Nordic Council of Ministers

SEAWEEDS FOR FOOD:

from production to consumer

A Nordic perspective on quality, processing and market advancements

Contents

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Terms and abbreviations

AI: adequate intake

AL: action level

a_w: water activity

BMDL: benchmark dose lower confidence limit

CFU: colony forming unit

DRI: daily reference intake

DW: dry weight

EC: European Commission

ED: eliciting dose

EFSA: European Food Safety Authority

ELISA: enzyme linked immunosorbent assay

EU: European Union

FAO: Food and Agriculture Organization

FRL: food-related lifestyle

FW: fresh water

GDA: generic descriptive analysis

GHG: greenhouse gas

GMP: guanosine-5′-monophosphate

HACCP: hazard analysis and critical control points

HPP: high pressure processing

IMP: inosine-5′-monophosphate

LAB: lactic acid bacteria

LCA: lifecycle assessment

LOQ: limit of quantification

MC: moisture content

MD: mechanical dewatering

ML: maximum level

MoE: margin of exposure

MRL: maximum residue level

MSG: monosodium glutamate

MVD: microwave vacuum drying

PAL: precautionary allergen labelling

PEF: pulsed electric field

PTE: potentially toxic element

RTE: ready-to-eat

SEC: specific energy consumption

SW: seawater

UL: tolerable upper intake level

US: ultrasound

VITAL: voluntary incidental trace allergen labelling

WHO: World health Organisation

WW: wet weight

Highlights

- Seaweeds are **low-calorie food ingredients rich in micronutrients** that can contribute minerals, vitamins, dietary fibres and bioactive compounds, promoting nutritious diets and reformulation of processed foods. While seaweeds contain a wide range of bioactive compounds with promising health-related properties, most evidence is currently derived from *in vitro* and animal studies. Further studies with **human subjects including carefully designed clinical studies** are required to substantiate health and functional claims and to support high-value food and nutraceutical applications.
- Seaweeds offer valuable **sensory and functional properties**, serving as natural sources of umami, enabling salt reduction and providing textural functionality. As such, they represent promising alternatives to ultra-processed ingredients, supporting cleaner labels, improved nutritional quality and innovation in sustainable food systems.
- **Food safety risks** associated with seaweeds can be addressed through robust controls, including monitoring of iodine, non-essential metals, allergens and microbiological hazards, supported by HACCP-based systems.
- Seaweeds represent a **potential dietary source of iodine** for European populations that are generally considered iodine deficient. However, careful iodine management is essential for their safe use in foods, particularly for kelp species. Targeted processing strategies to reduce iodine content and/or controlled inclusion levels in food formulations are necessary to prevent excessive exposure of consumers of seaweed-based foods.
- **Diversification of cultivated and commercialised seaweed species** beyond kelps is essential to reduce regulatory, food safety and market risks. Green and red seaweeds generally exhibit lower iodine levels and offer greater formulation flexibility, supporting broader food applications and contributing to a more resilient and versatile European seaweed sector.
- **Tailored post-harvest processing** adds value to seaweed biomass while balancing nutrient retention, flavour, functionality, and environmental impact. Crucially, processing also serves as a key control point for **food safety and quality consistency**, enabling predictable management of iodine, microbiological risks and selected contaminants, and supporting the integration of seaweed ingredients into mainstream food products.

- **The successful integration of seaweeds in European food systems** requires a shift from viewing seaweed as raw biomass to an application-driven ingredient approach. Species choice, processing intensity and inclusion levels should be tailored to specific food applications to ensure functionality, safety and consumer acceptance. Regulatory and risk-management frameworks should therefore focus increasingly on contaminant and iodine levels in final food products rather than solely on raw materials, supported by **end-product assessment, clear labelling and dietary guidance**.
- **Processing remains the main environmental hotspot** across the value-chain, especially drying and freezing, highlighting the need for energy-efficient technologies. **Low-energy stabilisation** routes, such as fermentation and acid preservation, show promise for shelf-stable seaweed foods, but require further optimisation, safety guidance and validation of functional benefits.
- **Consumer acceptance** towards seaweed as food in Western markets is positive but segmented. Early adopters are receptive and knowledgeable, while a broader use in the food industry will rely on product taste, familiarity, price and availability. **Clear communication and strategic branding** are essential, including decisions on when to highlight seaweed explicitly *versus* using it as a background functional ingredient e.g., to provide texture.
- **Scaling the European seaweed sector** requires diversification of the commercial biomass production beyond kelp species, harmonised quality frameworks and evidence-based regulatory developments. Investments in centralised processing hubs can strengthen the sector, increase processing capacity and efficiency, while improving competitiveness of the seaweed sector. In this context, **Nordic countries** are well positioned to play a central role in the future European seaweed sector, given their extensive coastline, water quality and the ongoing development of industrial-scale seaweed farming.
- **Seaweed cultivation supports sustainability goals,** including nutrient recovery and low land use, but climate and biodiversity benefits must be communicated carefully and supported by transparent assessments.
- Large-scale expansion will only be achievable with **continued national, private or blended investments** to support technology development, product specification, and market positioning. In parallel, **long-term offtake commitments from leading companies** are essential to secure the scaling of cultivation operations at sea, and seaweed-based products.

Summary

The present report addresses a central challenge for the European seaweed and food sectors: how to enable the broader use of seaweed biomass as **safe, flavourful, functional and sustainable ingredients** in manufactured food products. This work synthesises state-of-the-art knowledge and industry experiences across the seaweed food value-chain, from post-harvest handling to consumer acceptance and sustainability assessment.

Seaweeds are inherently **low-calorie raw materials, dense in micronutrients** with the potential to deliver essential minerals, vitamins, dietary fibres and bioactive compounds when used at low and realistic inclusion levels. Seaweed ingredients can enhance nutritional quality, contribute to salt reduction, and provide **natural flavour and textural functionality**, while supporting cleaner-label food formulation. However, unlocking this potential requires carefully designed processing routes, robust food safety management, and targeted communication strategies.

Post-harvest processing is identified as a critical step for maintaining safety and quality of seaweed biomass. Fresh seaweed deteriorates rapidly, making early stabilisation essential. This report demonstrates that tailored processing strategies, ranging from gentle treatments (e.g., mild seawater blanching) that preserve flavour and water-soluble nutrients to more intensive approaches (e.g., pulsed electric field (PEF) and high temperature blanching) aimed at fibre enrichment or bioactive extraction, enable the development of ingredients adapted to specific food applications and iodine-targeted inclusion levels. Processing steps such as mild seawater blanching, fermentation, acid preservation and emerging technologies (e.g., PEF, ultrasound, high-pressure processing) can substantially improve microbial safety and manage iodine levels while maintaining nutritional and sensory quality, provided that industrial feasibility and energy efficiency are addressed.

Food safety is a central consideration for the expansion of seaweed-based foods in Europe. Seaweeds represent one of the few natural, plant-based dietary sources of iodine, offering an important opportunity to help address iodine insufficiency, which remains a public-health concern in the majority of European populations. At the same time, iodine levels can be high and vary widely across seaweed species and processing conditions, particularly in kelps, and therefore require careful management. The reviewed evidence show that iodine content in seaweed ingredients can be effectively controlled through species selection, tailored processing (e.g., blanching), and appropriate inclusion levels. In this context, seaweeds can provide a **safe and valuable source of dietary iodine**, while green and red species, which generally contain lower iodine levels, offer additional flexibility for product development and diversification beyond kelp-dominated systems.

Iodine content is identified as the primary factor limiting the inclusion level of seaweed ingredients in formulated foods, particularly for kelp species. As a consequence, the contribution of other nutrients such as protein, dietary fibre, vitamins and most minerals is inherently constrained by iodine-related safety considerations rather than by technological feasibility or nutritional potential. This underscores the importance of **species selection, iodine-targeted processing and realistic portion-based assessments** when evaluating both nutritional benefits and regulatory compliance of seaweed-based food products. Accordingly, nutritional claims and sustainability narratives should be framed in relation to iodine-limited inclusion levels in final food products rather than on the compositional richness of raw seaweed biomass alone.

Food safety considerations extend beyond iodine to include **potentially toxic elements such as cadmium, lead, mercury and inorganic arsenic**. Based on current consumption scenarios and available occurrence data, edible seaweeds commercialised in Europe generally represent a minor contribution to dietary exposure to these contaminants. Risks are strongly species- and site-dependent and can be effectively managed through appropriate sourcing, batch-wise monitoring and good manufacturing practices. While some processing methods may modestly influence contaminant levels, **upstream control and end-product assessment** remain the most effective risk-management strategies. This contrasts with a common perception of seaweeds as inherently high-risk foods with respect to contaminants.

Sensory quality emerges as a key driver of consumer acceptance. Seaweeds offer strong potential as natural **sources of umami flavour, salt replacement and texture**, but sensory outcomes are highly dependent on species, processing and storage. The report demonstrates how processing choices influence flavour intensity, aroma profiles and texture, and highlights opportunities for **flavour development** inspired by traditional Asian practices. Establishing a harmonised sensory vocabulary and quality framework for edible seaweeds is recommended to support consistent product development and market positioning.

Consumer studies show that seaweed-based foods are still a niche market in Europe and Nordic countries, but generally benefit from **positive consumer perception**. Current consumers of seaweed-based products value sustainability, health and culinary novelty, while a greater acceptance among European consumers depends on how seaweed product will fit into everyday culinary practices. Taste quality, product familiarity, price competitiveness and retail presence emerge as decisive factors. These findings underline the importance of application-driven product development and carefully adapted communication strategies, including realistic portion size, frequency of consumption and nutritional contribution. Furthermore, food producers should make deliberate choices about whether seaweed is positioned as a visible selling point or integrated more discreetly as a functional ingredient depending on end-product and targeted consumer segments.

In terms of **environmental performance**, cultivated seaweed has clear potential to support resource-efficient food systems and circular bioeconomy pathways, particularly through nutrient uptake and low reliance on land and freshwater resources. At the same time, the overall sustainability of seaweed-based food ingredients is strongly influenced by downstream processing choices. Energy-intensive operations such as drying and freezing account for a substantial share of environmental impacts, making process optimisation a key lever for improvement. Therefore, this report stresses the need for **transparent, evidence-based sustainability assessments** to support claims related to biodiversity and environmental benefits when substituting or replacing seaweed as ingredient in food products. Furthermore, the short-term carbon storage from producing seaweeds to food applications should be distinguished from long-term climate mitigation.

Overall, this work demonstrates that seaweeds can become **viable, high-quality food ingredients for the food industry**, if processing is tailored to product goals, safety risks are proactively managed, sensory quality is prioritised, and sustainability performance is credibly documented. The report provides a knowledge base to support innovation, guide industry investment, inform regulatory development, and accelerate the responsible integration of seaweed into Nordic and European food systems through safe, application-driven and evidence-based use.

1. Introduction

Food production systems and global diets

The rising global population demands an increasing production of food. It is projected that the global demand for food will increase by 50–60% in 2050, compared to the baseline of 2019 (Falcon et al. 2022). However, global food production is one of the primary drivers of climate change and ecosystem degradation. Hence, producing quality food in sufficient quantity without any or minimal environmental degradation is one of the major future global targets. Furthermore, unhealthy diets, whether due to undernutrition, overconsumption or poor-quality food, are among the major causes of several global health burdens. Achieving healthy diets from sustainable food systems requires major shifts in dietary composition, including increasing the share of plant-based food, paired with the reduction of red meat consumption (Poore and Nemecek 2018; Willett et al. 2019).

Seaweed as industrial feedstock

Alternative food resources from the marine environment may contribute to more sustainable sourcing of food in the future. In this context, seaweeds (i.e., marine macroalgae) are considered a promising resource for food and supporting human and animal nutrition and health (Araújo et al. 2021; Mapelli-Brahm et al. 2023; Hofmann et al. 2025). Seaweeds also hold potential as feedstocks for several other industrial applications, including biofuels, -plastics and -chemicals, plant bio-stimulants, cosmetic and pharmaceutical products (Rotter et al. 2020). Seaweed biomass can be cultivated at sea on a large scale without using chemicals and fertilizers and does not require fresh water or soil resources. If properly regulated, seaweed cultivation can also provide ecosystem services, such as supporting biodiversity and mitigating CO_2 emissions (Cotas et al. 2023). Alternatively, seaweeds can be cultivated under controlled conditions in land-based facilities, allowing for further optimization of growth and biomass quality, and allowing wastewater integration from e.g., finfish aquaculture for nutrient recycling (Neori et al. 2004; Troell et al. 2009).

Seaweed aquaculture in Europe

In Europe, seaweed cultivation is considered as an alternative food supply chain contributing to diversifying aquaculture production while minimizing the environmental footprint (European Commission 2021d). Although most of the European seaweed supply still relies on wild-harvested biomass, industrial cultivation is developing rapidly, particularly in Nordic countries such as Norway, Sweden, Denmark, the Faroe Islands, Greenland, and Iceland (Stévant et al. 2017c; Vazquez Calderon and Sanchez Lopez 2022). Large scale cultivation protocols are well established for kelp species, mainly sugar kelp (*Saccharina latissima*) and winged kelp (*Alaria esculenta*), and are also being developed for other high-value species like dulse (*Palmaria palmata*) and sea lettuce (*Ulva* spp.). These countries benefit from extensive coastal and offshore areas, established aquaculture sectors (and industrial seaweed harvesting in the case of Norway and Iceland), as well as strong research infrastructures. Together, these factors provide favourable conditions for fostering a thriving seaweed industry.

Blue bioeconomy & future perspectives

According to recent forecasts, global seaweed demand for direct food consumption and food additives, primarily in East Asia, remains the main driver of industry growth (Aarnes et al. 2024). Most of the existing seaweed-producing companies (both from aquaculture and wild-harvest) direct their biomass to food and food-related uses (Araújo et al. 2021). However, demand is also rising for seaweed biomass in the broader bio-based economy, including applications such as feed and food supplements, pharmaceuticals, bio-packaging materials, and plant biostimulants. This trend aligns with EU policies promoting the Blue Bioeconomy, Blue Growth and sustainable development. The European seaweed aquaculture sector is expected to expand in response to the growing global demand for high-quality, sustainably produced seaweed biomass. By 2030, the European Commission aims to increase production to 8 million tonnes, valued at 9 billion €, and potentially creating 85,000 jobs (Vincent et al. 2020). Nonetheless, risks related to the establishment of a large-scale cultivation of seaweed in Europe are still poorly reported and knowledge gaps persist in areas such as biology, production technology, environmental impacts and market access (Loureiro et al. 2015; Campbell et al. 2019).

Seaweed as food and food ingredient

Seaweeds are widely regarded as a rich source of flavours and nutrients, including minerals, fibres, vitamins, trace elements and other health-promoting compounds, that may offer benefits beyond basic nutrition (Holdt and Kraan 2011; Wells et al. 2017). In Europe, predominantly wild-harvested seaweeds have traditionally been used for industrial extraction of phycocolloids (alginates, carrageenan and agar), which are primarily utilised as food additives owing to their thickening and gelling properties. Interest in seaweeds as food items or ingredients (i.e., sea vegetables, condiments) has grown in recent decades, driven by global trends favouring natural food products, plant-based diets and the popularity of Asian dishes (Aarnes et al. 2024). In response, the European Commission (EC) has compiled a list of seaweed species recognized as non-novel (i.e., consumed in any European Union (EU) member state before 15 May 1997) and authorized as food after approval procedures. Most of these species are valued for their distinctive nutritional and flavour profiles and hold promise for everyday culinary uses. The four species mentioned above (highlighted in green in **Table 1**) are native, non-novel, cultivated, already present on the market, and well-studied. They are therefore the focus of this report. Despite the culinary potential, seaweed remains underutilized in European and Nordic food industries. This is partly due to relatively high production costs and limited supply of biomass at this early stage of industry development, variabilities in the quality of seaweed ingredients caused by the lack of quality consistent production methods, concerns about food safety (e.g., high iodine content), as well as low consumer awareness of the benefits of seaweed as food.

