharides and laminari-oligosaccharides (DP2-4), further investigations were undertaken to explore the feasibility of directly fermenting seaweed slurries. For this, a 20% seaweed slurry (g wet seaweed/g slurry), either autoclaved or not, was inoculated with the LAB consortium (2×10^6 CFU/g slurry). The fermentation ran for seven days at 37°C and reached a pH of around 4.5 after 24 hours (Figure 4a). Similar outcomes were reached for both autoclaved and non-treated seaweed. Colony counting demonstrated good proliferation among the bacteria, which reached a density of almost 3×10^7 CFU/mL after 72 hours (Figure 4b), and no gas formation was observed. Mannitol, the most prevalent free carbohydrate in brown seaweed and the only quantifiable sugar in the slurry supernatant, was completely depleted after seven days. All dissolved mannitol was converted to lactic acid throughout the fermentation. Autoclaved control samples were subjected to growth of spoilage bacteria (relative abundance 96%), fungi (relative abundance 2.8%), and minor amounts of archaea, viruses, and eukaryotes (relative abundance 1.4%). The bacterial fraction contained a combination of spore-forming bacteria strains, with 93.76% belonging to the *Bacillus* genus and 6.23% to the *Paenibacillus* genus. Non-autoclaved seaweed slurry without LAB inoculation exhibited comparable spoilage. However, attempts to analyse its metagenome at the external lab were unsuccessful due to insufficient DNA quantities for sequencing.

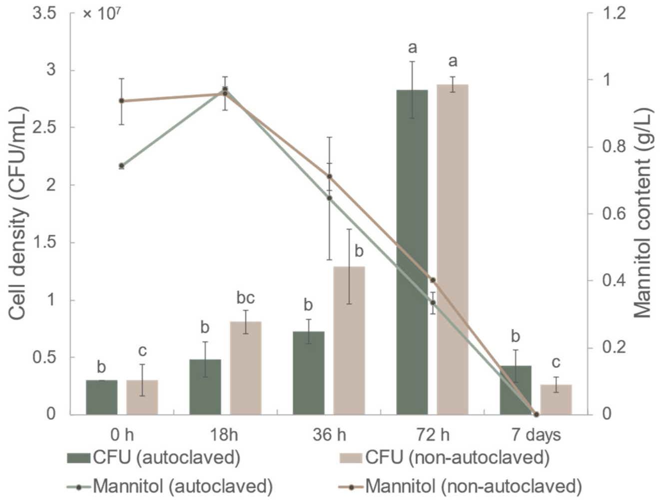
From **Paper II** we conclude that fermentation by LAB is a promising method for the preservation of seaweed. This is supported by the rapid pH decrease, the proliferation of LAB from mannitol consumption, and the observed lack of spoilage bacteria compared to the controls. However, future studies should focus on solid-state fermentation, i.e. no added water, as it is more feasible from an industrial perspective.

In addition to preservation benefits through fermentation, another proposed effect of fermenting seaweed is the enhancement of taste. Bruhn et al. [78] showed that LAB fermentation of *S. latissima* altered its characteristics by reducing the saltiness, sea smell, and slimy look. Fermentation could prove an important process step in the development of new seaweed-based food products. Therefore, more research on the subject is necessary to map the perceived sensory alterations and volatile composition after LAB fermentation.

The next section takes a giant leap in the history of processing techniques, from the traditional approach of fermenting to a more novel method of food preservation. Here high pressure is explored as a means of enhancing the microbial and physicochemical properties of seaweed.



a)



b)

Figure 4. Change in **a)** pH and **b)** cell density (CFU/mL) and substrate content (mannitol, g/L) over the course of fermentation. Adapted from **Paper II**.

High-pressure processing: a modern method of food preservation

Compared to the long-standing tradition of fermentation, which spans thousands of years, high-pressure processing (HPP) emerges as a modern addition to the range of preservation methods available.

HPP is a method employed to preserve various types of refrigerated fresh food items. It is considered a mild treatment, often considered a “natural” process by consumers, since it lacks negative associations such as chemical additives or irradiation [63].

The technique involves placing the product inside a pressure vessel, which is filled with a pressure-transmitting medium, such as re-circulating water, to achieve the desired pressure level. The product is held under this pressure for a predetermined duration before the system is depressurized, and the product is removed. The pressure is uniformly distributed throughout the sample to ensure consistent treatment. For solid products, the process is carried out in batches. HPP’s antimicrobial effects result from various changes in the associated microorganisms, such as alterations in cell morphology, biochemical reactions, and the denaturation of important enzymes. One of the advantages of HPP is that it does not involve heat, allowing the product to retain its desired nutritional and sensory properties. This maintenance of properties may be attributed to the minimal impact on covalent bonds. Currently, HPP is used for solid, semi-solid, and liquid food items, including jams, dairy products, salads, fruit and vegetable sauces, juices, smoothies, as well as mashes such as hummus and guacamole [79,80].

The microbial inactivation potential of HPP is attributed to several process parameters (pressure, time, temperature; see Table 2) and product parameters (pH, composition, water activity). The process has most effect on yeast and mould, followed by Gram-negative bacteria, Gram-positive bacteria, and lastly spores. To inactivate spores, several cycles or a moderate increase in temperature may be necessary.

Table 2. Typical process parameters for HPP treatment. Tank temperature refers to incoming process water whereas vessel temperature can be equated to product temperature. Adapted from **Paper I**.

Set pressure (MPa)	Vessel temp. (°C)		Pressure (MPa)		Pressurization time (sec)	Hold time (sec)	Decompression time (sec)
	Min	Max	Min	Max			
600	22.1	23.6	598.1	604.6	110	180	15
400	17.5	20.0	401.4	405.2	80	180	13
200	12.9	17.4	202.2	204.8	45	180	10

In **Paper I**, the preservative effect of HPP on seaweed proved difficult to evaluate. We believe that the observed inconsistency may be attributed to several factors. Firstly, working with natural material always poses a challenge, and the observed inhomogeneous microbial load on seaweed fronds causes variation between samples. To overcome this difficulty, more replicates per sample could be analysed to include the variation in the method, which, however, would imply that the current plate counting method would not be feasible. Attempts were made to develop a flow cytometry method, which could be better suited. Secondly, the low initial load of colonizing microorganisms may indicate that the analysis is performed below the quantification limit. However, from a food perspective, a low initial load is the best result possible. Thirdly, our theory is that three independent variables influence the HPP treatment of seaweed:

1. How the pressure harms the colonizing microorganisms,
2. How the pressure activates spore germination, and
3. How nutrients are dispersed in the matrix.

This suggests that different pressures can have different effects on seaweed and its microflora, while the three variables also follow diverse kinetics, which cause inconsistent results. Additionally, the vacuum packaging itself maintains an oxygen depleted environment around the seaweed, hindering growth of microorganisms and facilitating a prolonged shelf-life.

Although the preservative effect of HPP was indistinct, the influence on the texture and structure of treated seaweed was noticeably apparent. The hardness of seaweed material decreased by up to 87.7% when applying 600 MPa pressure (74.0% and 67.7% when applying 400 MPa and 200 MPa pressure, respectively). The compression (chewiness) followed a similar pattern, decreasing by 60.0%, 49.1%, and 38.2% when applying 600, 400 and 200 MPa, respectively (Figure 5). Similar to texture alterations, variations in the structure of the seaweed were observed using scanning electron microscopy (SEM) when comparing untreated and pressurized (600 MPa) seaweed (note that the brown seaweed *A. esculenta* was used instead of *S. latissima* for this analysis). Figure 6 shows that the smooth surface in untreated material transforms into a more irregular structure after pressure treatment at 600 MPa.

This alteration in texture and structure caused by high pressure is likely attributed to the modification of the specific arrangements of protein and carbohydrate biopolymers in the algae. The disruption of carbohydrate structures can lead to gelatinization, a phenomenon that has been observed to intensify with higher pressure levels [81].

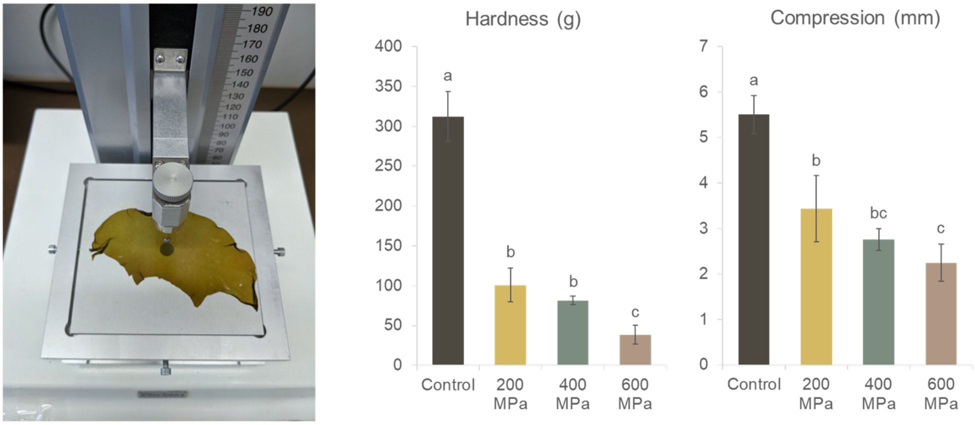
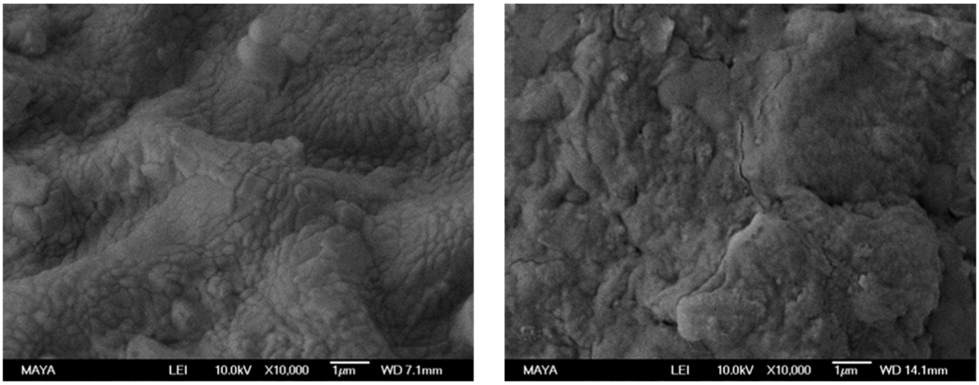


Figure 5. Experimental set up of texture analysis and resulting outcomes corresponding to hardness and compression (chewiness) of pressure treated and untreated *Saccharina latissima*.



a) **b)**

Figure 6. Structural images of **a)** untreated, and **b)** pressure treated (600 MPa) brown seaweed *Alaria esculenta* by scanning electron microscopy (SEM).

This chapter has covered the challenge of the microbial quality of seaweed, attributed to its complex associations with surrounding microorganisms and high water content and water activity. Although microbial colonization can be initially low, efficient techniques must be applied to prolong the shelf-life of seaweed. Fermentation is a promising method to enhance the stability and sensory properties of seaweeds, and HPP has been shown to alter its texture and structure. To further understand the efficiency of these, and forthcoming, preservation methods, long-term stability studies must be conducted together with investigations of the effect on perceived sensory properties and changes in chemical composition.

In the next chapter, we focus on the chemical hazards associated with seaweed consumption.

Chemical quality

"*Seaweed is a contradictory phenomenon and is described as healthy and useful, but also as dirty and toxic*" – this fascinating interpretation of seaweed, reflecting consumer attitudes towards these sea vegetables, was described in Merkel et al. [35].

In the previous chapter, the microbial quality of seaweed was addressed, and in this section, our focus will instead shift to an adjacent aspect – the chemical quality of seaweed. Since the nutritional content was covered previously, this chapter is exclusively dedicated to the chemical safety aspects of consuming seaweed. What is underlying the views of seaweed being "dirty and toxic"?

In 2020, the World Health Organization (WHO) presented a list of 10 chemicals of public health concern that we may encounter in our everyday lives (Figure 7) [82]. Four of these compounds – arsenic, cadmium, mercury, and lead, all well known for their toxicity – are often referred to as potentially toxic elements (PTEs) or non-essential minerals in these circumstances. Adding to this, another element found at potentially toxic levels in certain seaweed species is iodine. Drawing from our present understanding of algae, the most significant hazards are posed by cadmium, arsenic, and elevated levels of iodine.

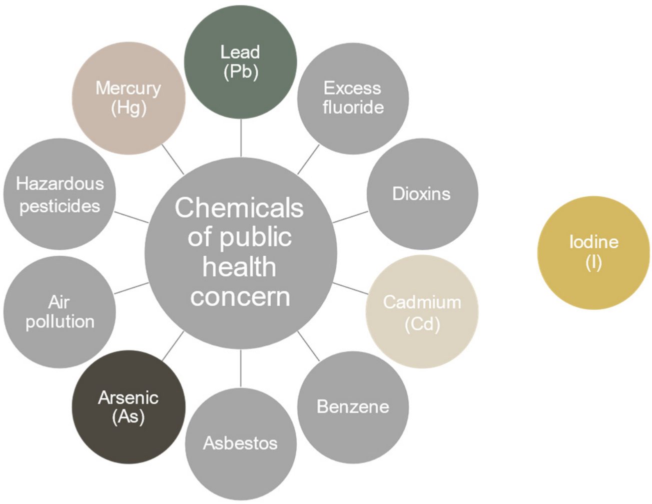


Figure 7. WHO's list of "chemicals of public health concern" [82] and iodine which exerts a potential hazard in some seaweed species.

The occurrence of PTEs in foods, whether from natural or anthropogenic sources, has raised concerns within the European Food Safety Authority (EFSA) [83,84]. In seaweeds, these compounds may occur at elevated levels, depending on several factors, such as the type and physiology of the seaweed, cultivation season and site, harvesting methods and processing [83]. It is therefore of great importance to map the levels of PTEs in seaweeds when expanding the seaweed market.

Despite the concerns about PTEs in foods, regulations and guidance documents pertaining to the cultivation and utilization of seaweed are still lacking in the EU. However, the French Agency for Food, Environmental and Occupational Health and Safety (ANSES) and the Algae Technology and Information Centre (CEVA) have determined acceptance limits (Figure 8) for several PTEs in seaweed [85,86], and EFSA guidelines specify tolerable weekly intake levels of these elements [87-91]. We revisit these thresholds in the section titled *Potential health risks of seaweed consumption*.

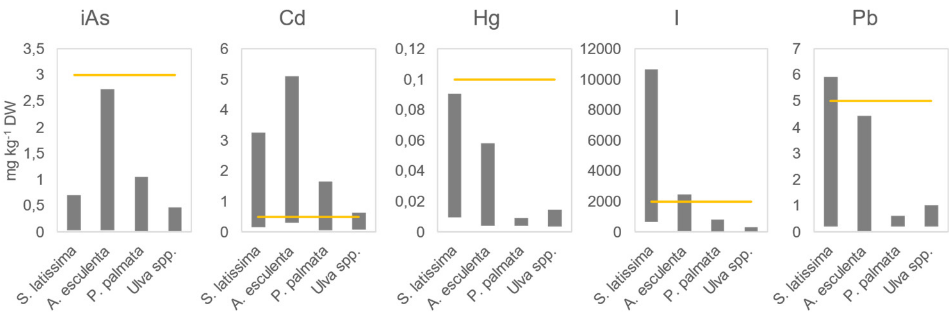


Figure 8. Normal ranges of potentially toxic elements in four seaweed species (grey bars; data obtained from Duinker et al. [92]) with respective acceptance limit (orange lines) according to ANSES [85] and CEVA [86].

The following sections of this chapter dive deeper into factors influencing the uptake of PTEs in seaweed, and how they distribute depending on species, growth site and thallus age, as well as discussing their potential health hazards. The primary way of limiting PTEs in seaweed is to minimize their exposure to these elements, by for instance the choice of cultivation sites. However, in the final section of this chapter, strategies for removal of PTEs from seaweeds are discussed.

Factors affecting seaweed's uptake of potentially toxic elements

In the previous chapter about the microbial quality of seaweed, an intra-species variation of microbial colonization was observed. This chapter further demonstrates that both intra-species and inter-species variation of chemical hazards occur for seaweed. And just like the uptake mechanisms of different PTEs appear to vary, so does the effectiveness of studied extraction methods in removing these substances. To better understand the chemical variations of seaweed, it should first be clarified how seaweeds grow and what uptake mechanisms exists.

Unlike many terrestrial plants, algae acquire nutrients directly from the surrounding water and do not rely on root-like functions [93]. Seaweed has adjusted to a life in water, and the uptake of nutrition is instead directly associated with all thallus tissue.

Species within the three classes of seaweeds exhibit different growth patterns, and variances in differently aged tissue are best evaluated from kelps due to their longitudinal growth. Hence, the brown seaweed *S. latissima* was predominantly investigated in **Paper III.** *S. latissima* expands longitudinally, by basal growth, from the meristematic tissue located above the stipe (Figure 9). Proximal (basal) regions of the lamina correspond to younger tissue compared to the older distal (top) parts. Therefore, different parts of the algae represent tissue of various age [94]. Contrary to brown seaweeds, red and green species demonstrate different growth patterns. The red seaweed *P. palmata* relies on apical growth, meaning the meristematic cells reside in the marginal tissue, facilitating vegetative expansion and the development of new fronds from old thalli [95,96]. The green seaweed *U. lactuca* lacks a distinct localized meristem and instead expands uniformly through diffuse growth across the blade in all directions [96].

By analysing *S. latissima* from three growth sites, different parts of *S. latissima* from one seaweed farm, and four different species (*S. latissima, A. esculenta, P. palmata,* and *U. lactuca*) in **Paper III**, we concluded that factors influencing the PTE levels include the algal growth location, tissue age, and species (Figure 10). Blikra et al. [97] further demonstrated variations in PTE content in *S. latissima* dependent on cultivation depth.