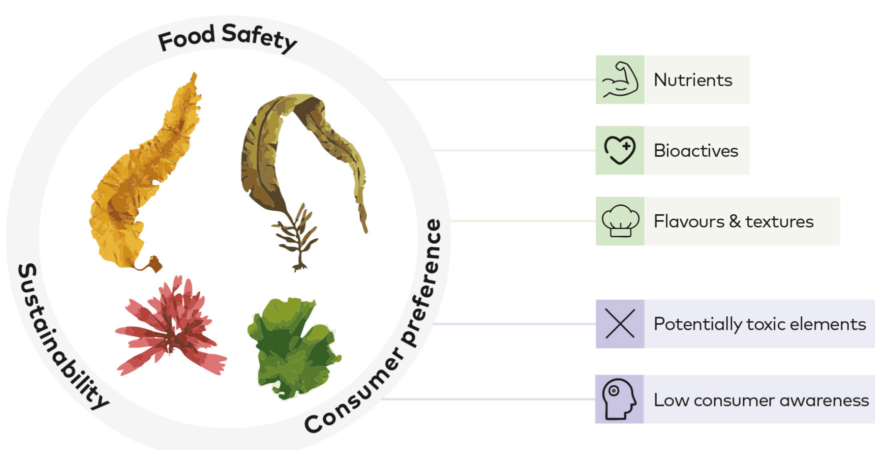

Figure 1: Schematic overview of the potential benefits and current challenges associated with the use of seaweeds (*Saccharina latissima, Alaria esculenta, Palmaria palmata, Ulva* spp.) in food applications. Food ingredients from seaweeds must be produced within the boundaries of food safety, sustainability (environmental, economic, and social), and consumer preferences to support their broader integration into the food system.

Addressing challenges

For seaweeds to be more widely incorporated into food products, their production must comply with food safety regulations, align with environmental, economic and social sustainability principles, and deliver clear value in terms of functionality, quality and consumer acceptance (**Figure 1**). In recent years, collaborative efforts between research institutions and industry have focused on improving seaweed quality and post-harvest processing for food applications. Among these, the SusKelpFood project (2021–2024, financed by the Research Council of Norway) addressed cultivated kelps as renewable, climate-resilient food crops by developing efficient post-harvest processing strategies, managing iodine and allergen levels while retaining nutrients, and characterising sensory properties and consumer preferences. Together, these efforts have contributed to a strong scientific and technological foundation for the use of kelp in the food value chain.

This guideline report supports decision-making, practice and policy by synthesising state-of-the-art knowledge on the use of commercially important species (i.e., *S. latissima*, *A. esculenta*, *P. palmata,* and *Ulva* spp.) for food applications. It addresses post-harvest processing and stabilisation alongside food safety and regulatory frameworks, sensory quality, consumer acceptance, sustainability and value-chain design. By framing seaweed as an application-driven food ingredient rather than a raw biomass, the report provides guidance on inclusion levels, processing strategies, scaling bottlenecks and industry readiness, with a particular emphasis on the Nordic region and the European seaweed food sector.

Table 1: List of seaweed species in the EU Novel Food catalogue (as per January 2026) (European Commission 2024). Abbreviation: non novel (NN). Species covered by this report are marked in green.

Scientific name	Common name	Status	Scientific name	Common name	Status
Brown seaweeds			**Red seaweeds**		
Alaria esculenta	Winged kelp	NN in food	*Chondrus crispus*	Irish moss	NN in food
Alsidium helminth-ochorton		NN in food supplement	*Corallina officinalis*	Coral weed	NN in food supplement
Ascophyllum nodosum	Egg wrack	NN in food	*Corallina officinalis*	Coral weed	NN in food supplement
Durvillaea antarctica	Bull kelp	NN in food supplement	*Erythroglossum laciniatum*	Laver	NN in food
Eisenia bicyclis	*Arame*	NN in food	*Eucheuma denticulatum*	Sea moss	NN in food supplement
Ecklonia cava	Paddle weed	NN in food supplement	*Eucheuma horridum*	Sea moss	NN in food supplement
Fucus serratus	Toothed wrack	NN in food	*Gelidium amansii*	Agar	NN in food
Fucus spiralis	Spiral wrack	NN in food	*Gelidium corneum*	Atlantic agar	NN in food
Fucus vesiculosus	Bladder wrack	NN in food	*Gracilaria gracilis*	Slender wart weed	NN in food supplement
Himanthalia elongata	Sea spaghetti	NN in food	*Gracilariopsis longissima*	Long wart weed	NN in food
Laminaria digitata	Oarweed	NN in food	*Mastocarpus stellatus*	False Irish moss	NN in food supplement
Laminaria hyperborea	Tangle	NN in food	*Pyropia tenera*	Laver, *nori*	NN in food
Macrocystis pyrifera	Giant kelp	NN in food supplement	*Palmaria palmata*	Dulse	NN in food
Saccharina japonica	*Kombu*	NN in food	*Phymatolithon calcareum*	Maërl	NN in food
Saccharina latissima	Sugar kelp	NN in food	*Porphyra dioica*	Laver, *nori*	NN in food
Undaria pinnatifida	*Wakame*	NN in food	*Porphyra purpurea*	Laver, *nori*	NN in food
Sargassum fusiforme	*Hijiki*	NN in food	*Porphyra umbilicalis*	Laver, *nori*	NN in food
Green seaweeds			*Pyropia leucosticta*	Laver, *nori*	NN in food
Ulva lactuca [1]	Sea lettuce	NN in food			
Ulva intestinalis	Sea lettuce	NN in food			

[1] Morphology-based identification of the common foliose *Ulva* species has proven difficult as many *Ulva* species display subtle morphological differences. As a result, specie names attributed in the database and literature must be considered with precaution (Fort et al. 2022). Correct species identification considering morphological characteristics, DNA sequencing and species biogeography is critical to commercial applications and should be updated in the database of the European Commission.

2. Nutrients and bioactive compounds in edible seaweeds

Seaweeds are a diverse group (red, green and brown) of photosynthetic marine organisms whose chemical composition varies considerably with species, season, and habitat. The fresh biomass of seaweed typically contains 80–90% water. In the dry matter, most seaweed species are characterized by high levels of carbohydrates and minerals, moderate to low protein, and low lipid levels.

This section provides an overview of the nutritional characteristics, bioactive compounds and associated health benefits of seaweeds, particularly in the context of their use in large-scale food applications. It summarizes key findings from the literature and presents new data on the levels of specific compounds (e.g., vitamins) and their potential dietary contributions based on realistic consumption scenario.

2.1. Carbohydrates

Dietary fibres

Carbohydrates in seaweeds, comprising both structural and storage polysaccharides, typically account for 40–60% of the dry weight (DW) (Stiger-Pouvreau et al. 2016). A large proportion of these polysaccharides, such as alginates, fucoidans, and cellulose in brown seaweeds; sulphated galactans (agar and carrageenans), xylans, and mannans in red seaweeds; and cellulose, xylans, and mannans in green seaweeds (Lahaye and Kaeffer 1997), are not digestible by humans and are therefore classified as dietary fibres. Consequently, seaweeds are low in calories. From a nutritional perspective, dietary fibres have several benefits as they can increase faecal bulk, retain water, reduce intestinal transit, and modulate gastrointestinal microbiota (Brownlee et al. 2005). Based on fibre content data reported in the scientific literature, Jacobsen et al. (2023) estimated that a 5 g portion of *S. latissima* and *Ulva* spp. provides approximately 3–6% of the daily reference intake (DRI) in fibres. Since the fibre content of *P. palmata* and *A. esculenta* is similar, their dietary contributions are likely at comparable levels.

Seaweeds as texture ingredients

Alginates extracted from kelps (e.g., *L. hyperborea*), as well as agar and carrageenans derived from red seaweeds, are widely used as gel-forming additives in the food and pharmaceutical industries. These phycocolloids are industrially manufactured and typically classified as ultra-processed food ingredients. They belong to a broader category of additives for which growing evidence links high intake of ultra-processed foods to adverse health outcomes, including cardiovascular disease, type-2 diabetes and inflammatory bowel disease (Monteiro et al. 2025). Using edible seaweeds in minimally processed forms (e.g., blanched, dried; see Chapter 4) offers an alternative approach for providing natural texture and mouthfeel (Mouritsen 2013; Chapman et al. 2015; Mouritsen et al. 2019b) as well as fibre and micronutrients. This aligns with recent recommendations from public health and nutrition experts encouraging a shift from ultra-processed to whole or minimally processed food ingredients (Baker et al. 2025).

Bioactive polysaccharides

In kelps such as *A. esculenta* and *S. latissima*, soluble glucose occurs in the form of laminaran, a storage glucan accumulating in the biomass during summer and autumn. Another carbohydrate, fucose, is mainly found in sulphated form as the main constituent of fucoidans. Evidence from both *in vitro* and *in vivo* studies suggests that these compounds exhibit various bioactivities, including roles in immunoregulation (Neyrinck et al. 2007), prebiotic effects (O'Sullivan et al. 2010), anti-inflammatory activity (Ale and Meyer 2013) and anti-obesity effects (Sharma and Baskaran 2021; Zheng et al. 2024).

2.2. Protein

Protein content in seaweeds varies considerably among taxonomic groups, being generally lowest in brown seaweeds (3–15% DW), moderate in green seaweeds (9–26% DW), and highest in red seaweeds (up to 47% DW) (Fleurence 1999). It should be noted that protein contents reported for seaweeds in the literature may be overestimated, because of the use of the standard nitrogen-to-protein conversion factor of 6.25, which does not account for non-protein nitrogenous compounds (e.g., nitrate, free amino acids). Seaweeds can contain up to 45% non-protein nitrogen (Biancarosa et al. 2017) and up to 24% of free amino acids (Vieira et al. 2018). A common conversion factor of 5 has therefore been suggested as more appropriate for seaweeds (Angell et al. 2016). The reported ranges of protein concentrations in the four main commercial edible seaweed species in Europe are given in Table 2. According to estimates of the dietary contribution from a 5-gram portion of dried material, seaweed does not provide meaningful amounts of protein *per* serving (Jacobsen et al. 2023), although it can supply certain essential amino acids (e.g., leucine, phenylalanine, lysine).

Amino acid profile

Although seaweeds are often considered a potential alternative source of protein for human and animal nutrition, only a few species reach protein levels comparable to conventional protein-rich foods such as pulses, beans, and soy (approximately 20–35 g per 100 g DW) (Fleurence 1999). In general, the protein-bound amino acid profile of seaweeds is dominated by glutamic and aspartic acids, and essential amino acids are well represented (Bak et al. 2019; Stévant et al. 2023), although substantial interspecific variations in protein composition have been reported.

Table 2: Reported ranges of protein concentration (as % of dry weight) in *Alaria esculenta*, *Saccharina latissima*, *Palmaria palmata* and *Ulva* spp.

S. latissima	*A. esculenta*	*P. palmata*	*Ulva* spp.
1–16 [2]	9–20 [1]	8–20 [3]	4–27 [4]

References: [1] Sæther et al. (2024); [2] Kraan (2020); [3] Stévant et al. (2023); [4] Hofmann et al. (2025).

Dietary contribution

As already mentioned, the protein in seaweed does not contribute a lot to the diet (Jacobsen et al. 2023), but protein content can be up-concentrated in the solid fraction of processed seaweed using various technologies (see **Chapter 4**) such as pulsed electric field or enzymatic extraction (Naseri et al. 2020; Steinbruch et al. 2024). These approaches have been proposed to produce protein-rich ingredients from seaweeds (e.g., *Ulva* spp., *P. palmata*), although the economic viability of their production has yet to be demonstrated.

2.3. Minerals

Seaweeds are rich sources of both macrominerals (such as sodium, potassium, calcium and magnesium) and trace elements (such as iron, manganese and zinc) (Biancarosa et al. 2018; Circuncisão et al. 2018). The mineral profiles of the four species studied are shown in **Figure 2**. While the total mineral or ash content of land vegetables rarely exceeds 20% of dry weight (DW), it can reach up to 40% DW in seaweeds (Rupérez 2002).

Sodium salt reduction

Seaweeds typically contain potassium (K) levels equal to or higher than sodium (Na), which is nutritionally beneficial, as high dietary Na/K ratios are linked to hypertension and cardiovascular diseases (Perez and Chang 2014). Reducing sodium intake is therefore a public health priority in many Western countries, as processed foods such as meat, bread, sauces, and condiments often exhibit Na/K ratios above 5.0 (Circuncisão et al. 2018). The World Health Organization (WHO) recommends a Na/K ratio close to 1.0, indicating that foods with lower ratios support cardiovascular health. In this context, edible seaweeds are promising functional ingredients for salt reduction. Even at low inclusion levels (≤ 5%) in processed foods, edible seaweeds have been shown to improve mineral balance by lowering Na/K ratios (López-López et al. 2009; Sund et al. 2025a). Processing methods such as blanching tend to increase the ratio, because of greater potassium reduction compared to sodium (see **Chapter 4**).

Iodine

Seaweeds are also an excellent plant-based source of iodine, a micronutrient required in small amounts for the synthesis of thyroid hormones involved in the regulation of metabolism, growth, and numerous body functions. While iodine deficiency disorders (IDDs) are associated with multiple adverse health effects on growth and development, including impaired cognitive development in children (de Benoist et al. 2008), excessive iodine intake can also have negative consequences. This is particularly relevant when considering iodine-rich seaweed species (i.e., kelps) as discussed in **Section 3.2**. Adequate iodine nutrition remains a global challenge, particularly in Europe and Nordic countries, despite national salt iodisation programmes. This is partly due to changing dietary patterns, including reduced intake of seafood and dairy products and increased consumption of plant-based alternatives, as well as food-industry practices such as salt reduction initiatives aimed at lowering the risk of hypertension and other non-communicable diseases (Zimmermann and Andersson 2021). Incorporating seaweeds at low inclusion rates into formulated foods can help supply iodine to foods that typically contain very little (e.g., plant-based products) (Ballance et al. 2024). However, the iodine content of the final product must be carefully monitored and controlled, for example, through processing (see **Chapter 4**), or merely by low inclusion, to avoid excessive intakes (Blikra et al. 2024c; Stévant et al. 2025a). For most edible seaweeds, iodine content is the primary factor determining maximum inclusion levels in foods and therefore governs the achievable dietary contribution of other minerals.

Dietary contributions

Based on mean %DRI per portion (5 g DW), *S. latissima* and *Ulva* sp. are considered as good sources (%DRI >15) of calcium, magnesium, iron, selenium (Jacobsen et al. 2023). These conclusions can reasonably be extended to *A. esculenta* and *P. palmata*, given their relatively similar mineral profiles (**Figure 2**). However, the mineral composition of edible seaweeds can be altered by post-harvest and processing steps, which will in turn influence their dietary contribution (Stévant et al. 2025a). Under an iodine-limiting scenario, only potassium in *P. palmata* and magnesium in *Ulva* spp. exceed 15% of the DRI when inclusion levels are constrained by the tolerable upper intake level (UL) of 600 µg iodine per day for adults established by the EC (**Appendix Table 4**). If higher intakes were considered acceptable, such as in Japan (UL = 3 000 µg iodine per day for adults) (Katagiri et al. 2015), *P. palmata* and *Ulva* spp., as well as iodine-reduced kelp by warm seawater treatment, would contribute a broader range of minerals above 15% DRI while kelps would still mainly contribute iodine and sodium (data not shown).

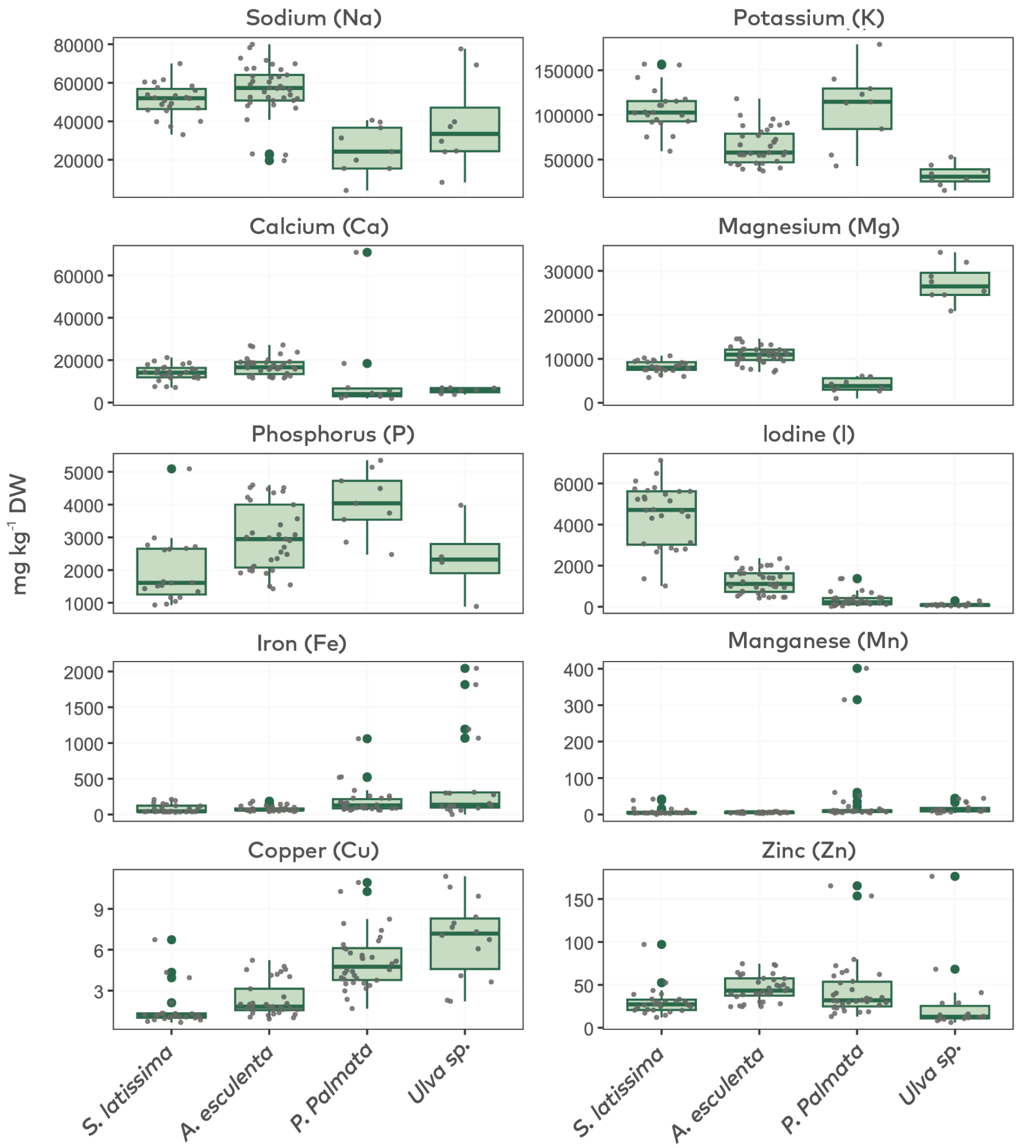

Figure 2: Mineral concentrations (in mg per kg dry weight (DW)) measured in dried unprocessed samples of *Saccharina latissima* (farmed), *Alaria esculenta* (farmed), *Palmaria palmata* (wild-harvested) and *Ulva* sp. (farmed) after harvest. Data from the SusKelpFood project, the Technical University of Denmark (DTU) and Nordic SeaFarm. Daily reference intakes (DRIs) for these elements are given in **Appendix Table 2**. Mineral dietary contributions based on iodine-limiting portion size are presented in **Appendix Table 4**.

2.4. Lipids

The lipid content of commonly consumed European seaweeds is low (0.5–4% DW), but their fatty acid profile is noteworthy. They contain a relatively high proportion of polyunsaturated fatty acids (PUFAs), including n-3 long-chain PUFAs such as EPA and DHA, as well as polar lipids (Moreira et al. 2021; Rocha et al. 2021). Lipid composition varies widely with season, location, and methodological differences in extraction and analysis, so reported values must be interpreted with caution.

Lipid profile

Foseid et al. (2020) highlighted the particularly favourable lipid profiles of *S. latissima*, *A. esculenta*, and *P. palmata*. While these species cannot serve as major dietary sources of n-3 PUFAs, they can nonetheless contribute meaningfully to n-3 intake, particularly high-quality EPA and DHA from marine sources, and help improve the omega-6/omega-3 ratio. This is relevant given that Western diets are typically skewed toward omega-6, a pattern associated with chronic inflammation.

Lipid analysis

It should be noted that lipid content is often underestimated in seaweed. Different extraction methods can yield substantially different lipid or total fatty acid contents from seaweed, mainly because they vary in solvent polarity, extraction time, and ability to disrupt cell walls. Direct transesterification is the most accurate method and gives 1.5 to 2 times higher yields of total fatty acids compared to even the most effective conventional solvent methods (Kumari et al. 2011; Saini et al. 2021).

2.5. Vitamins

Vitamins are a diverse group of organic compounds essential for human health, functioning as coenzymes in metabolic processes, antioxidants, or regulators of gene expression (Gregory 2007). Seaweeds are often promoted as rich sources of vitamins. However, given the diversity of both seaweed species and vitamin compounds, such generalizations are limited. As with other nutrients, the vitamin composition of seaweeds varies substantially with species, season, growth stage, and environmental conditions, and are also affected by processing.

Dietary contributions

Recent data for B-group and C-vitamin concentrations in *S. latissima, A. esculenta* and *Ulva* spp. are presented in **Table 3**. A review by Nielsen et al. (2021) indicated that while seaweeds can contribute to daily vitamin C intake, they are not particularly rich sources compared to common vegetables, such as lettuce or broccoli. *Ulva* spp. and *P. palmata* generally contain higher vitamin C levels than the kelps *A. esculenta* and *S. latissima* (Jacobsen et al. 2023; Stévant et al. 2023). *Saccharina latissima* and to an even greater extent *Ulva* spp., have been highlighted as notable sources of vitamin B12, although substantial variations among individual samples have been reported (Jacobsen et al. 2023). Iodine-reduced *A. esculenta* (processed by mild seawater blanching) was also identified as a potential dietary contributor of vitamin B9 (Stévant et al. 2025a).

Overall, vitamin data for edible seaweeds remain limited. More comprehensive and systematic assessments are needed to substantiate nutritional claims regarding vitamin content in edible seaweeds.

Table 3: Concentrations (mg per kg dry weight) of selected vitamins in dried unprocessed samples of farmed *Saccharina latissima*, *Alaria esculenta*, and *Ulva* sp. Data from the SusKelpFood project, the Technical University of Denmark (DTU), and Nordic SeaFarm. Values are given as mean ± st. dev. Daily reference intakes (DRIs) for these vitamins are given in **Appendix Table 2**. Vitamin dietary contributions based on iodine-limiting portion size are presented in **Appendix Table 4**.

	Unit	*S. latissima*	*A. esculenta*	*Ulv* sp.
B1 (thiamine)	mg kg^{-1}	2.6 ± 0.35 (*n* = 9)	2.4 ± 0.90 (*n* = 16)	n.a.
B2 (riboflavin)	mg kg^{-1}	5.1 ± 0.23 (*n* = 3)	12 ± 0.49 (*n* = 3)	n.a.
B3 (niacin)	mg kg^{-1}	10 ± 2.5 (*n* = 3)	41 ± 1.2 (*n* = 3)	n.a.
B5 (pantothenic acid)	mg kg^{-1}	6.7 ± 0.12 (*n* = 3)	4.9 ± 0.34 (*n* = 3)	n.a.
B6 (pyridoxine)	mg kg^{-1}	0.64 ± 0.02 (*n* = 3)	0.9 ± 0.07 (*n* = 3)	n.a.
B9 (folic acid)	mg kg^{-1}	1.7 ± 1.2 (*n* = 9)	19 ± 20 (*n* = 16)	n.a.
C (ascorbic acid)	mg kg^{-1}	100 ± 74 (*n* = 9)	47 ± 130 (*n* = 16)	650 ± 770 (*n* = 3)

n.a.: not analysed.

2.6. Bioactivity

The bioactive compounds of seaweeds (e.g., polysaccharides, polyphenols) have been reported to exhibit several health-beneficial bioactivities, including antioxidative, anti-inflammatory, antihypertensive, and antidiabetic effects (Wells et al. 2017; Cherry et al. 2019; Peñalver et al. 2020). The bioactivities have been tested by diverse *in vitro* and *in vivo* models, but there are currently limited clinical data available to substantiate the positive claims related to individual metabolites on human health. However, there is increasing evidence that the consumption of seaweeds is associated with health and nutritional benefits. Studies conducted in Japan positively correlated the typical Japanese dietary pattern, which includes the daily consumption of seaweeds (3.3 to 5.3 g DW day^{-1} according to Darcy-Vrillon (1993) and Matsumura (2001)), with decreased mortality from some forms of cancer and cardiovascular diseases (Iso and Kubota 2007; Shimazu et al. 2007). In another study based on a clinical trial, the daily consumption of seaweeds was proposed as a factor explaining the lower postmenopausal breast cancer incidence and mortality rates in Japan (Teas et al. 2013). Evidence from the Nutrition and Health Surveys in Taiwan associated several foods, including seaweeds, with limiting the increase in metabolic syndrome prevalence among women (Yeh et al. 2011).

The bioactivity of whole seaweed ingredients or seaweed-derived extracts is influenced by post-harvest and processing methods. While numerous *in vitro* and *in vivo* studies indicate potential bioactivities, human intervention and clinical data remain limited. Population-based observations, mainly from East Asia, suggest associations between seaweed consumption and health outcomes, but causality remains difficult to establish.

2.7. Nutritional claims

Nutrition claims

Assessing the nutritional profile of food ingredients from edible seaweeds and comparing their nutrient levels with DRIs and conventional reference foods provides important insights into their potential contribution to future sustainable diets. The nutritional benefits derived from seaweed-based foods will ultimately depend on the extent to which key nutrients remain available after processing and the amount of seaweed incorporated into the final product. Within the EU, the use of nutrition and health claims is regulated by Regulation (EC) No 1924/2006, which aims to protect consumers and ensure transparent product labelling. The regulation specifies that a claim may only be made when "the substance that is the subject of the claim is present in the final product in quantities that are sufficient (...) to produce the nutritional or physiological effect claimed". In the context of seaweed-based products, this means that nutrient levels in the finished food (not the raw seaweed) must comply with the required threshold. Conditions relevant to seaweed ingredients, including criteria for "source of" and "high in" claims for vitamins and minerals, are summarised in **Appendix Table 1** and **Appendix Table 2**. For example, modest inclusion levels of minimally processed kelp may allow a product to qualify as a "source of iodine" while higher inclusion levels of iodine-reduced kelp could support claims such as "source of fibre" or "source of calcium", provided the regulatory thresholds are met.

2.8. Conclusions

Seaweeds combine a nutrient-dense composition with low energy content. Their actual nutritional contribution in foods is, however, determined by realistic inclusion levels, species choice, processing, and food safety considerations. When used appropriately, seaweeds can enhance the nutritional and functional quality of formulated foods, supporting healthier dietary patterns without substantially increasing energy intake making them attractive food ingredients.

- **Source of nutrients:** Seaweeds are low in calories yet naturally rich in essential micronutrients. Depending on species and processing, they can provide meaningful amounts of macrominerals (e.g., calcium, magnesium, potassium), trace minerals (e.g., iron, selenium, iodine), and selected vitamins (e.g., B9, B12). Iodine levels in final products should be monitored and controlled to avoid excessive dietary exposure.
- **Sources of dietary fibre:** Minimally processed edible seaweeds offer a valuable alternative to ultra-processed food ingredients, supplying both functional fibres and micronutrients. When incorporated into formulated foods, they can contribute texture, water/oil-binding properties and support more balanced dietary patterns.
- **Salt reduction:** Even at low inclusion rates, seaweeds can act as functional ingredients for sodium reduction, helping food manufacturers lower the sodium-to-potassium ratio and improve overall nutritional quality.
- **Functional ingredients and nutraceutical potential:** Numerous *in vitro* and *in vivo* studies indicate diverse bioactivities across seaweed-derived compounds. However, more studies with human subjects including clinical studies are needed to document health effects and substantiate functional claims for whole seaweeds, extracts, and purified compounds. Such evidence will support high-value applications based on small quantities of raw material.

3. Food safety

Besides being a source of nutrients and bioactive substances, seaweeds may also accumulate potentially toxic elements (PTEs) which may have negative effects on human health. Both non-essential metals as well as essential elements, especially iodine, in excessive amounts may limit the use of seaweeds in large-scale food applications (Sá Monteiro et al. 2019; Banach et al. 2020; Blikra et al. 2022a). An overview of the range of concentrations of the most relevant PTEs in *S. latissima*, *A. esculenta*, *P. palmata* and *Ulva* spp. is shown in **Figure 3**.

Dietary exposure to PTEs from edible seaweeds depends on both the concentration in the seaweed, the frequency of consumption and the quantity of seaweed ingested per meal. Seaweed is not a traditional food in Europe and consumption data is limited. Risk assessments based on consumption scenarios (Sá Monteiro et al. 2019; Vellinga et al. 2022), consumer survey (Babaahmadifooladia et al. 2022; Ficheux et al. 2023) and exposure estimates among the relatively small group of seaweed consumers (EFSA et al. 2023) conclude that occasional intake of common edible species (including *S. latissima*, *A. esculenta*, *P. palmata* and *Ulva* spp.) does not pose a major risk. However, single servings of iodine-rich species (kelps) typically exceed recommended daily intakes, raising concern with frequent consumption, particularly in sensitive subgroups like pregnant and lactating women, children and people with thyroid disorders. The dietary contribution of other PTEs such as cadmium, inorganic arsenic and lead, may also be relevant but varies greatly among seaweed species and consumption scenario. EFSA concluded that the impact of a future increase in seaweed consumption ('per capita') on the dietary exposure to heavy metals and iodine intake will strongly depend on the seaweeds consumed (EFSA et al. 2023). This chapter summarises the regulatory context and reviews iodine, PTEs, microbiological risks and allergens, with emphasis on mitigation through sourcing, processing and end-product control.