One interesting observation was the low levels of cadmium in old tissue from *S. latissima* (**Paper III**). This was believed to relate to the low content of alginate and high level of mannitol. Also, high levels of inorganic arsenic were observed in Irish brown seaweed. However, **Paper III** should be considered a snapshot of the PTE levels in studied samples. To obtain a full picture of the prevalence of PTEs in seaweed, a comprehensive collection of data from different sites, species, harvesting years and seasons, growth depths, tissue parts and age is required.

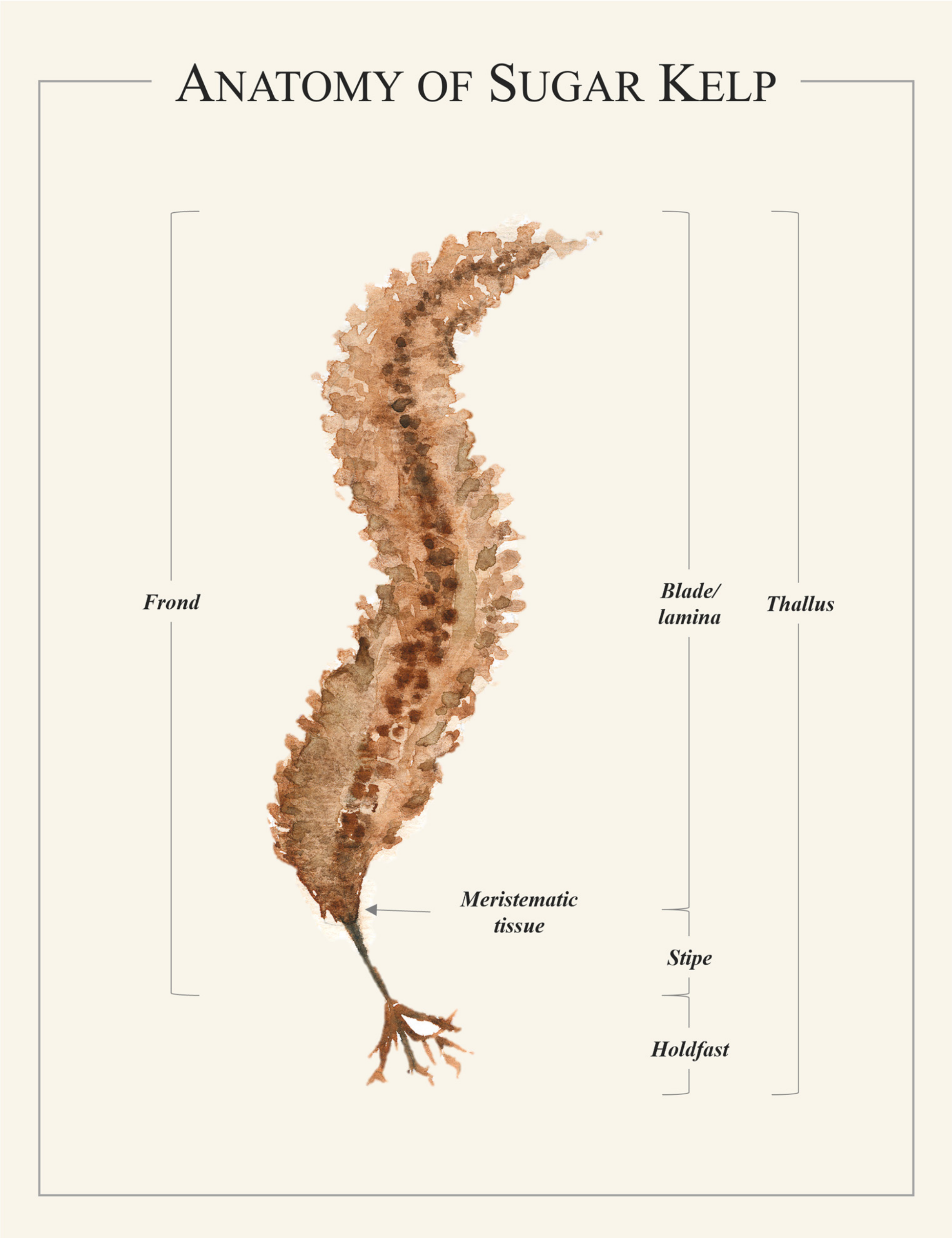


Figure 9. Anatomy of sugar kelp (*Saccharina latissima*). The term “blade” includes the tissue from above the stipe, whereas “frond” includes the stipe and the blade, and the term “thallus” includes the whole algal body with blade, stipe, and holdfast. Longitudinal growth occurs from the meristematic tissue. The holdfast resembles the roots of terrestrial plants, but only acts as an anchor to avoid drifting with currents and does not serve as the centrum for nutrition uptake. The uptake of nutrition is instead directly associated with all thallus tissue.

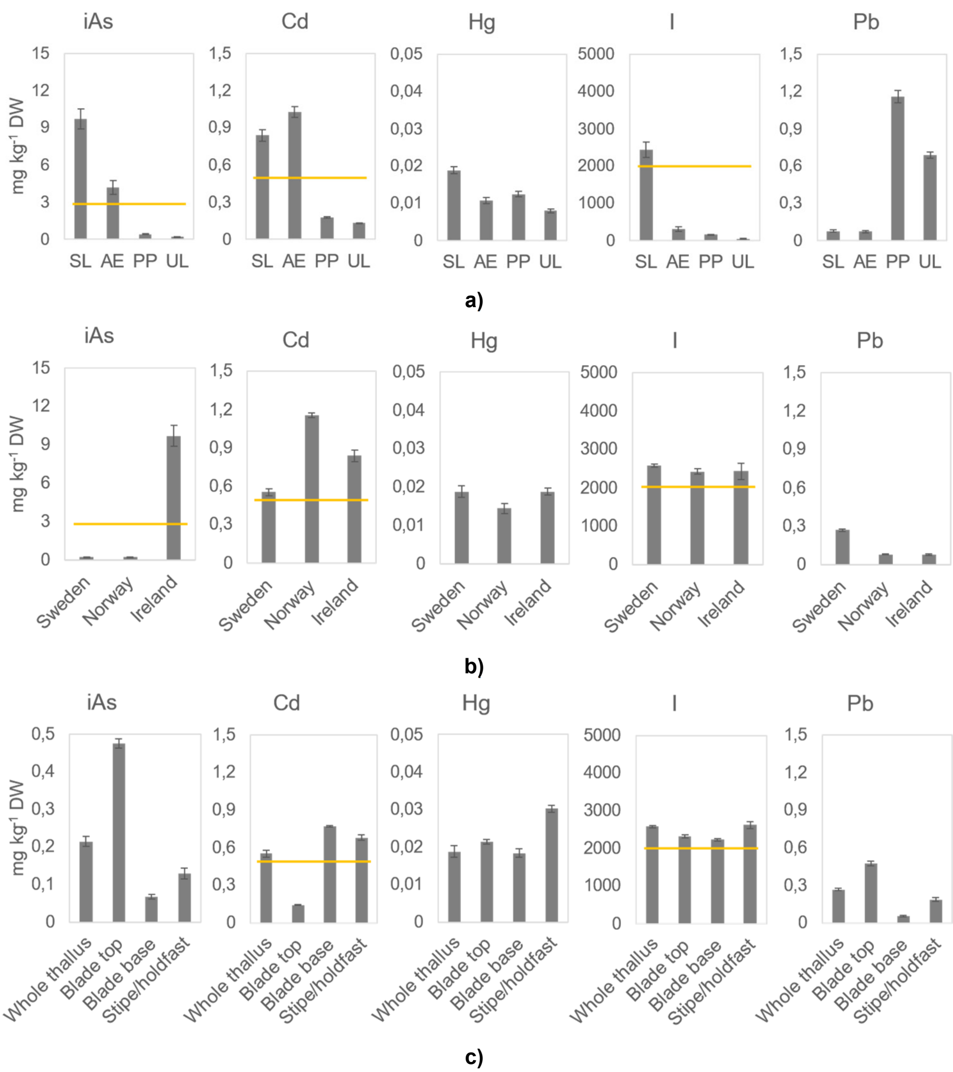


Figure 10. PTE variation in seaweed depends on **a)** species, **b)** spatial, and **c)** thallus part/age factors. Swedish *Saccharina latissima* harvested in 2021 was used in **b–c**. Values are given as mean ± standard deviation. Adapted from **Paper III**.

The nutritional uptake by seaweeds is explained by several biosorption mechanisms (Figure 11). The process of biosorption in seaweed is attributed to surface precipitation, complexation, or ion-exchange mechanisms, which have been primarily studied in brown seaweed [98,99]. The uptake of elements by algae is attributed to their structural and functional compounds, such as the cell wall polysaccharides. Particularly, the presence of functional groups such as carboxyl, hydroxyl, sulphate, phosphate, and amine groups in these polysaccharides play a crucial role in metal binding. Ion exchange is an important mechanism for the biosorption of heavy metals, replacing lighter metals (particularly Ca^{2+} and Mg^{2+}, as monovalent ions like Na+ and K+ cannot form strong cross-linkages). Alginates exhibit a higher affinity for divalent cations. The binding affinity of alginates and fucoidan to metal ions depends on stereochemical effects, with larger ions (such as $Pb^{2+} > Cu^{2+} > Cd^{2+} > Zn^{2+} > Ni^{2+} > Ca^{2+} > Mg^{2+}$) having a stronger binding tendency to two distant functional groups [98,100]. Nonetheless, in **Paper III**, it was observed that cadmium exhibited stronger binding to alginate compared to lead, suggesting that electronegativity may influence the process.