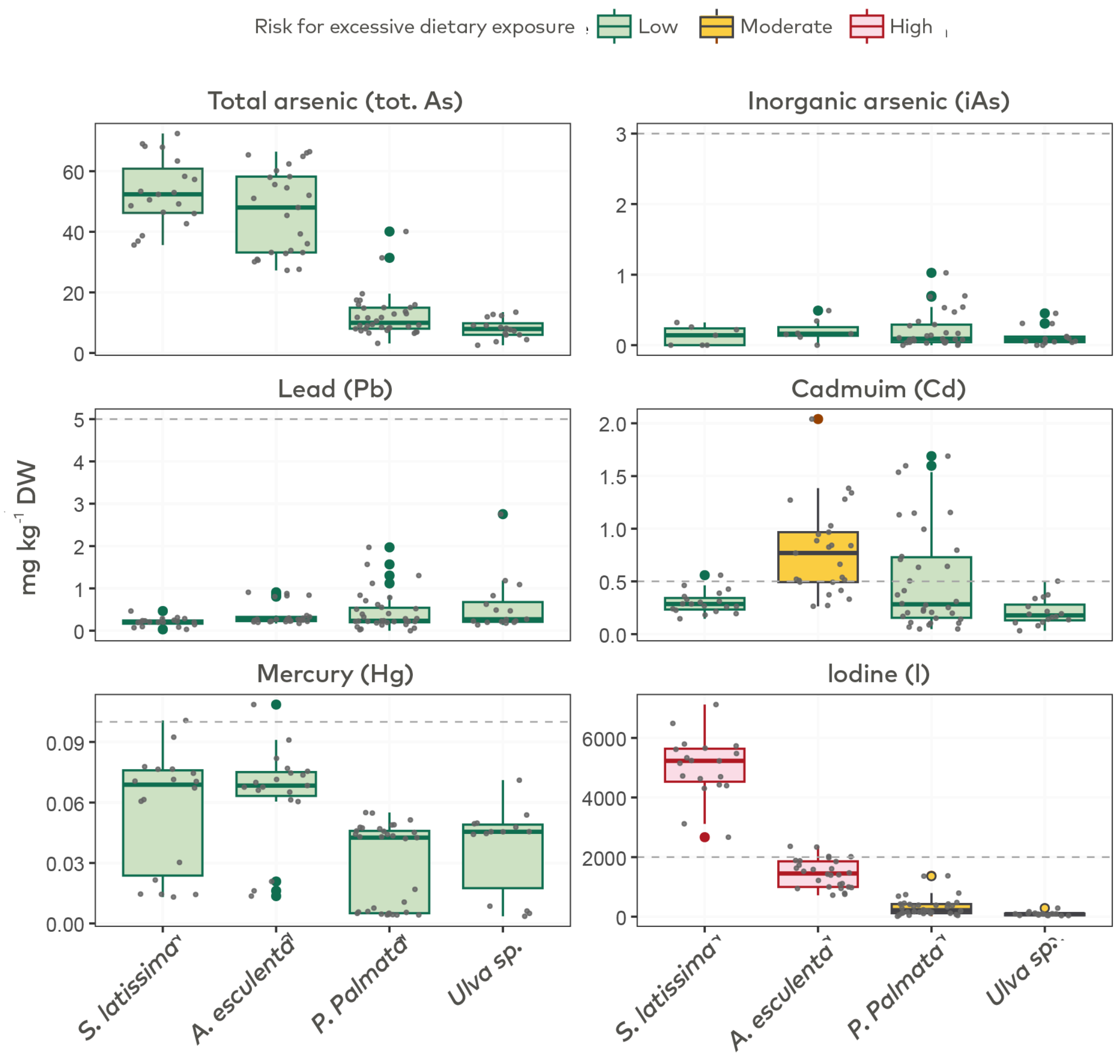

Figure 3: Levels of potentially toxic elements (PTEs) in dried unprocessed samples of *Saccharina latissima* and *Alaria esculenta* (cultivated) as well as in *Palmaria palmata* (wild-harvested) and *Ulva* sp. (cultivated and wild-harvested). The dashed lines represent the current French national recommendations regarding levels of PTEs in edible seaweeds as vegetables or condiments (see Table 4). Data from the SusKelpFood project, the Technical University of Denmark (DTU) and Nordic SeaFarm, obtained from inductively coupled plasma mass spectrometry (ICP-MS). For Hg and Pb, most of the data are below the limit of quantification (LOQ) and hence the values are upper-bound estimates.

3.1. Ongoing regulatory process by EFSA

Current status (as per January 2026)

Seaweed is the world's largest aquaculture product in volume, and its production is expected to grow in the coming years. However, while EU legislation establishes maximum levels (MLs) for several contaminants in foods, seaweed-specific thresholds remain limited and are currently most developed for food supplements and selected national guidelines (FAO and WHO 2022; AFSSA 2009). In Europe, MLs for various PTEs in foods, including heavy metals but excluding iodine, are established under EC food legislation (EU No 2023/915). However, seaweed-specific MLs for use as food are currently restricted to a French national recommendation (CSHPF 1990; AFSSA 2009) and a section of the EC food legislation applying only to seaweed used as food supplements (EU No 2023/915) (Table 4). In recent years, the European Food Safety Authority (EFSA) identified seaweed consumption as an emerging risk for public health and the EC recommended monitoring of PTEs and iodine for future risk management of seaweed as food and feed (EU No 2018/464). A recent initiative by the national food authorities of the Nordic countries (Norway, Iceland, Denmark, Sweden, and the Faroe Islands) recommends developing harmonised legislation on seaweed food safety, with seaweed classified as a distinct group of foodstuffs (Hogstad et al. 2023).

Table 4: Overview of maximum limits (MLs) for relevant contaminants in seaweeds as food (French recommendation) or food supplements in Europe.

	MLs in mg kg^{-1} DW	
	France [1]	EU (food supplements) [2]
Inorganic arsenic (iAs)	3.0	No regulation
Lead (Pb)	5.0	3.0
Cadmium (Cd)	0.5	3.0
Mercury (Hg)	0.1	0.1
Iodine (I)	2,000	No regulation

[1] National recommendation applied to seaweeds as vegetables or condiments (CSHPF 01/1990; AFSSA 04/2009);
[2] MLs for food supplements (Commission Regulation (EU) 2023/915)

Ongoing process

Based on monitoring PTE concentrations in edible seaweeds commercialized in Europe (EFSA et al. 2023), threshold values for cadmium, lead and inorganic arsenic were drafted by EFSA following a hearing process, specifically to seaweed groups (brown, red, green) or in some cases species, but not yet adopted (SANTE PLAN 2025). The proposed ML values are based on occurrence data and aim to exclude samples with concentrations well above typical levels, such as those affected by environmental pollution. In addition, a ML for iodine was suggested. In this draft, the suggested ML for cadmium is 3.0 mg kg^{-1} in brown and 4.0 mg kg^{-1} in red and green seaweeds. In contrast, the iodine threshold was set as low as 1,000 mg kg^{-1} DW (as sold seaweed product e.g., fresh, dried flakes, dried powder, fermented), a change that is expected to have significant consequences for companies producing seaweed (particularly kelp species) for food applications. As of January 2026, input from research and industry stakeholders has highlighted the need for proportionate risk management, including (i) clear consumer labelling and dietary guidance, and (ii) a stronger focus on iodine levels in final foods and portion-based exposure rather than restrictive limits on raw seaweed ingredients alone. This approach would avoid unnecessarily constraining innovation, particularly for kelp-based seasonings and other low-inclusion food applications.

3.2. Iodine

Iodine is an essential micromineral involved in the synthesis of thyroid hormones, namely thyroxine (T4) and triiodothyronine (T3), which play a key role in foetal growth, brain development of children and regulates metabolic functions. Iodine deficiency is a recognized problem globally and particularly among the European population (Andersson et al. 2007; de Benoist et al. 2008). Iodine deficiency disorders (IDDs) include hypo- and hyperthyroidism, goitre, cretinism, increased infant mortality and impaired child growth and development. High iodine intake is generally well tolerated by healthy adults, as excess iodine is not absorbed by the thyroid gland (Wolff-Chaikoff effect) but excreted in the urine. However, vulnerable groups such as pregnant and lactating women, young children, elderly and individuals with known or undiagnosed thyroid disorders may experience dysfunction, leading to symptoms resembling IDDs, as well as thyroid autoimmunity (Farebrother et al. 2019).

Dietary exposure and risk

The EFSA recommends a daily adequate intake (AI) of iodine of 150 μg day^{1} for adults (EFSA 2014) and a tolerable upper intake level (UL) of 600 μg day^{-1} (EFSA 2006). Common dietary sources of iodine are white fish, eggs and milk. From a toxicological perspective, iodine is a challenging element, since there is a small window of suitable iodine intake levels. Several physicochemical properties and physiological mechanisms (e.g., Wolff-Chaikoff effect) indicate that occasional high intakes (acute exposure) are generally not problematic, whereas substantially lower sustained daily intakes (chronic daily exposure) can pose a risk (FAO and WHO 2022). Occasional high iodine intake from seaweed has not yet been formally risk-assessed; however, emerging evidence suggests that such exposures may also present risks in individuals without identified sensitivity (Blikra et al. 2024c). Consequently, establishing a single fixed ML for iodine in seaweed foods is challenging, underscoring the critical importance of clear dietary guidelines and consumer advice. Extra care should be taken when incorporating iodine-rich kelp ingredients into foods intended for daily consumption, ensuring low inclusion levels so that iodine intake per portion remains well below the UL (Max Hansen, Toxicologist and Food Authority advisor, DTU Food, pers. comm. 2025).

Iodine and food safety in seaweeds

Brown seaweeds generally contain higher levels of iodine compared to other foods, with kelp species (*Laminariales*) being the highest iodine accumulators among all living systems (Ar Gall et al. 2004). Among edible kelps, species of the *Laminaria* and *Saccharina* genera (*Laminariaceae* family), contain higher levels of iodine than species of the *Alaria* and *Undaria* genera (*Alariaceae* family) (Blikra et al. 2022a) (**Figure 3**). Iodine in kelps has a physiological role as inorganic antioxidant, and a role in defence against bacterial grazing has also been suggested (Küpper et al. 2008). Iodine accumulates in the form of iodide (I^-) (Küpper et al. 2008). Jerše et al. (2023) showed that in all seaweeds studied within the brown, red and green species, iodide was the predominant species, constituting between 65% and 100% to the sum of the iodine species. Iodide is highly water-soluble and bioavailable to the human body compared to other forms. *In vivo* studies estimate the bioavailability of iodine from *S. latissima* and *A. esculenta* to range between 57% and 78% (Blikra et al. 2022a; Fjære et al. 2022). Hence, the iodine concentration in kelps is one of the main food safety concerns regarding the increasing interest in seaweeds as food. Considering the AI and UL, only small amounts of unprocessed dried kelp (approx. 1 g and below depending on the species) should be consumed to prevent exceeding these limits (Aakre et al. 2021; Jacobsen et al. 2023; Blikra et al. 2024c; Stévant et al. 2025a). Red and green seaweeds (e.g., *P. palmata* and *Ulva* sp.) typically have lower iodine levels (**Figure 3**) (Biancarosa et al. 2018; Duinker et al. 2020) and therefore, do not represent a high risk of excessive dietary iodine exposure. However, these iodine concentrations are still much higher than other high iodine foods such as white fish (typically between 3 and 10 mg kg^{-1}). Moreover, food processing methods (e.g., blanching at 40–100 °C) can significantly reduce the iodine concentration in kelps and, therefore, the risk of excessive iodine exposure upon consumption.

Processing and iodine reduction

Blanching is an effective strategy to reduce the iodine content of kelps, while pulsed electric field (PEF) treatment can also achieve iodine reduction, although typically to a lesser extent. Optimisation and practical implementation of post-harvest processing are addressed in the **Chapter 4**. Iodine reduction may also occur during conservation processes, such as fermentation (Bruhn et al. 2019; Krook et al. 2024), acid preservation (Krook et al. 2024), salt-pickling (Klein et al. under review) and freezing/thawing (Stévant et al. 2024; Sund et al. 2024), during which iodine leaks into the liquid fraction. However, the extent of reduction achieved through these methods is generally lower than that obtained with blanching or PEF treatment.

Future perspectives

Edible seaweeds contain iodine at varying levels, which can be adjusted to predictable ranges through processing. Importantly, iodine-related risk is a function of intake and consumption frequency rather than iodine concentration in the raw material alone. Commercially available seaweeds therefore represent a valuable plant-based source of dietary iodine, particularly for populations at risk of deficiency. Minimally processed kelp included at low levels in foods can provide natural iodine without extensive reduction steps, while also contributing desirable flavour characteristics in products such as dehydrated soups and seasonings, with iodine levels per portion remaining well below the tolerable upper intake level (UL) (Krook et al. 2023). Establishing strict MLs for iodine concentration in raw seaweed would likely exclude some of the most economically important species produced in Europe (e.g., *Saccharina latissima*), as well as entire product categories such as dehydrated condiments and seasonings, without necessarily improving consumer protection. Raw materials marginally below a proposed ML could still lead to excessive iodine intake when used at high inclusion levels. The development of seaweed-based food products would benefit from focusing on the iodine content in the final product rather than on restrictive limits for raw seaweed ingredients alone. Clear product labelling and tailored dietary guidance will allow kelps and other edible seaweeds to be incorporated sustainably into a variety of food formulations while providing a predictable and nutritionally valuable source of plant-based iodine. This intake-based approach is consistent with existing EU food-safety practice for nutrients such as sodium, for which no MLs are established in foods despite well-documented associated chronic diseases, relying instead on labelling, intake recommendations and national reformulation strategies.

3.3. Arsenic

Arsenic in edible seaweeds

Arsenic is a metalloid occurring in the environment both naturally and through anthropogenic activities, such as the use of fertilizers and pesticides. It exists in both organic and inorganic forms, of which the inorganic forms are considered the most toxic and can be associated with adverse health effects, including lung, skin, and bladder cancers (EFSA 2014). In the kelps *A. esculenta* and *S. latissima*, arsenic is predominantly found in organic forms such as arsenosugars (50%–80% total arsenic) and lower levels of arsenolipids (mostly below 10%) (Pétursdóttir et al. 2019; Sim and Petursdottir 2024), which are regarded as non-toxic or whose toxicity is not yet fully characterized (Taylor et al. 2017; Cubadda et al. 2017). The main contributors of dietary exposure to inorganic arsenic are cereals, rice and drinking water. Inorganic arsenic is usually present at low levels in seafood, with the notable exception of the brown seaweed hijiki (*Sargassum fusiforme*), widely consumed in Asian food traditions, and has been reported to contain 42–117 mg kg^{-1} DW (Almela et al. 2006). Comparable levels have been observed in other species of the *Sargassum* genus e.g., the non-native *Sargassum muticum* found in the Nordic waters. Elevated levels of inorganic arsenic have also been reported in oarweed (*Laminaria digitata*) collected along the Norwegian coast, with concentrations ranging from 0.06 to 79 mg kg^{-1} DW, and 50% of the samples containing more than 24 mg kg^{-1} DW (Duinker et al. 2020). Hence, a warning has been issued by the Norwegian Food Safety Authority regarding *L. digitata*. In general, arsenic concentrations are higher in brown compared to red seaweeds. However, inorganic arsenic levels are low in *A. esculenta* and *S. latissima*, i.e., respectively 0.5% and 0.4% of the total based on the data presented in **Figure 3** (median concentrations below 0.2 mg kg^{-1} DW for both species). Short blanching treatments can reduce the total arsenic concentration by half (Krook et al. 2023; Stévant et al. 2024; Stévant et al. 2025a; Sund et al. 2025a).

Dietary exposure and risk

No MLs for total or inorganic arsenic have been established for seaweeds as food, except the French recommendation of 3 mg kg^{-1} DW for inorganic arsenic (**Table 4**). Most edible seaweed species commercialised in Europe contain inorganic arsenic below this limit, except *hijiki* (*S. fusiforme*) and *L. digitata*. New MLs have recently been proposed for inorganic arsenic, namely 1 mg kg^{-1} DW for brown and green seaweeds and 0.5 mg kg^{-1} DW for red seaweeds. Based on the occurrence data shown in **Figure 3** and in Duinker et al. (2020), cultivated Norwegian kelps (*S. latissima* and *A. esculenta*) would comply with the proposed limit. However, broader datasets from European seaweed-producing countries, covering both cultivated and wild-harvested kelps as well as other edible brown, red and green seaweeds, show that the proposed MLs overlap with observed concentration ranges. While most values remain below the French recommendation, the proposed limits would exclude a substantial share of the produced biomass from the market. Based on current consumption patterns, seaweeds do not pose a significant risk to dietary exposure to inorganic arsenic (Ficheux et al. 2023). Monitoring arsenic levels in end products (e.g., seaweed condiments or seaweed-containing food products) will provide better exposure estimates for risk assessment, as processing steps can influence concentrations. Future risk assessments considering both inorganic arsenic and potentially toxic organic species, are also warranted (Taylor et al. 2017; EFSA et al. 2023).

3.4. Cadmium

Cadmium levels in seaweeds

Human exposure to cadmium is of concern as it can cause kidney failure and is associated with increased risks of cancers (lung, endometrium, bladder and breast) as well as bone demineralisation (EFSA 2012). Seaweeds generally contain low levels of cadmium and under current consumption patterns, they do not significantly increase dietary exposure. They are therefore considered minor contributors to overall cadmium intake (Ficheux et al. 2023; EFSA et al. 2023). Nevertheless, EFSA has highlighted seaweed as a food category with relatively high cadmium concentrations (EFSA 2012). In general, higher levels are reported in brown and red seaweeds compared to green species, although large variations occur both between and within species. Among the most consumed seaweeds, the highest levels have been reported in *Undaria pinnatifida* (*wakame*, 0.72–4.0 mg kg^{-1} DW), and *Porphyra/Pyropia* spp. (*nori*, 0.17–3.4 mg kg^{-1} DW) (Duinker et al. 2020). Relatively high levels are also found in *A. esculenta* (0.26–1.4 mg kg^{-1} DW, **Figure 3**), often exceeding the recommended ML recommended by the French food safety authority (0.5 mg kg^{-1} DW, **Table 6**). However, these concentrations will generally be below the new proposed MLs of 3 mg kg^{-1} DW for brown and green seaweeds and 4 mg kg^{-1} DW for red seaweeds.

Effect of processing on cadmium levels

Cadmium in seaweeds is largely bound to structural cell wall compounds, such as alginates in kelps, meaning levels are not significantly reduced by most processing steps, including blanching (Stévant et al. 2017a; Stévant et al. 2024; Blikra et al. 2024b; Sund et al. 2025b). Processing methods involving low pH, such as fermentation, may partly dissociate cadmium from alginates and thereby lower concentrations, as reported by Bruhn et al. (2019) following the fermentation of *S. latissima* with *Lactobacillus plantarum*. However, this effect was not confirmed in a study investigating acid preservation and spontaneous fermentation of the same species (Krook et al. 2024). In a small trial from the SusKelpFood project, cadmium levels were reduced when using seawater at 45 °C adjusted to pH 2.5 with acid, whereas no reduction was observed at pH 3.7 (Duinker, unpubl. results). Salting treatments, whether brining (Stévant et al. 2017a) or dry salting (Stévant et al. 2024) also appear to reduce cadmium concentrations to some extent.

Dietary exposure and risk

The cadmium contribution from servings of dried warm seawater-treated *A. esculenta* (1.9–4.6 g) with cadmium concentrations of 1.4–1.6 mg kg^{-1} DW has been estimated to provide 12–25% of the tolerable daily intake (TDI), whereas a similar contribution from *S. latissima* was less than 2% (Stévant et al. 2025a), derived from the tolerable weekly intake (TWI) of 2.5 µg (kg body weight $(bw))^{-1}$ $week^{-1}$ (EFSA 2012). In the context of developing seaweed-based foods for larger consumer markets, such contributions highlight the need to monitor cadmium levels in raw materials and finished products, to avoid substantially increasing overall dietary exposure. Cadmium concentrations from *A. esculenta* show substantial site-to-site variability (Roleda et al. 2019). Monitoring within the SusKelpFood project showed higher concentrations in wild-harvested *A. esculenta* compared to cultivated samples (Stévant et al. 2025a, **Appendix table 3**). Current average dietary exposure of the European population to cadmium already ranges from 1.5 to 2.2 µg kg^{-1} bw $week^{-1}$, close to the TWI (EFSA 2012), suggesting that additional dietary sources of cadmium should be limited. In this regard, targeted monitoring of cadmium levels in seaweeds, combined with better understanding of accumulation patterns in *A. esculenta* and other edible seaweeds, will help prevent unintended increases in dietary cadmium exposure.

Bioavailability

The chelation of cadmium by alginates in kelp suggests that its bioavailability in the human body may be low. This is supported by Fjære et al. (2022), who reported that 93% of ingested cadmium was excreted by rats fed with *S. latissima*. However, they also found elevated cadmium levels in the liver and kidney tissues of rats receiving a high-kelp diet (5%). Further research is needed to clarify cadmium bioavailability and metabolism in humans following seaweed consumption.

3.5. Lead

The presence of lead in the environment largely results from anthropogenic activities such as mining, manufacturing (e.g., batteries, ammunition), and the historical use of lead in paints and petrol. Human exposure to lead occurs through food, water, air, and dust particles. Lead exposure is associated with adverse effects on multiple body systems, including cardiovascular, renal, gastrointestinal, and reproductive functions. The most critical issue of lead exposure remains for children, as even a low exposure can result in impaired cognitive development and reduce intellectual performance (EFSA 2010).

Lead levels in seaweeds

MLs for lead in foodstuffs range from 0.01 mg kg^{-1} wet weight (WW) for infant liquid formulae to 1.5 mg kg^{-1} WW for bivalve molluscs (EU No 2023/915). MLs for seaweed are defined on a DW basis, likely reflecting the predominance of dried products on the marked. So far, only the French limit of 5.0 mg kg^{-1} DW for dried seaweeds and the EU ML of 3.0 mg kg^{-1} DW for food supplements consisting of seaweeds have been established (**Table 4**). Reported concentrations in most edible species are below 1.0 mg kg^{-1} DW and often below the limit of quantification (LOQ) of the analytical methods (**Figure 3**). However, occasional higher levels have been observed in *A. esculenta* and *S. latissima* (Duinker et al. 2020), as well as *Ulva* spp. (Desideri et al. 2016; Jacobsen et al. 2023). Newly proposed MLs, based on occurrence data, are 1.5 mg kg^{-1} DW for brown, and 2.0 mg kg^{-1} DW for green and red seaweeds except for *Pyropia*/*Porphyra* spp., for which a lower ML of 0.5 mg kg^{-1} is suggested. Based on the concentration data presented here for the four main edible seaweed species commercialized in Europe, compliance with the proposed MLs can generally be expected. However, monitoring data from a wider geographic range across Europe and including several edible species (data not shown) suggest that these limits may exclude a substantial share of seaweed samples from the market.

Risk assessment

Since no evidence supports a threshold exposure level for several critical health endpoints of lead (e.g., nephrotoxicity, developmental neurotoxicity), previous toxicological guidelines are no longer considered appropriate. Instead, risk assessment is now based on the margin of exposure (MoE) approach (EFSA 2010). Stévant et al. (2025a) calculated MoE for lead intake from iodine-reduced kelp with kelp portions limited by the UL for iodine (600 µg day^{-1}), and found MoEs corresponding to exposure levels that can be regarded as low and of no appreciable risk. Similar calculations can be done with other species and intake scenarios. A risk assessment based on current consumption patterns in Western Brittany, France, concluded that seaweed are relatively low contributors to dietary lead exposure (Ficheux et al. 2023). EFSA similarly notes that increased seaweed consumption may contribute to lead exposure, but generally within the range of existing dietary exposure, depending on species and consumption levels (EFSA et al. 2023). In this context, the proposed MLs for lead in seaweed appear more stringent than those applied to other seafood. For example, the ML for lead in shellfish is 1.5 mg kg^{-1} WW, corresponding to approximately 10 mg kg^{-1} DW (assuming a dry matter content of 15%). Harmonization with comparable food categories will help maintain a high level of consumer protection while avoiding disproportionate regulation. In addition, establishing relevant MLs using a percentile-based methodology requires robust and representative data covering European population and measured across various production systems and seaweed species.

3.6. Mercury

Regulatory status

Under Regulation (EC) No 2018/73 a maximum residue level (MRL) for mercury in algae and prokaryotic organisms is established at the default level of 0.01 mg kg^{-1}. This limit is considerably lower than the MLs applied to other seafood commodities such as fish and bivalves, and it remains uncertain whether this MRL will be implemented in practice. Mercury is also not included among the MLs proposed by EFSA for seaweeds in 2025.

Mercury in seaweeds

In seaweeds, most measured mercury concentrations fall below the LOQ (**Figure 3**). The LOQs themselves vary due to differences in sample dilution, which is often necessary because of the high salt content in seaweed and can lead to elevated LOQs. In the SusKelpFood dataset, the highest upper-bound mercury values corresponded to LOQ values. Therefore, differences between species cannot be meaningfully interpreted based on these results. Overall, mercury concentrations in seaweed are generally low (Duinker et al. 2020), and consequently, the dietary exposure risk is considered low.

3.7. Microbiological safety

General facts on microbiological safety of seaweeds

Compared with iodine and PTEs, the evidence base for seaweed-specific microbiological risk patterns is more heterogeneous and strongly dependent on processing and handling practices. Bacterial pathogens on seaweeds for human consumption may originate from two main sources: the environment in which they are grown and contamination from equipment and humans during post-harvest handling and processing. While bacterial density and composition often reflect the surrounding water, the seaweed-associated microbiota is typically distinct from seawater communities (Chan and McManus 1969; Hollants et al. 2013). High initial bacterial loads can reduce shelf-life and sensory quality of seaweeds, but do not necessarily make the product unsafe. Conversely, low bacterial counts do not guarantee safety, as toxin-producing pathogens may cause illness even at low levels. Human pathogens are generally assumed to occur on seaweeds in similar densities as in surrounding waters; hence, cultivation or wild-harvesting sites near polluted coastal areas pose a higher risk. Seaweed harvested from clean waters, i.e., away from harbours and agricultural and industrial run-off areas, are considered safe in Denmark (Hendriksen and Lundsteen 2014). A Norwegian risk assessment concluded that the likelihood of foodborne disease from consuming seaweed is no greater than that of other non-filter-feeding marine organisms, including fish (Duinker et al. 2020). However, contamination or recontamination may occur during handling and processing (Sakon et al. 2018; Banach et al. 2020).

Main risks

According to Løvdal et al. (2021), the main bacterial groups of concern in seaweeds are *Bacillus* spp., *Vibrio* spp., and *Aeromonas* spp. *Bacillus* forms heat-resistant spores and produces heat-stable toxins, while *Vibrio* and *Aeromonas* can grow under chilled conditions. Other pathogens, such as *E. coli*, *Salmonella* spp., *Staphylococcus aureus*, *Listeria monocytogenes*, Norovirus, and Hepatitis A virus, can mainly be introduced by accidental contamination. Occasionally, *Campylobacter*, *Shigella*, yeasts and moulds may be reported, typically following serious hygiene failures. The occurrence and concentrations of pathogenic microorganisms found in edible seaweeds harvested in Europe are summarised in Table 5. Seaweed products are considered safe when pH remains below 4.3 at 4 °C (or below 3.8 at higher temperatures), provided water activity limits pathogen growth (Løvdal et al. 2021)

Table 5: Food pathogens detected in edible seaweeds in Europe.

Pathogens	Seaweed species	Product types	Location, Year	Concentration (CFU g^{-1})	Reference
Bacillus licheniformis	*A. esculenta*	Raw	West Norway, April 2015	< 200	Blikra et al. (2018)
Bacillus pumilus	*A. esculenta*	Raw		< 200	
Bacillus subtilis/ amyloliquefaciens	*S. latissima*	Raw		< 200	
Bacillus licheniformis	*S. latissima*	Raw		< 200	
Bacillus pumilus	*S. latissima*	Raw		< 200	
Bacillus spp.	*L. digitata*	Raw	West Norway, March 2015	257	Løvdal et al. (unpubl. results)
Bacillus spp.	*S. latissima*	Raw		240	
Bacillus spp.	*A. esculenta*	Raw		226	
Bacillus spp.	*A. esculenta*	Raw		1,109	
Bacillus spp.	*A. esculenta*	Blanched (85 °C, 15 min)		< 100	
Bacillus spp.	*S. latissima*	Raw		245	

Bacillus spp.	*S. latissima*	Blanched (100 °C, 15 min)	< 100		
Bacillus spp.	*S. latissima*	Fresh	Sweden, April 2021	n.d.	Jönsson et al. (2023a)
Clostridium spp.	*S. latissima*	Fresh		n.d.	
Bacillus spp.	*S. latissima*	Frozen		n.d.	
Bacillus subtilis	*H. elongata*	Blanched (85 °C, 15 min)	Ireland, September 2008	n.d.	Gupta et al. (2010)
Bacillus subtilis	*L. digitata*	Blanched (85 °C, 15 min)	Ireland, September 2008	n.d.	
Bacillus subtilis	*S. latissima*	Blanched (85 °C, 15 min)	Ireland, September 2008	n.d.	
Bacillus licheniformis	*S. latissima*	Blanched (85 °C, 15 min)	Ireland, September 2008	n.d.	
Bacillus spp.	*A. esculenta*	Dried	Scotland, 2019	~ 10,000	Lytou et al. (2021)
Bacillus spp.	*A. esculenta*	Dried	Scotland, 2020	~ 1,000	
Bacillus spp.	*S. latissima*	Dried	Scotland, 2019	~ 1,000	
Bacillus spp.	*S. latissima*	Dried	Scotland, 2020	~ 1,000	
Yeasts/Molds	*A. esculenta*	Dried	Scotland, 2019	~ 1,000	
Yeasts/Molds	*A. esculenta*	Dried	Scotland, 2020	~ 100	
Yeasts/Molds	*S. latissima*	Dried	Scotland, 2019	~ 1,000	
Yeasts/Molds	*S. latissima*	Dried	Scotland, 2020	~ 100	
Vibrio alginolyticus	*A. esculenta*	Dried	Scotland, 2020	n.d.	
Listeria monocytogenes	*A. esculenta*	Dried	Scotland, 2020	n.d.	
Moulds	*P. palmata*	Dried	France/ November 2017	350–830	Stévant et al. (2020)

Reported concentrations are given as colony-forming units (CFU) per gram, except for Jönsson et al. (2023a) and Gupta et al. (2010), where microbial characterisation was performed using high-throughput sequencing (16S rRNA amplicon).