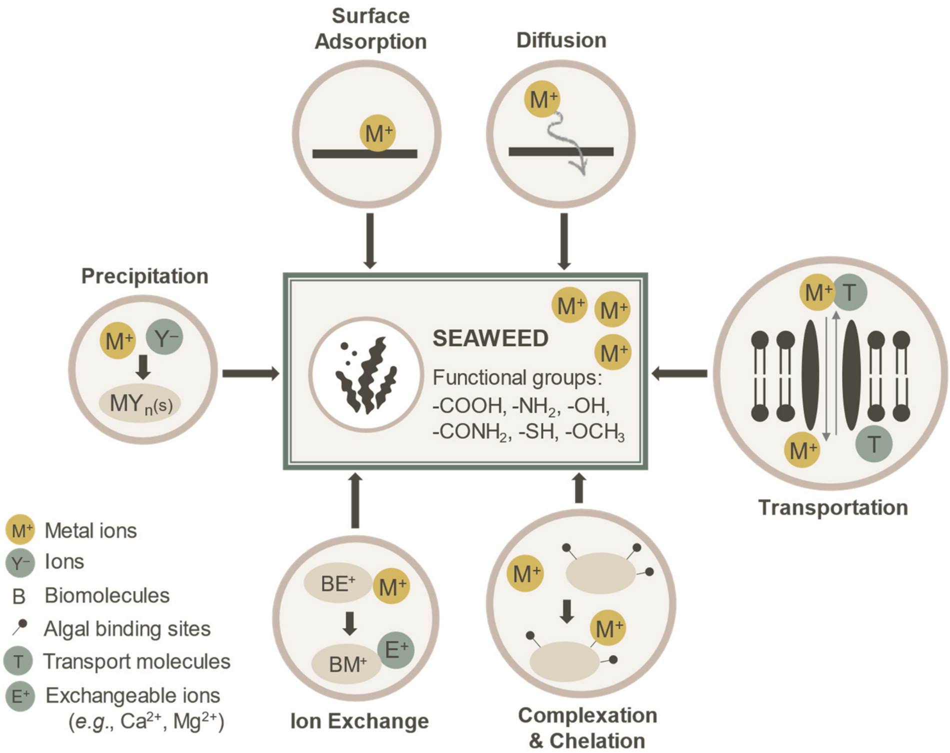


Figure 11. Seaweed's uptake mechanisms (adapted from Sud et al. [99] and He and Chen [98]).

In **Paper III**, we hypothesize that cadmium and mercury, which associated strongly with studied seaweeds, might interact with alginate, particularly the M-blocks, through complexation and/or ion exchange. Previous research has shown that mercury interacts with carboxylate groups in seaweed [101,102] and cadmium is incorporated through chelation [103]. In **Paper III**, lead was postulated to interact through ion exchange or complexation, favouring interaction with polysaccharides found in green and red species. According to Raize, Argaman, and Yannai [103], the binding mechanisms of lead exert a mix of ion exchange, chelation, reduction reactions, and precipitation. In **Paper III** we further hypothesized that inorganic arsenic, total arsenic, as well as sodium and iron (found in significant levels in the ash fraction) bind to macroalgae through surface precipitation and potentially form weak bonds with alginate. This was concluded because they were easily removed during processing. According to Roleda et al. [101], the uptake of arsenic is attributed to both adsorption and active uptake dependent on metabolic mechanisms.

In summary, factors influencing seaweed's uptake of PTEs include species, growth sites, growth depth, thallus age, as well as the mechanisms for uptake and accumulation. These factors are directly important to consider for seaweed farmers and product developers when introducing and expanding seaweed products on new markets. We conclude from **Paper III**, in line with previous research [83,104], that iodine and cadmium are the main concerns for seaweed consumption and that some Irish seaweed species exhibit high levels of inorganic arsenic. Consequently, the next section focuses on the potential health risks of consuming seaweed.

Potential health risks of seaweed consumption

The PTE analysis of seaweed samples in **Paper III** (as shown in Figure 10) reveals that the primary elements of concern in the examined seaweeds are iodine and cadmium. This observation is in line with the normal range reference values reported in an extensive study conducted by Duinker et al. [92] (as depicted previously in Figure 8). However, the content of inorganic arsenic in some Irish species in **Paper III** was observed to surpass the limits and normal values. It is further worth noting that lead levels in specific types of seaweed also occasionally surpass the established acceptance limits. Accordingly, considering occasionally elevated levels of various PTEs in seaweeds, it is crucial to comprehend their potential health impacts on human consumption.

Iodine is an essential element required for the normal function of thyroid hormones in humans. However, chronic excessive intakes of iodine can lead to thyroid disorders including hypothyroidism or hyperthyroidism, autoimmune thyroiditis, and thyroid cancer [105-107]. A sufficient intake of 150 µg/day is proposed for adults, with a tolerable maximum level of 600 µg/day [87,105]. Iodine found in brown algae predominantly exists as iodide (I^-), although some species contain organically bound iodine and oxidized forms (iodate, IO_3^-). The bioavailability of iodine from brown algae is notably substantial, ranging from 31% to 90%, as determined by in vivo bioavailability studies [108]. In line with the literature, **Paper III** shows that *S. latissima* contains the highest levels of iodine of the studied species, allowing a tolerable consumption of only 0.2 g for an average 70 kg adult based on EFSA's levels. In contrast, the corresponding amount of *U. lactuca* is 14 g.

Cadmium, which can also constitute a limiting factor for the usability of seaweed, occurs in the environment from both natural and anthropological origins. The severe effects of excess cadmium intake are primarily linked to the liver and kidney, as their tissue is particularly sensitive to the toxic effects of cadmium and can bioaccumulate over time [89,109]. Hence, EFSA states a tolerable weekly intake level of 2.5 µg/kg body weight (b.w.) [89]. According to **Paper III**, the cadmium levels in seaweed are both species and site dependent. Based on the EFSA limits, a daily intake of 24 g *A. esculenta* (Ireland) and 22 g of *S. latissima* (Norway) is considered tolerable for an average 70 kg adult.

Another element of concern in seaweed is arsenic. The levels of inorganic arsenic in Swedish *S. latissima* (~200 µg/kg DW) was found to be slightly higher than for rice (63-117 µg/kg DW) (**Paper III**, [110]). Organic forms of arsenic are generally considered less toxic than their inorganic counterparts, although potential toxicity occurs [106,111,112]. Adverse effects associated with inorganic arsenic are related to DNA damage, potentially rendering carcinogenesis of the cell. Bladder, skin, lung, and kidney cancers are the main types of cancers reported [106,111]. EFSA does not provide a tolerable limit for arsenic in food and considers the previous limit of 15 µg/kg b.w. [88] to be no longer appropriate. However, comparing the levels of inorganic arsenic in the species studied in **Paper III** with maximum levels provided by ANSES and CEVA, it appears arsenic should not be a main concern as a chemical food hazard, although caution should be exercised regarding the source of the seaweed. The toxicology of organic arsenics in seaweeds may need to be investigated further.

Less food safety concern is directed towards lead and mercury in seaweed. For lead on the one hand, EFSA does not provide a tolerable limit and considers the previous limit of 25 µg/kg b.w. [91] to be no longer appropriate. For inorganic mercury, on the other hand, EFSA has established a tolerable weekly intake level of 4 µg/kg b.w. [90]. From **Paper III**, there appears to be no immediate risk of ingesting elevated levels of lead and mercury when consuming seaweed.

Overall, more clinical data on seaweed toxicology is needed to establish reasonable limits in Europe, where regulations are presently fragmented. A pilot food safety study was completed by the University of Bergen in 2023 [113], and a study on iodine bioavailability was conducted by the University of Glasgow [114].

Considering the significant levels of iodine and cadmium in some species of seaweed, it may become useful to include post-harvest removal of PTEs from seaweed, and therefore the following section demonstrates the efficiency of PTE-removal employing non-destructive extraction methods suitable for industrial use.

Removal of potentially toxic elements from seaweed

Several methods can be used for the removal of PTEs in seaweed. However, most methods are not selective for a certain element, and will consequently co-extract other compounds in seaweed. The level in the biomass after extraction is therefore relative to what it was before extraction. In the scope of this thesis, six methods for PTE removal were evaluated using *S. latissima* harvested in Sweden in April 2021. By employing non-destructive removal methods suitable for industrial use, a decrease in total ash content can be achieved, while reducing total arsenic by 61%, inorganic arsenic by 92%, lead by 49%, and iodine by 73% (**Paper III**; Table 3). Among the various methods tested for reducing PTEs in seaweed, heat-assisted extraction demonstrated the highest effectiveness overall. Below follows an overview of the different methods.

High-pressure processing

Fresh seaweed material was subjected to a set pressure of 600 MPa for 180 seconds. The actual parameters are presented in Table 2. After the treatment by high pressure, the biomass was washed with 3 sets of 500 mL distilled water to eliminate any potential extractives. The remaining material was freeze-dried, ground, and sieved through a 2 mm mesh.