Bacillus spp

Occurrence of *Bacillus* species has been reported on edible seaweeds and products, including cultivated kelp (Blikra et al. 2018; Lytou et al. 2021) and wild-harvested seaweed (Gupta et al. 2010) in Europe, and ready-to-eat (RTE) seaweed-based foods (Martelli et al. 2021). Although *Bacillus* levels on fresh seaweed are generally low, further growth may occur during improper handling and storage. Modelling studies of RTE *kimbap* (popular Korean dish made of cooked rice and various fillings in a sheet of *nori*) show that manual preparation and room-temperature storage strongly promote *B. cereus* proliferation (Park et al. 2005). Illness is linked to their toxin production, typically occurring above ~10^5 colony forming units (CFU) per gram (Salkinoja-Salonen et al. 1999; Granum and Braid-Parker 2000). *Bacillus* spores are highly resistant, tolerating over 100 °C and pH below 3.0 for several minutes (Setlow 2006), though they cannot reproduce under such conditions. Once favourable conditions return, spores may germinate, grow, and produce toxins. After heat treatment, non-spore-forming bacteria are generally eliminated, and spore-forming bacteria can proliferate faster than in untreated products. For seaweed, similar precautions as for rice are recommended, i.e., cooked product should be cooled quickly to prevent outgrowth of *B. cereus* or *Clostridium perfringens.*

Vibrio spp

Pathogenic *Vibrio* species, i.e., *V. parahaemolyticus* and *V. vulnificus*, have been detected on both wild and cultivated seaweeds across different species and growing conditions (Mahmud et al. 2007; Mahmud et al. 2008; Musa and Wei 2008; Kudaka et al. 2008; Barberi et al. 2020). Their occurrence indicates a potential food safety risk when seaweeds are consumed raw and underscores the need for strict hygiene during post-harvest handling, particularly during summer when *Vibrio* levels peak. *Vibrio alginolyticus,* a potential but uncommon foodborne pathogen, was isolated from fresh *A. esculenta* cultivated in Scotland, but not from dried samples (Lytou et al. 2021), while no *Vibrio* spp. were found in wild *P. palmata* from Ireland (Moore et al. 2002). *Vibrio parahaemolyticus* and *V. vulnificus* are well-known causes of illness from other seafoods such as prawns and oysters (Honda and Iida 1993; Sumner and Ross 2002), but cases of food poisoning linked to *Vibrio* spp. in seaweed are extremely rare. *Vibrio* spp. are sensitive to thermal processing but may survive mild drying. For instance, low levels (below 10 CFU g^{-1}) were found in low-temperature dried *Ulva lactuca* from Turkey, suggesting incomplete inactivation (Karacalar and Gamze 2008). Therefore, suitable handling procedures are crucial, particularly for seaweeds consumed raw or lightly processed.

Aeromonas spp

Aeromonas spp. are potential foodborne pathogens which may occur on seaweeds and survive or grow at chilled temperatures. Most studies have dealt with *A. hydrofila*, which have been implicated in many seafood-borne outbreaks, but evidence of seaweed-specific outbreaks is scarce. However, based on their indigenous aquatic prevalence, *Aeromonas* spp. could be expected to colonize seaweeds and possibly follow the raw material to processing. Occasional detections of *Aeromonas* spp. in e.g., air-dried *Ulva reticulata* from Malaysia (Vairappan and Suzuki 2000), and fresh *Chondrus crispus* and *Chondracanthus teedii* from Italy (Ziino et al. 2010) suggest the need for attention to hygiene and cold-chain handling.

Escherichia coli, Salmonella spp., *Listeria monocytogenes, Staphylococcus aureus and other pathogens*

Studies show variable contamination levels, with generally low counts in most regions but occasional detections near pollution sources. In Maine, USA, *E. coli* and *Vibrio* spp. were found on farmed *S. latissima* from multiple sites although at low levels (Barberi et al. 2020). The same study also reported the detection of *Salmonella* and enterohemorrhagic *E. coli* in several kelp samples subjected to a microbiological enrichment step (i.e., to detect microbes present in small numbers) prior to characterisation using molecular methods. Several European studies did not detect gastrointestinal pathogens on wild or farmed seaweeds (Liot et al. 1993; Moore et al. 2002; Gupta et al. 2010; Duinker et al. 2020). In Norway and Scotland, *L. monocytogenes*, *Salmonella*, *E. coli*, and *S. aureus* were largely absent (Blikra et al. 2018; Lytou et al. 2021), with one *A. esculenta* sample positive for *L. monocytogenes* likely contaminated during handling (Lytou et al. 2021). RTE products containing seaweed tend to show higher contamination rates, likely due to handling failures rather than the seaweed itself. Hygiene surveys of Korean *kimbap* frequently reported *S. aureus*, *B. cereus*, and occasionally *Salmonella* (Park et al. 2005; Cho et al. 2008; Kim et al. 2008).

Other potential hazardous microorganisms include:

- *Campylobacter jejuni* and *Yersinia enterocolitica*: rarely detected but may grow under refrigeration upon contamination.
- *Clostridium* spp.: occasionally detected in *nori*, but not the pathogenic species *C. botulinum* nor *C. perfringens* (Choi et al. 2014).
- *Shigella* spp.: detected in a minority of *kimbap* samples using enrichment methods (Cho et al. 2008).
- Yeasts and moulds: generally absent from fresh seaweed; may appear during prolonged storage of dried products (Stévant et al. 2020).

Viruses

Norovirus and Hepatitis A virus are the main foodborne viruses relevant to seaweed. Several outbreaks, in Asia (Kusumi et al. 2017; Sakon et al. 2018) linked to dried, shredded, or uncooked *nori* contaminated during processing or handling, and in Norway from a contaminated wakame salad (Folkehelseinstituttet 2019).

Norovirus is environmentally robust and can remain infectious for months under dry conditions. Heat treatments ≥ 90 °C for longer than 90 seconds effectively inactivate enteric viruses, but post-processing contamination remains a key risk (Bosch et al. 2018). Refrigeration and freezing do not eliminate viral infectivity.

3.8. Allergens

Allergens in seaweeds

To date, seaweed protein is not among the established food allergens, and there is limited data on the allergenicity of seaweed proteins by themselves (Garciarena et al. 2022). Proteins extracted from *Ulva* sp. were annotated to known allergens using sequence similarity (Polikovsky et al. 2019), however, assessing the allergenic potential of novel proteins is a complex process, as complete allergens need to bind IgE-antibodies, elicit an allergic reaction, and have *de novo* sensitisation capacity (Verhoeckx et al. 2019). On the other hand, seaweed farming infrastructure in the marine environment creates habitats for a variety of fish and shellfish species. The marine food allergens crustacean and mollusc tropomyosin and fish parvalbumin have previously been detected in edible seaweeds (Motoyama et al. 2007; Mildenberger et al. 2022). The European food regulation imposes the labelling of specified allergenic foods when used or added to food products and encourages the precautionary labelling of unintentionally occurring allergens (EU No 1169/2011). Therefore, to enable the broad inclusion of seaweeds in food products, the allergenic potential of seaweed-based ingredients must be better characterized in relation to different seasons and locations.

Regulation and product labelling

The European food regulation (EU No 1169/2011; article 36) also states that voluntary information should not be misleading or ambiguous, and should be based on scientific data to not unnecessarily restrict the available food products for allergenic customers. The Voluntary Incidental Trace Allergen Labelling (VITAL®) approach was developed over time to establish a program of risk-based precautionary allergen labelling (PAL) (Allergen Bureau 2024a). The key parameter in the current risk assessment framework (VITAL 4.0) is the eliciting dose (ED), specifically ED_{05}, which is used as the reference dose. ED_{05} represents the amount of protein from a given allergenic food below which only 5% of the allergic population is expected to experience objective symptoms (Allergen Bureau 2024b). ED_{05} has been adopted in place of the more conservative ED_{01} used in the previous VITAL 3.0 framework with the aim to increase food choice for allergic consumers while maintaining a minimal risk to public health. With ED_{05}, it is still extremely unlikely that life-threatening reactions occur, and allergic symptoms will be mild or moderate for most (>95%) of the 5 % of reacting allergic consumers (Allergen

Bureau 2024b). VITAL 4.0 additionally includes a reference dose for molluscs, which was missing in the previous framework. Consumer exposure to allergenic proteins further depends on the quantity of the food typically consumed in a single eating occasion (referred to as the reference amount). Action levels (ALs) are defined to guide when precautionary allergen labelling (PAL) should be used. AL1 indicates that PAL is not recommended, while AL2 means that PAL is warranted. The cut-off between AL1 and AL2 corresponds to the amount of allergenic protein in a typical serving (reference amount) that would expose consumers to the reference dose (ED_{05}), i.e., the level at which allergic reactions could occur (FAO and WHO 2023; Allergen Bureau 2024a). The recommended reference doses for seafood allergens from current and previous VITAL risk assessment frameworks, as well as AL transition points and the highest measured levels of this study are summarised in Table 6.

Table 6: Recommended reference doses for seafood allergens from the current and previous Voluntary Incidental Trace Allergen Labelling (VITAL) risk assessment frameworks (Allergen Bureau 2024b). Calculated action levels (AL) transition points based on VITAL 4.0 values and a reference amount of 3 g, and the highest levels detected in the raw seaweed samples during the SusKelpFood project, shown as organism protein. For conversion factors and calculations, see Mildenberger and Rebours (2025).

	Reference doses (mg protein)			
Allergen (protein)	**VITAL 3.0 [a]**	**VITAL 4.0 [b]**	**AL transition point (mg kg^{-1}) [c]**	**Highest amount detected (organism protein, mg kg^{-1}) [d]**
Fish (parvalbumin)	1.3	5.0	1,667	21.3
Crustacea (tropomyosin)	25	200	66,667	560
Mollusc (tropomyosin)	-	20	6,667	4,047

Reference doses based on [a] ED_{01} and [b] ED_{05}.

[c] based on VITAL 4.0 values and a reference amount of 3 g.

[d] in raw/unprocessed seaweed samples.

Risk assessment

In the SusKelpFood project, the occurrence of marine allergens was investigated in samples of cultivated kelp (*A. esculenta* and *S. latissima*) collected over two consecutive years from four Norwegian farms and covering several cultivation and post-harvest methods (Mildenberger and Rebours 2025). Crustacean, mollusc, and fish allergens were detected in many of the samples, regardless of the kelp species, at varying levels and with no consistent distribution pattern (**Figure 4**). All detected concentrations remained below levels of food safety concern (**Table 6**), even with the more conservative ED_{01} values, and would not require PAL. While the detected levels of crustacean and fish were clearly lower than the AL transition points, calculation with the newly adopted reference dose for mollusc shows that mollusc is closest to its AL transition point and thus closest to requiring PAL. Crustacean tropomyosin exhibited the highest variability among the samples (**Figure 4**). It has previously been suggested that a minimum of eight subsamples might be needed to improve the confidence of the estimate for this analysis (Faassen et al. 2024). The results of the study further suggested that position within a single farm (upstream vs. downstream), cultivation method (direct seeding vs. twine seeding) and timing of harvest (early vs. late) may affect the occurrence of crustacean and mollusc tropomyosin. Extensive complementary data would be needed to identify the factors influencing the presence of marine allergens in seaweeds cultivated in open-water environments. Food processing steps including blanching and fermentation as performed and assessed in the study did not affect the concentrations of marine allergens (Mildenberger and Rebours 2025), but reports of reduced allergenicity after processing exist (Fu et al. 2019; Dong and Raghavan 2022; Healy et al. 2024; Dong et al. 2025). Thus, if needed, it might be possible to optimize the processing to further limit the allergenicity of kelp products. Considering the VITAL 4.0 reference doses, it seems that efforts to reduce allergens in kelp products might be most relevant to be targeted to reduce mollusc allergens. Homogenisation of several batches reduced the variation, making this a preferred stage for allergen analysis. Nevertheless, care must be taken to avoid cross-contamination e.g., from other production lines. The study of Mildenberger and Rebours (2025) used ELISA as detection method, which is a recognized method for the evaluation of allergens as it is based on the direct recognition of proteins (Allergen Bureau 2023). A verification by other methods could be needed in future studies if a reduction in allergen levels is suspected to be due to protein denaturation.

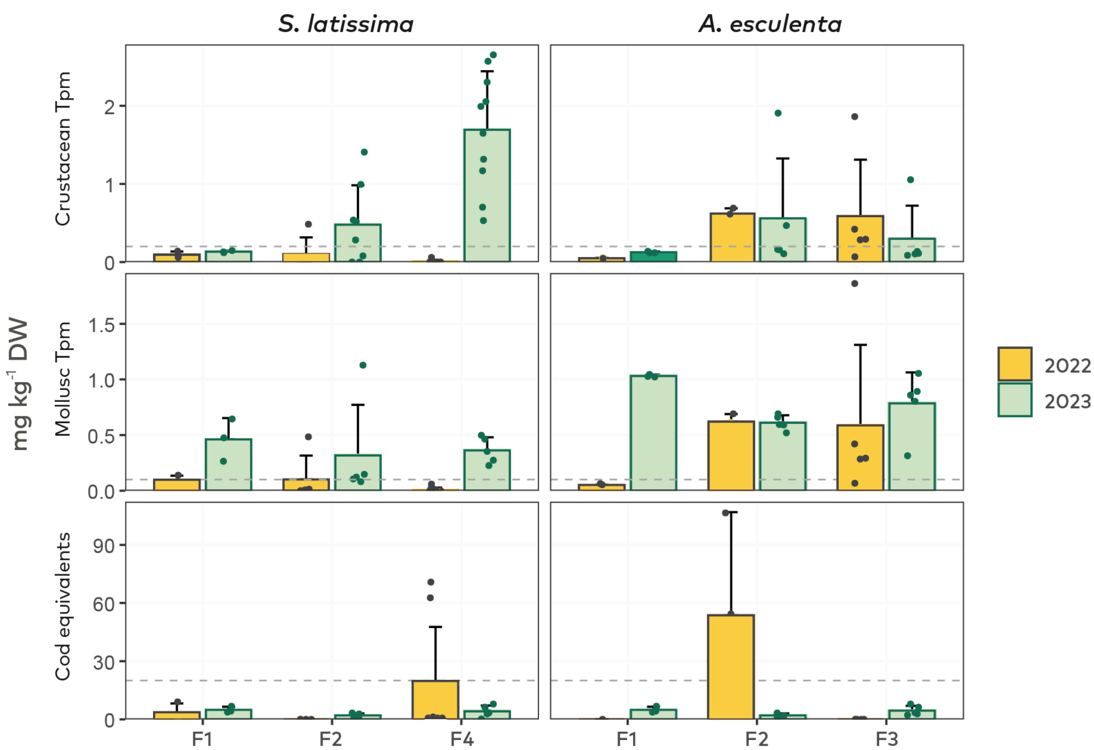

Figure 4: Assessment of the levels of marine allergens including crustacean and mollusc tropomyosin (Tpm) and fish parvalbumin (cod equivalents) in samples of *Saccharina latissima* and *Alaria esculenta* from Norwegian commercial kelp farms (F1–F4), where the same species was available from both 2022 and 2023. Values are given as mean ± st. dev. (*n* ranges from 3 to 10). The dashed lines indicate the low quantification limits of the assays. Data from Mildenberger and Rebours (2025).