High pressure significantly reduced four out of the six PTEs analysed. However, it led to a considerable concentration of cadmium in the algal material. Only HPP and heat-assisted extraction (HAE) proved capable of reducing the levels of iodine below the recommended maximum level, indicating that treatment with high pressure or high temperature for a certain time is required for its removal.

Soaking in water and mild acid

The process of soaking in water and mild acid played out very similarly. Thawed frozen seaweed material was mixed with either Milli-Q water or 3%(v/v) acetic acid at a concentration of 25% (g wet seaweed/ mL extraction medium). The extraction was carried out at 30°C for 30 minutes. Thereafter, the water was sieved off from the seaweed and the solids were pooled together and rinsed three times in 500 mL of distilled water. The seaweed was lyophilized, ground, and sieved through a 2 mm mesh.

Soaking with water and mild acid proved to successfully remove total and inorganic arsenic. The other compounds had a relative concentrating effect. Interestingly, when comparing soaking in water and soaking in acid, it was evident that lead was better extracted in acidic conditions, whereas cadmium and iodine were better removed by water.

Ultrasound-assisted extraction

Thawed frozen seaweed material was mixed with Milli-Q water at a ratio of 25% (g wet seaweed/ mL water). The ultrasound treatment was performed in a water bath for 2 hours at a temperature of 30°C. The temperature of the water in the bath was increased to a maximum of 48°C during the process. Thereafter, the water was sieved off from the seaweed and the solids were pooled together and rinsed three times in 500 mL of distilled water. The seaweed was lyophilized, ground, and sieved through a 2 mm mesh.

Extraction by ultrasound followed a similar pattern to soaking in water, but with better removal of lead and iodine.

Heat-assisted extraction

Thawed frozen seaweed material was mixed with Milli-Q water at a ratio of 25% (g wet seaweed/ mL water). The heat-assisted extraction was performed in a water bath for 30 min at a temperature of 100°C. Thereafter, the water was sieved off from the seaweed and the solids were pooled together and rinsed three times in 500 mL of distilled water. The seaweed was lyophilized, ground, and sieved through a 2 mm mesh.

Heat-assisted extraction demonstrated the highest effectiveness overall. It successfully decreased the levels of iodine, total arsenic, and inorganic arsenic, while the concentration of cadmium and lead remained unchanged. Combining HAE with acid treatment could potentially extract lead with higher effectiveness.

Blanching

Recently, blanching has been extensively evaluated for its potential to remove iodine in brown seaweed. In **Paper III**, thawed frozen seaweed material was immersed in 80°C distilled water for 2 min using a sieve. Pressure on top of the sieve made sure all algal samples were submerged in the water. Immediately after processing, the samples were cooled down and washed in 1.5 L of 12°C distilled water.

Blanching was able to remove a significant amount of iodine, but not to a level below acceptance criteria. Like the other methods studied, blanching efficiently removed total and inorganic arsenic.

Blanching has, as mentioned, recently been extensively studied for its potential to remove iodine from brown algae. Nielsen et al. [115] removed up to 94% of iodine from Norwegian *S. latissima* by blanching for 120 sec at 80°C. Trigo et al. [116] showed a slightly lower relative extraction yield of 85% under the same conditions. However, the Swedish seaweed material used had almost half as much iodine in the initial unprocessed material. Krook et al. [117] performed a similar fresh water extraction at 45°C for 120 sec using Norwegian *S. latissima* which resulted in a 73% iodine reduction. Based on this, why do we merely obtain a 15% reduction of iodine in **Paper III** when other studies achieve 73–94%? One methodological difference is that Nielsen et al. [115], Trigo et al. [116], and Krook et al. [117] use fresh seaweed for the blanching, while in **Paper III** the seaweed is frozen prior to the processing. Accordingly, my theory is that this methodological variation accounts for the difference in results. Since the iodine content is relative to the content of the biomass in total (hence all other compounds), a larger reduction in total ash together with concentration of total carbohydrates (to which the iodine is hypothesized to complex bind) gives a lower relative reduction.

Overall, blanching seems to be a feasible method primarily for the reduction of iodine in seaweed [108,115-119].

Other techniques

Available literature on the topic of reducing the content of PTEs in seaweed presents several other removal techniques, including pulsed electric field (PEF), soaking in hypersaline water, microwave-assisted extraction (MAE), freeze-thawing, and combination methods. Different techniques have proved capable of reducing the various PTEs to different extents, as exemplified in Table 3. MAE reduced 78% of inorganic arsenic, but neither PEF nor freeze-thawing were outstanding in their removal rates.

Previous knowledge shows that iodine followed by cadmium are limiting the acceptable daily intake levels of seaweed and are the most challenging elements to remove (**Paper III**). From Table 3, it becomes evident that the species and harvesting occasion influences the initial concentrations of iodine considerably (213–7977 mg/kg DW). And several methods can exert a relative reduction of up to 93.6%. However, when it comes to cadmium, the efficiency in processing is not as evident, with several methods even posing a relative concentrating effect. Among the “other methods”, a combination technique using the chelator EDTA (ethylenediaminetetraacetic acid) together with ultrasound has proved to be most effective, reducing the cadmium levels by up to 52%. Also, soaking in hypersaline water and fermentation were effective in removing cadmium (41% and 35% reduction, respectively). To further reduce the concentration of cadmium in seaweed, further studies building on the current knowledge should be performed.

Table 3. Overview of the effectiveness of removing PTEs from seaweed by processing. For further details on harvest sites, harvest time, handling procedures, and methods for elemental analysis, see respective reference.

Processing method	Seaweed species	Parameters	Pre-processing levels (mg/kg DW)	Post-processing levels (mg/kg DW)	Relative change (%)	Ref.
HPP	*Saccharina latissima*	600 MPa, 20°C, 3 min	tAs: 61.7 iAs: 0.214 Cd: 0.554 Hg: 0.0188 Pb: 0.269 I: 2 580	tAs: 41.3 iAs: 0.0798 Cd: 1.15 Hg: 0.0348 Pb: 0.136 I: 701	tAs: -33.1 iAs: -62.7 Cd: +108 Hg: +85.4 Pb: -49.2 I: -72.8	Paper III
Soaking	*Saccharina latissima*	20% wet seaweed in water, 30°C, 30 min	tAs: 61.7 iAs: 0.214 Cd: 0.554 Hg: 0.0188 Pb: 0.269 I: 2 580	tAs: 24.9 iAs: 0.0298 Cd: 0.869 Hg: 0.0265 Pb: 0.893 I: 3 610	tAs: -59.7 iAs: -86.1 Cd: +56.9 Hg: +41.1 Pb: +232 I: +39.9	Paper III
	Sargassum fusiforme	1:10 seaweed leaves in tap water, 20 min	tAs: 231.0	tAs: 96.5	tAs: -58.2	[120]
	Saccharina latissima	20% wet seaweed in diluted acetic acid, pH 3, 30°C, 30 min	tAs: 61.7 iAs: 0.214 Cd: 0.554 Hg: 0.0188 Pb: 0.269 I: 2 580	tAs: 32.5 iAs: 0.0263 Cd: 1.08 Hg: 0.0361 Pb: 0.379 I: 4 320	tAs: -47.4 iAs: -87.7 Cd: +95.2 Hg: +92.5 Pb: +41.0 I: +67.7	Paper III
	Saccharina latissima (2015-06)	5kg/100L fresh water, 32°C, 60 min	iAs: 0.23 Cd: 0.27 I: 6 568	I: 800	I: -87.8	[107]
	Alaria esculenta (2015-05)	5kg/100L fresh water, 16°C, 22h	iAs: 0.22 Cd: 2.01 I: 213	Cd: 2.9	Cd: +30.7	[107]
	Alaria esculenta (2016-05)	1kg/20L hypersaline water (2 M NaCl), 120 min, 16°C	Cd: 1.55	Cd: 0.92	Cd: -40.6	[107]
	Saccharina latissima	1:30 seaweed in tap water, 12°C, 2 min	tAs: 60.0 iAs: 0.119 Cd: 0.360 Hg: 0.021 Pb: 0.147 I: 2 648	tAs: 58.3 iAs: 0.079 Cd: 0.335 Hg: 0.023 Pb: 0.075 I: 2 749	tAs: -2.8 iAs: -33.6 Cd: -6.9 Hg: +8.7 Pb: -48.3 I: +3.7	[116]

Processing method	Seaweed species	Parameters	Pre-processing levels (mg/kg DW)	Post-processing levels (mg/kg DW)	Relative change (%)	Ref.
	Saccharina latissima	0.7kg/7L water (repeated 3 times)	tAs: 62.7 Cd: 1.77 Hg: 0.0323 Pb: 0.446 I: 4 100	tAs: 50.8 Cd: 2.05 Hg: 0.0424 Pb: 0.946 I: 3 600	tAs: -19.0 Cd: +13.7 Hg: +23.8 Pb: +52.9 I: -12.2	[97]
UAE	*Saccharina latissima*	20% wet seaweed in water, 30°C, 120 min	tAs: 61.7 iAs: 0.214 Cd: 0.554 Hg: 0.0188 Pb: 0.269 I: 2 580	tAs: 25.5 iAs: 0.0208 Cd: 0.751 Hg: 0.0293 Pb: 0.290 I: 2 510	tAs: -58.8 iAs: -90.3 Cd: +35.7 Hg: +56.4 Pb: +7.7 I: -2.8	Paper III
	Sargassum fusiforme	Ambient temperature 120 min	tAs: 83.96	tAs: 19.00	tAs: -77.4	[121]
	Laminaria hyperborea	50°C, 5 min, with addition of 1N EDTA	-	-	tAs: -32 Cd: -52 I: -31	[118]
HAE	*Saccharina latissima*	20% wet seaweed in water, 100°C, 30 min	tAs: 61.7 iAs: 0.214 Cd: 0.554 Hg: 0.0188 Pb: 0.269 I: 2 580	tAs: 24.0 iAs: 0.0162 Cd: 0.541 Hg: 0.0243 Pb: 0.275 I: 773	tAs: -61.2 iAs: -92.4 Cd: -2.4 Hg: +29.6 Pb: +2.2 I: -70.0	Paper III
	Sargassum fusiforme	100°C, 120 min	tAs: 83.96	tAs: 12.15	tAs: -85.5	[121]
	Saccharina latissima	0.5kg/5L water, 90-100°C, 15 min	tAs: 62.7 Cd: 1.77 Hg: 0.0323 Pb: 0.446 I: 4 100	tAs: 36.0 Cd: 2.19 Hg: 0.0280 Pb: 1.16 I: 600	tAs: -42.5 Cd: +19.2 Hg: -13.3 Pb: +61.6 I: -85.4	[97]
	Saccharina latissima	Thawed seaweed, 200g/750mL water, 95°C, 15 min, cooled to 37°C	tAs: 39.06 Cd: 3.03 Hg: 0.023 Pb: 0.82	tAs: 42.27 Cd: 3.61 Hg: 0.021 Pb: 1.06	tAs: +7.8 Cd: +16.1 Hg: -8.7 Pb: +22.6	[78]
Blanching	*Saccharina latissima*	80°C, 2 min	tAs: 61.7 iAs: 0.214 Cd: 0.554 Hg: 0.0188 Pb: 0.269 I: 2 580	tAs: 34.7 iAs: 0.0303 Cd: 0.941 Hg: 0.0284 Pb: 0.254 I: 2 180	tAs: -43.8 iAs: -85.9 Cd: +69.9 Hg: +51.5 Pb: -5.3 I: -15.4	Paper III

Processing method	Seaweed species	Parameters	Pre-processing levels (mg/kg DW)	Post-processing levels (mg/kg DW)	Relative change (%)	Ref.
	Saccharina latissima	1:30 seaweed in tap water, 80°C, 2 min	tAs: 60.0 iAs: 0.119 Cd: 0.360 Hg: 0.021 Pb: 0.147 I: 2 648	tAs: 40.0 iAs: 0.082 Cd: 0.695 Hg: 0.035 Pb: 0.584 I: 373	tAs: -33.3 iAs: -31.1 Cd: +48.2 Hg: +40.0 Pb: 74.8 I: 85.9	[116]
	Saccharina latissima	80°C, 2 min	I: 4 605	I: 293	I: -93.6	[115]
	Saccharina latissima	1kg/5L water, 45°C, 2 min	tAs:46 iAs: 0.067 Cd: 0.21 Hg: 0.01 Pb: 0.05 I: 7 977	tAs: 34 iAs: 0.063 Cd: 0.42 Hg: 0.03 Pb: 0.12 I: 2189	tAs: -26.1 iAs: -6.0 Cd: +50.0 Hg: +66.7 Pb: +58.3 I: -72.6	[117]
MAE	*Sargassum fusiforme*	80°C, 1 h	tAs: 83.96	tAs: 18.57	tAs: -77.9	[121]
PEF	*Saccharina latissima*	0.5kg/5 L, 20°C, 24 kV electrode voltage, 30 Hz frequency, 6 µs pulse width	tAs: 71 Cd: 2.1 Hg: 0.029 Pb: 0.9 I: 4 700	tAs: 63 Cd: 1.9 Hg: 0.023 Pb: 1.8 I: 2 700	tAs: -11.2 Cd: -9.5 Hg: -20.7 Pb: +50 I: -42.6	[122]
Fermen-tation	*Saccharina latissima*	Thawed heat-treated seaweed [7], 200g/750mL water, 37°C, 48 h, *Lactoplanti-bacillus plantarum*	tAs: 39.06 Cd: 3.03 Hg: 0.023 Pb: 0.82	tAs: 36.75 Cd: 1.96 Hg: 0.015 Pb: 0.91	tAs: -5.91 Cd: -35.3 Hg: -34.8 Pb: +9.9	[78]
Freeze-thawed	*Saccharina latissima*		I: 4 605	I: 4 057	I: -11.9	[115]
	Saccharina latissima		tAs: 71 Cd: 2.1 Hg: 0.029 Pb: 0.9 I: 4 700	tAs: 65 Cd: 2.2 Hg: 0.026 Pb: 1.4 I: 4 400	tAs: -8.5 Cd: +4.5 Hg: -10.3 Pb: +35.7 I: -6.4	[122]

HPP: High-pressure processing. UAE: Ultrasound-assisted extraction. HAE: Heat-assisted extraction. MAE: Microwave-assisted extraction. PEF: Pulsed electric field.

In summary, this chapter has provided insight into the chemical quality of seaweeds relevant to the scope of this thesis. For safe consumption of seaweed, measured selections of species and growth sites are important principal strategies. Scalable methods for the removal of elements have also proven efficient for several elements, including arsenic (total and inorganic), lead and iodine, whereas cadmium and mercury are more difficult to remove. Hence, more studies on the removal of these elements are of interest for the future. All in all, iodine and cadmium pose the largest threat to safe seaweed consumption. However, to verify this, more studies on bioavailability are imperative and acceptance limits should be revised and unified within the EU.

In this and the previous chapter, chemical and microbial challenges associated with seaweed have been discussed and suggestions for improvements have been laid out. The third challenge of introducing seaweed into Western markets covered by this thesis relates to its acceptance by the consumers. Hence, in the following chapter, seaweeds' sensory quality will be discussed.

Sensory quality

In this chapter, the navigation of challenges and opportunities across the value chain from seaweed production to consumption in emerging food markets culminates as it reaches the ultimate destination – the consumer. Seaweed consumption is intimately connected to social elements including acceptance, availability, choice, and food practices [59]. Overall, consumers in Western societies appear to hold a positive attitude to eating seaweed [7,123], but the action of consumption can be hindered by the intention-behaviour gap [124-126], which proposes that one's actions do not align with one's intentions.

On the one hand, several values have previously been reported to drive the intention to eat seaweed in Western societies. Birch et al. [127] recognized that factors such as education, familiarity, willingness to try new food, the symbolic value of food consumption, health awareness, and snacking habits significantly influenced the probability of consuming seaweed products. The main drivers for the intention to consume seaweed include healthiness, pro-environmental sustainability, and tastiness [7,123,128,129] as well as being natural and unique [124,128].

On the other hand, many elements have been shown to hinder the actual behaviour of implementing seaweed consumption in daily practices. These elements include price, taste, side effects, packaging, neophobia, lack of knowledge, accessibility and familiarity [128,129]. In this relation, Blikra et al. [13] recognize a lack of culinary innovation and commercial food product applications as present challenges for the consumption of seaweed in Europe.

Knowing the enablers and barriers to seaweed consumption in Western societies facilitates the introduction and expansion into new markets. **Paper IV** and **Paper V** delve deeper into the sensory aspects and consumer liking of four common seaweed species in northern Europe (*S. latissima, A. esculenta, P. palmata*, and *Ulva* sp. with tubular morphology), to increase gastronomic knowledge of potential application areas. With taste/flavour being one main driver for seaweed consumption, it is crucial to recognize variations between physiological and hedonic perceptions [130]. On the one hand, with taste as an example, the physiological sense is influenced by the five primary tastes (sweet, salty, sour, bitter, and umami) and can be linked to specific chemical compounds in food, which are identified by human receptors in the mouth and by neural pathways. Odour reception, or smell, is attributed to receptor structures mediated by membrane proteins in the nasal cavity, and the flavour profile arises as a combination of taste, odour, and irritancy (e.g. the burning of chilli) [131]. On the other hand, the hedonic perceptions of food occur from personal, social, cultural, psychological, and traditional experiences [130].

Hence, this chapter is divided into two sections which firstly discuss the sensory mapping of seaweed from a physiological perspective (descriptive sensory analysis; **Paper IV**), and secondly investigate consumer liking when placing seaweed on the menu (hedonic/affective sensory analysis; **Paper V**). This understanding may, for instance, be useful to chefs and product developers in increasing the familiarity and gastronomic experience of consuming seaweed in a systematic way.

Sensory mapping of seaweed

From a physiological perspective, the gastronomic perception of seaweed, just like other foods, originates from the engagement of a person's five senses. While taste and flavour are key components in a palatable recipe, sight, smell, touch, and hearing constitute other important ingredients [130,132]. Seaweeds are associated with unique textures, odours, tastes, and flavours arising from their physicochemical properties (**Paper IV**) which differ from many terrestrial plants, in terms of chemical composition, as well as physiological and morphological attributes. For instance, while terrestrial plants consist of lignocellulosic biomass that provides their rigidity, seaweeds contain several unique carbohydrates, as discussed initially in the thesis, and are rich in water and minerals [133].