Recommendations

According to the VITAL guidelines, all farmed seaweed that were analysed for allergens in the SusKelpFood project, fall into the category AL1 which does not require PAL, except for one batch contaminated during processing. The food producer is ultimately responsible for appropriate allergen labelling. The variability in the occurrence and diversity of marine organisms associated with seaweed farms as potential sources of food allergens, particularly in the context of a changing climate, warrants routine, batch-wise analysis prior to the inclusion of seaweeds in food products.

3.9. Conclusions

While seaweeds are a valuable source of nutrients, their frequent consumption by large population groups is not without risks. The main food safety concern in Europe relates to their high iodine content, particularly in kelp species, and the potential for excessive dietary exposure if seaweed-based foods are consumed in large quantities. At the same time, iodine deficiency remains an established public-health issue in Europe. When incorporated in appropriate forms and at suitable levels, seaweeds can provide a useful source of dietary iodine without exceeding safe intake levels. Other potentially harmful elements such as inorganic arsenic, cadmium and lead, as well as marine allergens, are also present in seaweeds. Although current data indicate that these are not major contributors to dietary exposure, their concentrations vary widely between species and can be influenced by environmental conditions and processing methods. Ensuring the safe use of seaweed ingredients therefore requires a robust food-safety management system, including good production and processing practices and careful monitoring of contaminants.

- **Iodine:** Seaweeds, particularly kelp species, contain naturally high levels of iodine, posing a risk for frequent consumption, particularly in sensitive groups (e.g., pregnant women, children, thyroid disorders). Safe use requires **low inclusion levels and portion-based control of iodine in final products**; processing (e.g., blanching) can substantially reduce iodine. Red and green species typically present **lower iodine risk** under realistic intake patterns.
- **Non-essential metals (i.e., inorganic arsenic, cadmium, lead, mercury):** Seaweeds can accumulate PTE's, with levels varying by **species and site**. Under current consumption patterns, they are generally **minor contributors** to dietary exposure, but routine monitoring remains important. More research is needed on **bioavailability and absorption** in humans.
- **Microbiological safety:** Microbial hazards primarily relate to **growing-site water quality** and **post-harvest handling**. The main bacterial groups of concern include *Bacillus*, *Vibrio* and *Aeromonas* species. HACCP-based controls, effective cooling/storage, and prevention of cross-contamination are essential.

- **Marine allergens:** Seaweeds may contain trace seafood allergens from co-occurring marine organisms (i.e., fish, crustaceans, molluscs). Available data indicate levels **below thresholds requiring precautionary allergen labelling (PAL**), but variability and occasional contamination justify **batch-wise checks and good hygiene.** Homogenising small batches prior to testing can help reduce analytical variability.
- **Regulatory framework:** Harmonised EU legislation for seaweed as a distinct food category is still evolving (as of January 2026), including maximum levels (MLs) for iodine and selected contaminants. For iodine, **portion-based limits, labelling and dietary advice** may be more effective than strict MLs for raw ingredients, which could disproportionately restrict the use of kelp in food at low inclusion levels. Representative occurrence data are needed to set proportional MLs for non-essential metals across species and groups.

4. Post-harvest processing

Seaweeds are highly perishable marine resources due to high water content, and biomass quality can degrade rapidly after harvest (e.g., upon exposure to air). EU strategic goals include scaling seaweed production to around 8 million tonnes by 2030 (Vincent et al. 2020), a substantial increase from current levels. Scaling production to meet European ambitions will require stabilising and processing large volumes of wet biomass within a short timeframe. Post-harvest handling and processing therefore remain a key bottleneck for upscaling seaweed value chains.

This chapter outlines how harvested seaweed biomass can be handled, stabilised, and transformed into food ingredients, and how processing choices critically influence product safety, nutritional quality, shelf-life, sustainability, and economic viability. **Post-harvest handling** encompasses all operations from harvest until the biomass is stabilised or converted into a product, including transport, size reduction and storage. The methods addressed in this chapter can be broadly grouped into pre-processing (or pre-treatment) methods and stabilisation methods.

Pre-processing methods are short treatments typically applied soon after harvest to improve food quality, including safety, sensory properties, functionality, and nutrient retention, while also enhancing the efficiency of subsequent stabilisation processes such as drying or fermentation. For kelps, these efforts have primarily focused on reducing iodine concentrations while preserving nutrients, bioactive compounds, and flavour.

Stabilisation methods aim to delay or stop natural degradation processes to ensure food safety and extend shelf-life. Conventional approaches, such as freezing and convective air-drying, can yield high-quality products but are often energy-intensive, costly, and challenging to scale, thereby limiting sustainability and profitability. As a result, alternative strategies, including fermentation, acid preservation, and novel drying technologies, are gaining interest but still require optimisation and industrial validation.

In practice, **hybrid processing strategies** are frequently employed, combining two or more operations to reduce energy demand, shorten processing time, and tailor product characteristics, thereby improving overall process efficiency and market value. Post-harvest handling of seaweed biomass (both wild-harvested and cultivated), together with key processing targets, is schematised in **Figure 5**.

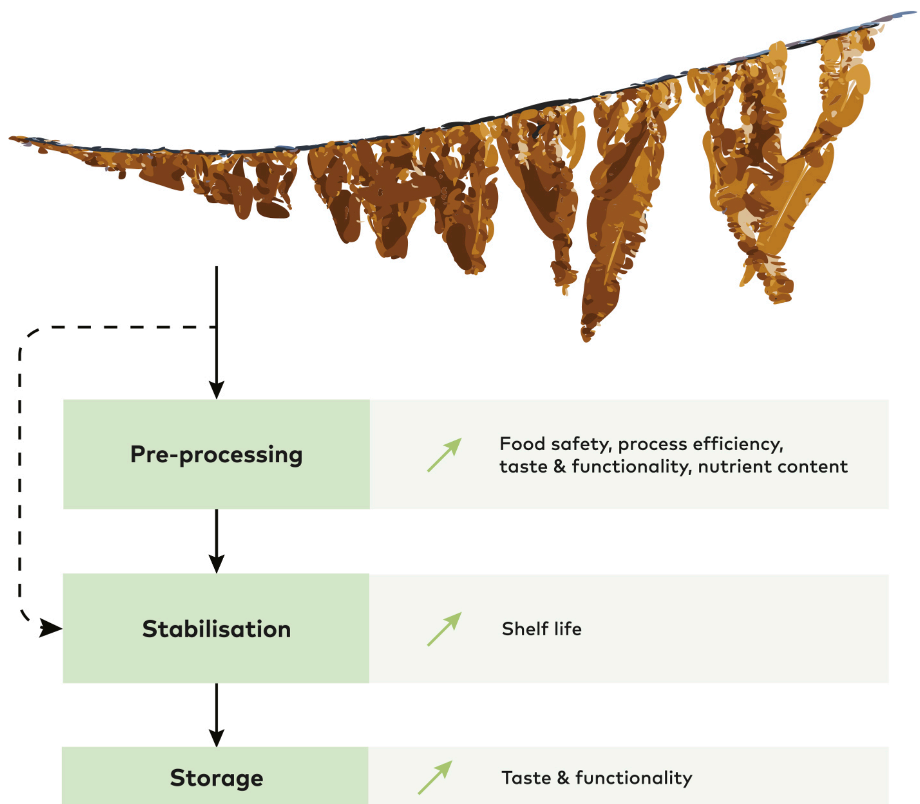

Figure 5: Processing chain of seaweed biomass for food applications, illustrating the main processing steps (pre-processing, stabilisation and storage) and their associated quality targets, including improved food safety, process efficiency, nutrient retention, enhanced taste and functionality, and prolonged shelf life.

Quality requirements

A key challenge is to balance food safety with nutritional and sensory quality. In the case of kelps, high iodine levels may pose a health risk upon frequent consumption in excessive amounts (see **Section 3.2**). Effective processing methods must therefore reduce the iodine content to safe levels while retaining valuable nutrients and flavours. This priority has guided recent research and development efforts (Blikra et al. 2022b; Stévant et al. 2025a).

The economic and environmental performance of seaweed processing systems must be improved. High production costs remain a barrier to market competitiveness, and life cycle assessments (LCAs) identified the processing phase as one of the main environmental hotspots, particularly due to energy consumption for drying or freezing, fuel consumption for transport and the resource intensity of infrastructure and processing operations (Thomas et al. 2021; Thomas et al. 2024; Waqas et al.

2024). Developing energy- and cost-efficient processes that meet food safety and quality standards while minimising environmental impacts is therefore critical for the long-term sustainability and commercial viability of seaweed-based food products.

Pooling resources for efficient processing

Establishing specialised processing facilities for large-scale handling of seaweed biomass, whether cultivated or wild-harvested and intended for food or other applications, represents a major investment, with significant operational costs. As proposed by Stévant and Rebours (2021), developing shared processing infrastructure could enable stakeholders to pool resources, thereby reducing individual financial barriers to implementing efficient large-scale processing solutions. Such collaborative models could enhance overall competitiveness, promote more efficient use of capital, and ultimately accelerate the upscaling of seaweed production.

Performance of seaweed processing techniques

Addressing these interconnected challenges requires a holistic approach that integrates technological innovations, process optimisation and economic and environmental sustainability assessments. Recent research, including work from the SusKelpFood project has focused on evaluating individual and combined processing strategies for pre-treatments and stabilisation methods. **Table 7** and **Table 8** summarise the performance of these approaches, which are discussed in more detail in this chapter.

Table 7: Summary of the performance of relevant seaweed pre-processing methods for food applications. Green, yellow and red colours indicate positive, moderate and negative outcomes, respectively, for each criterion. Abbreviations: *Alaria esculenta* (A); *Saccharina latissima* (S); potentially toxic elements (PTEs); fresh water (FW); seawater (SW); pulsed electric field (PEF; ultrasound (US). On-board op means operation that can be performed on board of the harvest vessel.

	FW blanching (low T°C)	**SW blanching (low T°C)**	**FW blanching (high T°C)**	**SW blanching (high T°C)**	**PEF**	**US**	**Steaming**
Quality							
Iodine reduction	90% reduction for 2 min at 45 °C, slow effect at 30 °C (A, S) [1-3]	90% reduction for 4 min at 45 °C not at 35 °C. Can be enhanced using successive water baths (S) [4]	90% reduction for 2 min (S) [5, 6]	90–95% reduction for 1.5–2 min (S) [5, 7]	25–68% reduction (A, S) [2, 8-10]	85% reduction with US treatment at 45 °C for 30 min (A) [9]. Moderate effect on *Laminaria hyperborea* [11]	Marginal reduction (S) [12, 13]
PTEs reduction	Only reduction of As (A, S) [10, 13]	Only reduction of As (S) [4, 13]	Only reduction of As (S) [6]		Only reduction of As (A, S) [2, 8-10]	Only reduction of As (A) [10]	(S) [12, 13]
Microbial safety			(A, S) [14, 15]	(S) [5]	Inactivation of microbes	Inactivation of microbes although no sterilization	Inactivation of microbes
Mineral retention	Losses of Na, K (S) [13]	Uptake of Na, loss of K	(S) [16]	(S) [5]	Generally high retention, some K losses (S) [9]	(A) [10]	(S) [12, 13]
Protein retention	(S) [9, 16]		(S) [16]		(A, S) [2, 9, 10]	(A) [10]	(S) [12, 13]

Flavour retention	Mild flavour (S) [13]	(S) [13, 17]	(S) [14]		Reduction in saltiness and umami [17]	Not sign. different flavour compared to blanched or PEF-treated kelp but more rubbery texture and less green colour (A) [10]	(S) [13]
Other bioactives	Can concentrate some bioactives (e.g, polyphenols) while heat will degrade others (e.g., pigments, vitamins) (S) [1, 3, 5, 7]				No thermal degradation	No thermal degradation	Preservation of bioactives during subsequent storage (S) [12]
Operational							
Energy consumption	High. Depends on volume of water ex: 150 kJ/kg for 0.5 kg kelp in 5 kg water at 45 °C [8]	High. Specific heat capacity of seawater slightly lower than FW but not a large influence on total energy input	High. Depends on volume of water ex: 340 kJ/kg for 0.5 kg kelp in 5 kg water at 95 °C [8]	High. Specific heat capacity of seawater slightly lower than FW but not a large influence on total energy input	Low. Vary depending on pulse count (3 - 53 KJ kg^{-1}) [8, 9]	Low. 59 kJ/kg [10]	Assumed to be closed to that of hot water blanching
Investment costs							
Operating costs							
On-board op. possible							

References: [1] Nielsen et al. (2020); [2] Blikra et al. (2024b); [3] Stévant et al. (2017a); [4] Stévant et al. (2025a); [5] Wirenfeldt et al. (2022); [6] Blikra et al. (2021b); [7] Lafeuille et al. (2023b); [8] Blikra et al. (2022b); [9] Sund et al. (2025b); [10] Sund et al. (2025a); [11] Noriega-Fernández et al. (2021); [12] Stévant et al. (2024); [13] Krook et al. (2023); [14] Akomea-Frempong et al. (2021) ; [15] Blikra et al. (2018); [16] Trigo et al. (2023); [17] Stévant et al. (*in prep.*).

Table 8: Summary of the performance of relevant seaweed stabilisation methods for food applications. Green, orange and red colours indicate positive, moderate and negative outcomes, respectively, for each criterion. Abbreviations: *Alaria esculenta* (A); *Saccharina latissima* (S); *Palmaria palmata* (P); *Ulva* spp. (U); potentially toxic elements (PTEs). LAB fermentation refers to lactic acid bacteria-induced fermentation.