Just as different terrestrial vegetables serve various gastronomic purposes, so should seaweeds as an entity be acknowledged as sea vegetables with varying sensory attributes. With a whole buffet of edible seaweeds available worldwide, there are many distinct colours, textures, tastes, and flavours to explore. The great diversity of attributes between seaweed species necessitates further research to map the sensory characteristics linked with each type, while also taking into account contributing factors, such as growth locations, cultivation modes, seasonality, plant parts and age, and processing conditions [134].

Accordingly, this section explores the current understanding of the physiological sensory attributes related to four common, local seaweed species in northern Europe. To assess the sensory profile of foods, analytical panels of experts in food perception are commonly used, thus constituting human measuring instruments.

The human measuring instrument

In analytical sensory analysis, the trained test panel is considered a human instrument, analysing small nuances in the taste, odour, appearance, and texture of a product. No subjective sentiment is allowed within this context. Instead, international standard procedures are followed to ensure coherence in the performance. Such procedures are, for example, provided by the International Organization for Standardization (ISO), the American Society for Testing and Materials (ASTM), and the Comité Européen de Normalisation (CEN).

Once the panel is selected, e.g. according to ISO 6658 [135], the panellists should start their training. A commonly used method within the area of analytical sensory is the quantitative descriptive analysis (QDA). Here, the sensory analysis often commences with descriptive training of the expert assessors, coordinated by a designated panel leader. The assessors are assigned to identify and articulate sensory attributes related to the provided product samples. Subsequently, the sensory attributes are subjected to a collaborative refinement process, facilitated by the panel leader, resulting in their concise definition and consensus agreement. Following this, the sensory panel is trained for the evaluation by reaching a consensus on how to perform the assessments and how to use the scale. During the final sensory assessment, each panellist assigns a value to individual attributes using, for instance, a linear intensity scale ranging from 0 to 100.

In **Paper IV**, the analytical sensory analysis was related to nutritional and physicochemical information on the four seaweed products. Nutritional content was determined by state-of-the-art methods for carbohydrates (including neutral monosaccharides, mannitol, and uronic acids), total protein and amino acids, total ash and minerals, total lipids and fatty acids, and dietary fibres (see also the chapter *Seaweed as a marine food resource*). Physicochemical analysis was performed to determine the texture and colour of the seaweed samples. Further analysis of volatile compounds in seaweeds is of interest for future studies when delving deeper into their chemical properties. Comparing sensory analysis with laboratory analyses is of interest in the endeavour of understanding the chemical, biological and physical reasons underlying the panel's perceptions.

Seaweed sensory profiles

Consumer acceptance of food is intimately related to its odour, flavour, and taste, with volatile compounds playing a major role in the perception. In this regard, hydrocarbons, ketones, aldehydes, alcohols, acids, and halogen compounds contribute to the sensory quality of seaweed and give them their characteristic flavours [136]. However, the whole buffet of sea vegetables available in the oceans comes with a variety of flavours, textures, appearances, and odours. Different species have different compositions of volatile compounds, giving them various perceived notes of grassiness, floweriness, or fishiness, for instance [137]. In addition to the volatile compounds, macronutrients such as carbohydrates, lipids, and proteins orchestrate the taste and flavour symphonies in foods.

To understand the perceptions of seaweed upon consumption, the physiological sensory attributes related to taste, flavour, appearance, texture, and odour need to be mapped. In **Paper IV**, the sensory attributes of four common northern European seaweed species (*S. latissima, A. esculenta, P. palmata*, and *Ulva* sp.) were investigated in relation to their physicochemical properties. Interestingly, while the two brown seaweed species were most similar, the red type was most distinctive among the species, followed by the green seaweed. Figure 12 illustrates the sensory profiles from **Paper IV** and Table 4 summarizes the descriptors from **Paper IV** together with what is previously described in the literature.

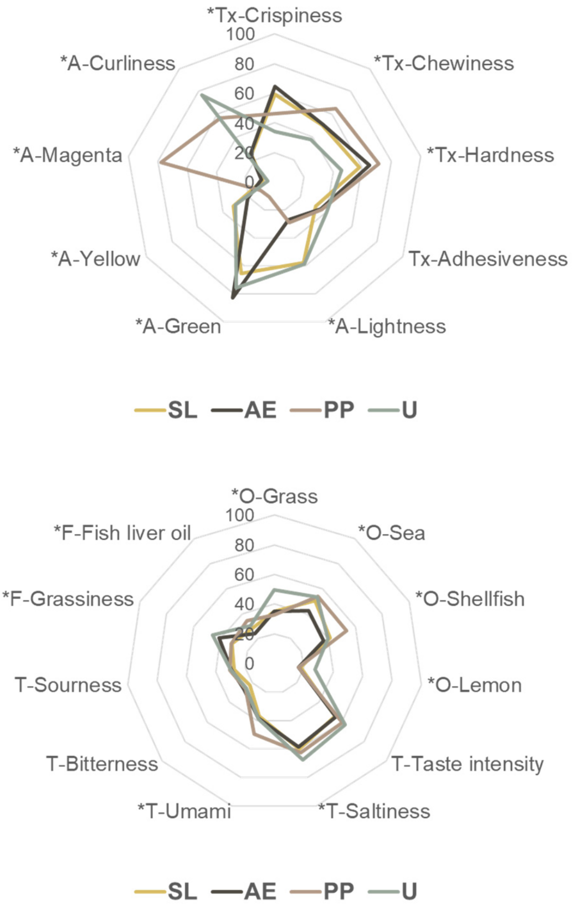


Figure 12. Appearance (A), texture (Tx), flavour (F), taste (T) and odour (O) of whole dried pieces of *Saccharina latissima* (SL), *Alaria esculenta* (AE), *Palmaria palmata* (PP), and *Ulva* sp. (tubular morphology; U). Adapted from **Paper IV**.

Table 4. Sensory profiles of four common northern European seaweed species previously described in literature.

Seaweed species	Form	Sensory descriptives	Ref.
S. latissima	Fresh	Odour of sea, salty taste, some taste of umami, and flavour of boiled vegetables, with a bitey texture.	[78]
	Dried	Salty flavour of fresh sea with crispy, viscous, and dissolving texture.	[138]
	Dried	Light yellow/green colour, more crispy than hard and chewy texture, with an odour of sea.	Paper IV
A. esculenta	Dried	Dark green, with hard and crispy texture. Least sea and shellfish associations.	Paper IV
P. palmata	Hydrated	Highly salty and low bitter tastes, strong marine (fish, seaweed) odour and flavour, and tough and crunchy texture.	[139]
	Dried	Dark magenta colour, umami taste and an odour of shellfish and sea. Hard and chewy texture.	Paper IV
Ulva spp.	Fresh (and treated)	*Ulva rigida* has shown characteristics of intensely green, high vegetable taste, medium hard and elastic texture, with a distinctive odour of seaweed and seaside.	[140]
	Dried	*Ulva* sp. (tubular morphology) had salty taste and flavour of grassiness, with an odour resembling lemon and fresh grass. Neither crispy, hard nor chewy texture, but a curly appearance.	Paper IV

Future research on sensory perceptions of seaweeds should also further investigate the effects of processing on seaweed attributes. Bruhn et al. [78], Skonberg et al. [141], and Hung et al. [137] have shown that fermentation alters some attributes of seaweed and can serve to enhance pleasant odours while reducing unpleasant ones. Jensen et al. [142] alter the sensory attributes by enzymatic processes and include seaweed in food products as a flavour enhancer and salt alternative. Stévant et al. [139] showed that semi-dry storage of *P. palmata* alters its sensory profile with higher diversity and content of volatile compounds and softer texture of the seaweed. In **Paper I**, we saw that high-pressure treatment altered the texture of seaweed, which can be useful when introducing it as an ingredient in foods. Hence, processing may have important implications for consumer acceptance and future gastronomic inventions.

In the following section, the physiological perception gives way to hedonic aspects when the gastronomic innovation is put to the test. Next, we introduce seaweed into two food products as a means of placing seaweed on the menu.

Placing seaweed on the menu

So far in this chapter, the focus has been on the physiological attributes of seaweed (descriptive analysis). As previously argued, physiological perceptions should be differentiated from hedonic liking (affective testing) [130]. Understanding the complex and contradictory practices of food consumption is an essential initial step when formulating new food alternatives and exploring seaweed as food. Consumer influence and acceptance play important roles in the development of processes to produce food ingredients and products from seaweed [59]. Research has shown that attitude strongly influences seaweed consumption [124,143]. Hence, this section engages the consumer to obtain hedonic views on seaweed food products.

Evaluating consumer liking

In contrast to the analytical sensory analysis described previously, a hedonic consumer study sets out to obtain the consumer's opinion on provided products. This can be performed in different settings and study environments depending on the desired investigation targets. In **Paper V**, a simple study design using a linear hedonic scale from 1 (dislike extremely) to 9 (like extremely) was used to evaluate the liking for two complementary seaweed-containing products among Swedish consumers.

Other methods for investigating food acceptance are dependent on the research question raised, but can include questionnaires/surveys [7,35,123,129], interviews and focus groups, shopping patterns, cooking experiences, product tasting evaluation by scoring (**Paper V**; [144]) or emotional response [145], and combinations of methods [146]. One limitation with consumer tasting studies is that they may be influenced by the environment in which the test person consumes the product. "*No man is an island*" as the English poet John Donne put it. Hence, new methods try to overcome this by, for instance, using virtual reality to simulate different surroundings [147].

The following section explores the current status of consumer acceptance towards seaweed as food in a Western setting.

Consumers' liking of seaweed products

In a recently published essay [130], the author plays with the naïve but evocative idea that *"[...] no food can be considered sustainable before it is eaten. Food not eaten must be considered as waste*". With this as a starting point, it becomes even more important to include the consumer's perspective in the development of new and sustainable food products.

Previous research [7,145] indicates that consumers demonstrate a greater inclination to incorporate seaweed into plant-based food items such as bread, noodles, biscuits, and pasta, as opposed to animal-derived products like yoghurt or sausages. It is also argued [130] that umami-rich seaweed can act as a taste enhancer for plant-based products in the green transition. In addition to the current array of dishes that already incorporate seaweed, there are numerous potential applications. However, a primary obstacle in Western societies lies in culinary innovation [13].

In **Paper V**, two familiar products, bread and spread, with the addition of seaweed powder were developed and introduced to consumers. Due to iodine restrictions, just 3.5% and 3% seaweed were added to the bread and spread, respectively. Overall, consumers liked the seaweed-containing products, generally favouring the inclusion of brown seaweeds. However, to make a sustainable impact using seaweed, we believe it is crucial to increase the daily intake. This was previously discussed in the chapter *Chemical quality*. In fact, similar to the chemical quality, the limit for sensory appeal is low (up to ~4% in bread) as described in previous studies [144,148-150]. Enhancing the sensory appeal can be achieved through processing by fermentation, for instance (**Paper II**; [78,137,151]), which can alter the flavour profile, or high-pressure treatment (**Paper I**) to soften the texture. Matching the right seaweed profile with the intended food product will be a task for product developers and chefs.

In Western societies, seaweeds, whole or as ingredients, are progressively being incorporated into novel commercial products, in the forms of main ingredient (salad, vegetable, garnish), flavour agent, bulking agent, nutrition enhancer, edible wrapping, texture and/or colour improvements [13], and especially introduced in plant-based products [152]. **Paper V** indicated that consumers overall like the seaweed-added products, with scores ranging from 5.6–6.3 for bread and 5.2–5.9 for spread. Taste and texture proved to influence the acceptance to the largest extent. Skrzypczyk et al. [153] demonstrated high consumer acceptance rates for soups and salads with the addition of different species of commercial seaweeds and wild-harvested Australian seaweeds (in varying amounts). On a 9-point linear scale, the liking scores were 7–8 for soup dishes and 6–8 for salad dishes. Another study by Fernandes et al. [154] introduced *P. palmata* in a vegan burger (at an undefined ratio) and showed that 64.0% of the participants found the vegan burger appealing (rating it 5/7 to 7/7), with 53.9% expressing an inclination to purchase it. The outcome of these studies agrees with what was concluded in **Paper V**.

In summary, this chapter raises the importance of separating physical and hedonic perceptions of seaweed, studied in **Paper IV** and **Paper V**, respectively. Further exploring the usability of seaweeds requires an understanding of their sensory profiles, as well as engaging the consumer in product development. Finally, processing of seaweed can help enhance the sensory appeal as well as its microbial and chemical quality. However, the impact of different treatments on the sensory profiles should be further studied in the future.

Concluding remarks and future perspectives

This thesis has investigated how microbial, chemical, and sensory challenges associated with seaweed for food can be overcome to facilitate its introduction and expansion into Western markets. The use of seaweed as a marine food resource is contextualized in the concept of the circular bioeconomy. Overall, methods for microbial stabilisation and removal of PTEs were proposed, variations of elements and compounds between different species, harvest sites, and algal parts were demonstrated, and sensory mapping as well as consumers' liking of seaweed-containing foods were outlined. Which processes and species to use for future seaweed foods depend much on the desired product and cannot be generalized.

In the section *Seaweed as a marine food resource*, the nutritional profile of seaweed was summarized. However, it was argued that variations in composition, from natural variation and different post-harvest handling, impede a coherent overview of the nutritional content. The postulated health effects of algal bioactive compounds need more clinical evidence, and the bioavailability in particular needs further research. Among the carbohydrates, green algal polysaccharides and oligosaccharides are less researched and could be the subject of more investigations in the future. In addition, taking Japan as a case example, there are observed variations in the availability, variability, and quality of seaweed products on emerging and established markets.

In emerging markets, seaweed products are associated with sustainable innovation potential, as discussed in the section *A sustainable food resource in the circular bioeconomy*. Systemic change in the food sector is argued for. One popular model is the circular economy, in which seaweed is proposed to fit and where interdisciplinary, or even transdisciplinary, work is advocated. While associated with auspicious conditions for seaweed farming, more research and environmental assessments are imperative to understand the ecological impact of upscaling the seaweed industry.

In addition to farming practices, the post-harvest processing for stabilisation of the harvested seaweed poses a challenge in emerging markets. This was discussed in the section *Microbial quality*. Previous studies show intricate interactions between seaweed and marine microflora, although a low initial load of microorganisms on

S. latissima from Sweden was observed in **Paper I**. Two methods for stabilisation of the biomass were studied: one traditional technique, fermentation (**Paper II**), and one modern method, HPP (**Paper I**). Fermentation by LAB proved to be a promising technique that was able to bring the pH around 4.5 after 24 hours, creating a hostile environment for spoiling microflora. However, improvements must be made to meet industrial demands, such as upscaled solid-state fermentation, where the focus should be on the desired product. There is a desire to increase the stability of seaweed after harvest by automated and cost-effective techniques, and their performance should be analysed by LCA and techno-economic assessments. Iterative design should be applied to build in quality and minimize waste. Processing also proved to alter the sensory properties, such as texture by HPP, as well as enhancing the composition, and organoleptic properties related to taste, flavour, and odour after fermentation.

Post-harvest processing can also become important for enhancing the chemical quality of seaweed (section *Chemical quality*). Presently, PTEs pose an issue for the expanded seaweed consumption. Especially iodine, which is highest in kelps, limits the tolerable daily intake (**Paper III**). In addition to interspecies variations, different growth sites and parts of the sugar kelp contributed to varying PTE levels. Hence, one approach to minimizing PTE sorption could be to source suitable cultivation sites. In **Paper III**, processing by different methods reduced the total ash content, leading to reductions in total arsenic (61.1%), inorganic arsenic (92.4%), lead (49.4%), and iodine (72.8%). However, further research on reducing PTEs, especially cadmium and iodine, is needed in relation to their impact on the algal sensory properties.

The lack of knowledge about the sensory quality of seaweed materials and culinary innovation were addressed in the section *Sensory quality*. Understanding the sensory profiles of seaweed is important for its expansion into various food applications. The sensory patterns proved to differ among the four species studied in **Paper IV**. More studies are needed to understand the sensory profile of different species, and the effects of the harvest site, season, and processing. Moreover, **Paper V** provided an understanding of consumer's liking of seaweed included in two food products in a Swedish context. Overall, consumers were slightly positive towards the two seaweed-containing products.

These findings can serve as valuable knowledge for the development and improvement of future seaweed products and their availability, either by industrial stakeholders, the academic community, and/or indirectly by consumers.

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Painting from the university corridors in Thórshavn, Faroe Islands, 2017.

I sometimes think of this ill-hung painting with its well-formulated saying: "*Smooth Seas Do Not Make Good Sailors*". Most PhD students, including me, experience this over the course of their studies, as the scientific seas we sail to reach doctorateness are not always smooth. And for me, rowing this ship ashore, I have been surrounded by people who have collaborated, helped, challenged, and inspired me to grow as a scientist. Therefore, I have many people to thank on my journey of striving to become a skilled sailor on the scientific seas.

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SCANDINAVIAN SEAWEED
selected
Bladder wrack | Blåstång
Fucus vesiculosus
Sea lettuce | Havssallat
Ulva lactuca
Sugar kelp | Sockertång
Saccharina latissima
Winged kelp | Havskål
Alaria esculenta
Knotted kelp | Knöltång
Ascophyllum nodosum
Gut weed | Tarmtång
Ulva sp.
Sea lace | Snärjtång
Chorda filum
Dulse | Söl
Palmaria palmata
Oarweed | Fingertång
Laminaria digitata

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Current food systems pose one of the greatest health and environmental challenges of the 21st century. A systemic shift in the food sector could be accelerated by technologies and innovations, such as seaweed food applications. However, introducing seaweed as a food resource into Western markets comes with several challenges. Among these challenges, this thesis focuses on several barriers across the value chain from production to consumption of future seaweed foods. How can microbial, chemical, and sensory challenges associated with seaweed for food be overcome to facilitate its introduction and expansion into Western markets?

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