	Convective air-drying 25–45 °C	Freeze-drying	LAB fermentation	Freezing	Acid preservation	Dry salting	Brining/salt-/acid pickling
Quality aspects							
Iodine reduction	(S) [1]	(S) [1]	Some iodine leaches into the liquid (A, S) [2, 3]	Some iodine leaches into the liquid upon thawing (A, S) [4, 5]	Iodine leaches into the liquid (S) [6]	Some iodine leaches (S) [5]	Iodine leaches into the liquid (S) [5] Around 60% reduction of iodine by ≥ 20% NaCl (S) [23]
PTEs reduction			Lower tot. As and Cd (A, S) [2]	Some As may be reduced (A, S) [4, 5]	Lower tot. As and Cd (S) [6]	Some reduction of As and Cd (S) [5]	Cd reduction at 2.0 M NaCl (A) [7]
Microbial safety	Some pathogens may survive (A, S) [8, 9]		Safe if low pH (< 4.3) is rapidly achieved and maintained (A, S) [10, 11]	Safe if cold chain maintained and if contamination of spore-forming bacteria avoided (A) [12]	At pH below 4 (A, S) [6, 13]	Reduces water activity. Shelf life prolonged for some weeks when combined with refrigerated storage (A, S) [14, 15]	Reduces water activity. Shelf life prolonged for some weeks or when preserved with ≥ 20% NaCl, up to a year when combined with refrigerated storage. (S) [15, 23]
Mineral retention	(S, P) [1, 16]	(S) [1]	Some minerals (e.g., K) may leach into the liquid	High drip loss removes some soluble minerals (Na, K mainly) (A, S) [4, 5]	Mainly loss of K (S) [6]	Na is added but other minerals (e.g., K) may leach (A, S) [5, 14]	Na is added but other minerals (e.g., K) may leach (A, S)
Protein retention	(S, P) [1, 16]	(S, P) [1, 17, 18]	(S) [3]	(A) [4]	(A, S) [6, 13]		
Flavour retention	Stable flavour at low moisture content (S) [1, 2]	(S) [1]	Sourness increases with storage (A) [2]	Develops "green" aromas (P) [19]	Sourness increases with storage (A, S) [6, 13]	Increases saltiness	Increases saltiness

Other bioactives	Oxidation of pigments and antioxidants may occur (S, P, U) [1, 16, 18, 20]		Pigments may be degraded while pre- and probiotic activity may increase [21]. Lower extractable polyphenols	Enzymatic degradation (e.g., pigments) (S) [5]	A, S [6, 13] Antioxidant activity decreases	Some losses expected but data missing	Some losses expected but data missing
Operational aspects							
Energy consumption	See Table 10.	See Table 10.	May require temperature control	Freezing + frozen storage	May require temperature control	Requires refrigeration	Requires refrigeration
Investment costs			Fermentation tanks	Industrial freezer + warehouse packaging systems	Containers for acidified storage	Cold storage	Cold storage
Operating costs	Energy costs	Energy costs	Starter culture (unless spontaneous), pH monitoring	Energy + handling (incl. packaging) [22]	Will depend on choice of acid (and costs) and handling	Energy for cold storage	Energy for cold storage
On-board op. possible	Require power supply and space on vessel		Needs adapted vessels & hygiene control	Require power supply and space on vessel			

References: [1] Stévant et al. (2018b); [2] Stévant et al. (in prep.); [3] Bruhn et al. (2019); [4] Sund et al. (2024); [5] Stévant et al. (2024); [6] Krook et al. (2024); [7] ; [8] Sørensen et al. (2023); [9] Lytou et al. (2021); [10] ; [11] Sørensen et al. (2021); [12] Blikra et al. (2018); [13] Hrólfsdóttir et al. (2024); [14] Perry et al. (2019); [15] Arya et al. (2024); [16] Lafeuille et al. (2023a); [17] Abdollahi et al. (2019); [18] Stévant (2019); [19] Le Pape et al. (2002); [20] Silva et al. (2019); [21] Monteiro et al. (2021); [22] Stévant and Rebours (2021); [23] Klein et al. (under review).

4.1. Pre-processing methods

4.1.1. Blanching and warm-water treatments

Blanching involves short immersion or scalding in boiling or warm water, typically between 70 °C and 100 °C, followed by rapid cooling to stop the cooking process. In seaweed processing, it is primarily used to inactivate enzymes and, in kelps, to reduce iodine through leaching into the water phase.

Iodine reduction and quality changes

In seaweed processing, blanching was first identified as a simple and effective method to reduce the iodine concentration of kelp (Lüning and Mortensen 2015), which is otherwise not significantly affected by gentle treatments (e.g., washing and dehydration) (Nitschke and Stengel 2016; Stévant et al. 2017b). Although blanching is typically applied at boiling temperature, treatments at lower temperatures, ranging from 45 to 60 °C, can achieve iodine reductions of more than 90% in *S. latissima* and *A. esculenta* (Nielsen et al. 2020; Blikra et al. 2024b). Such treatments may also remove approximately 50% of the arsenic in these kelps (Krook et al. 2023; Stévant et al. 2024; Stévant et al. 2025a; Sund et al. 2025a). Iodine reductions can be achieved at even lower temperatures (ca. 30 °C) but require longer exposure time (Stévant et al. 2017a; Nielsen et al. 2020). On the other hand, blanching is accompanied by the loss of water-soluble nutrients such as minerals (predominantly Na and K), simple sugars (mannitol), fucoxanthin and polyphenols (Stévant et al. 2017a; Nielsen et al. 2020; Lafeuille et al. 2023b; Blikra et al. 2024b). Moreover, blanching with freshwater significantly reduces the saltiness and umami flavours of kelp, thereby compromising its potential as a flavour-enhancing ingredient (Krook et al. 2023). Like other heat treatments, blanching also induces pronounced colour changes, e.g., turning kelp from olive-brown to bright green (Blikra et al. 2018), giving it a vegetable-like appearance considered more attractive to consumers (Akomea-Frempong et al. 2021).

Critical blanching parameters

Varying processing conditions lead to different iodine reduction yields, making it difficult to predict final levels from experimental studies in commercial settings. Recent research efforts have therefore focused on identifying critical blanching parameters for iodine reduction in kelps to optimise the process. Treatments using seawater, which is typically readily accessible near seaweed processing facilities, yield similar iodine reduction with improved nutrient and flavour retention compared to similar freshwater treatments (Krook et al. 2023; Stévant et al. 2025a). Short seawater blanching or warm water treatment steps (between 1 and 4 min) at temperatures above 40 °C (with 45 °C ensuring satisfactory results) have been shown to provide substantial iodine reduction (79% to 93% in *S. latissima*) (Stévant et al. 2025a) (Figure 6). Lower seaweed-to-water ratio, stirring of kelp biomass during the process and applying successive seawater baths (50 °C) further enhanced the reduction (Blikra et al., submitted). This is supported by another study (Sletta et al. 2025) where increasing the seaweed-to-water (fresh water) ratio (50 to 500 g L^{-1}) resulted in less effective iodine reduction for both *S. latissima* and *A. esculenta*. Adding this larger proportion of seaweed to 80 °C treatment water, dropped temperature by approximately 20 °C which presumably reduced the blanching efficiency. The lower iodine efflux from the seaweed with increased seaweed-to-water ratio could also be due to iodine saturation in the water. Consistent with this hypothesis, the same blanching water could be reused up to ten times for the treatment of *A. esculenta* without compromising iodine reduction. However, for the more iodine-rich species *S. latissima*, blanching efficiency was substantially reduced (Sletta et al. 2025). Reusing blanching water should be optimised to provide safe and predictable iodine levels in kelps while reducing costs, water consumption, and carbon emissions associated with the process.

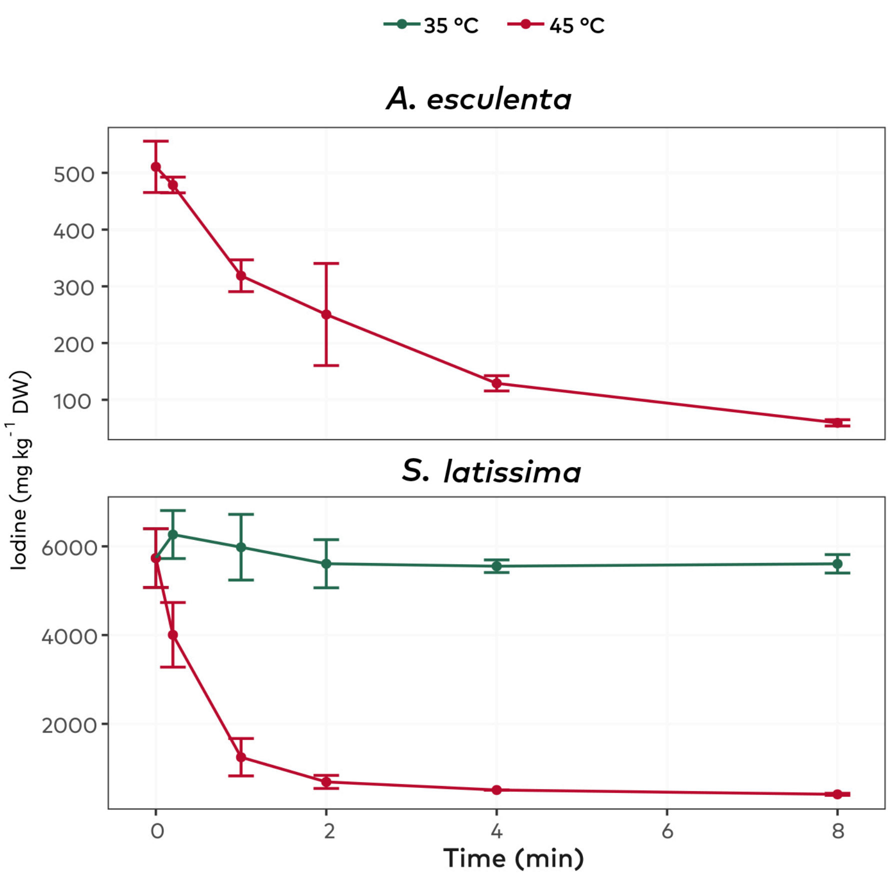

Figure 6: Effect of treatment time and temperature upon warm-seawater treatment of *Alaria esculenta* and *Saccharina latissima* on iodine concentrations in kelp (Stévant et al. 2025).

Combination of blanching and other processing methods

For enhanced effect, blanching can be combined with other treatments such as microwaves, ultrasound (US) (Zhu et al. 2022), and pulsed electric field processing (PEF) (Blikra et al. 2024b). More intensive processing can maximise the release of iodine and other water-soluble compounds producing a fibre-rich solid fraction with potential as a minimally processed texture ingredient, such as alginate, cellulose, and other insoluble fibres. Such fibre-rich fractions could serve as alternatives to ultra-processed texture ingredients (Chapman et al. 2015; Blikra et al. 2021a) in food formulations and contribute to improved gut health, without excessive dietary iodine exposure. Evaluating these ingredients in manufactured food products could reveal innovative applications, enhance the functional properties of foods, and promote the use of natural texture ingredients in the food industry. Where feasible, the liquid fraction should be recovered and valorised and used in food or other industrial applications (e.g. through further separation in biorefinery schemes).

4.1.2. Pulsed electric field (PEF)

PEF is a non-thermal food processing technology in which a food product, placed in a chamber with water, is exposed to high-voltage electric pulses (1 to 100 kV cm^{-1}) of very short durations (nanoseconds to microseconds), inducing cell membrane permeabilization. At higher intensities, electroporation causes irreversible increase in permeability of vegetal, animal or microbial cell membranes, resulting in microbial inactivation and extended shelf-life. PEF can also enhance extraction yields, improve texture and increase mass transfer, thereby improving the efficiency of subsequent processes such as drying, cutting or brining (Toepfl et al. 2006). If PEF is used to enhance drying, a mechanical dewatering step after PEF processing is advantageous (Prabhu et al. 2020). Applying PEF prior to fermentation of *S. latissima* with lactic acid bacteria strains resulted in a faster pH decrease below the safety threshold compared to untreated biomass (Sund et al., submitted). This effect is likely due to the release of fermentable sugars during PEF processing. The liquid after PEF processing is itself valuable and has several potential uses (Blikra et al. 2024a).

Green extraction of high-value components

PEF shows potential for improved extraction of bioactive compounds such as polyphenols and pigments (Polikovsky et al. 2016; Prabhu et al. 2020; Steinbruch et al. 2024). Protein extraction from seaweed is difficult since the proteins are embedded in the complex fibre matrix. Studies found that processing with PEF increased protein content in the residual biomass due to the extraction of other components (Maribu et al. 2024). Despite this, PEF can improve the extraction yield of proteins compared to other treatments, and some successful schemes for *Ulva* spp. have been developed, where PEF was combined with either enzymatic treatment with cellulase or mechanical dewatering (Prabhu et al. 2020; Steinbruch et al. 2024).

Reduction of PTEs

PEF can also be applied to extract PTEs, such as iodine and arsenic, thereby reducing their content in the residual biomass. Under certain conditions, PEF processing has been shown to reduce the iodine concentration in *S. latissima* up to 50% (Blikra et al. 2022b; Blikra et al. 2024b; Sund et al. 2025b) and may be combined with blanching treatments for further reduction (Blikra et al. 2024b). However, the reduction yield varies considerably among studies, and further work is needed to optimize process parameters for more predictable iodine removal in kelps. An overview of relevant data from recent studies is presented in **Table 9**. The highest iodine reductions in *S. latissima* (42% and 50%) were achieved under markedly different processing conditions, including water-to-seaweed ratios (10:1 and 2:1), pulse counts (220 and 300), and using whole versus ground biomass. In contrast, some processing combinations resulted in reductions as low as 2.5%. This variability may partly reflect differences in initial iodine concentrations between *S. latissima* batches.

Table 9: Overview of the processing conditions and achieved iodine and arsenic reduction during studies on pulsed electric field (PEF) treatment of *Saccharina latissima*.

Variable	Blikra et al. (2022b)		Blikra et al. (2024b)	Sund et al. (2025b)		
PEF settings						
Voltage (kV)	24	24	24	24	24	24
Frequency (Hz)	30	30	30	30	30	30
Pulse duration (μs)	6	6	6	6	6	6
Pulse count	200	800	300	200	500	800
Energy (kJ)	2.7	14	11	11	28	46
Raw material						
Ground/whole kelp	Whole	Whole	Ground	Ground	Ground	Ground
Water: seaweed ratio	10:1	10:1	2:1	2:1	2:1	2:1
% reduction						
Iodine	42%	38%	50%	2.5%	3.3%	25%
Arsenic	11%	12%	1.4%	0%	0%	0%

Commercial and economic aspects

Commercial PEF processing lines have been successfully implemented, for example, in potato production. The technology offers several advantages, including substantially lower energy demand compared to thermal processes, shorter processing and higher production capacity. Industrial PEF systems are available in various configurations, including continuous-flow units and batch units. For potato processing, capacities of up to 100 tonnes per hour have been reported, while continuous systems with capacities as low as 1 ton per hour are also commercially available. Although the optimal processing capacity for seaweed remains to be established, the scalability of current systems suggests significant potential. However, PEF equipment represents a considerable capital investment, with a 200 kW system estimated to cost € 250,000–400,000 (Kempkes 2017). This cost may be prohibitive for smaller individual producers, but feasible for large seaweed processors, co-operatives or the broader food industry.

PEF in biorefinery processes

Generally, PEF processing results in the extraction of minerals and other water-soluble compounds, including both valuable and unwanted constituents, to varying degrees depending on operational settings. As an example, PEF processing of *S. latissima* resulted in 40% extraction of dry matter (Blikra et al. 2024b). Utilising the liquid side stream is therefore necessary for full biomass valorisation. One method is to remove unwanted constituents (arsenic, iodine, salt, water) by filtration technology. After that, the liquid could be reintroduced with the residual biomass (in case of 1 product), used as a product itself (e.g., plant biostimulant), or be a feedstock for further biorefinery (**Figure 7**) (Rode et al. 2025). The extracted liquid has shown significant antioxidant activities (Steinbruch et al. 2024), and contains bioactive compounds such as phenolics, as well as sugars and amino acids with potential for applications such as plant biostimulants, health care, or nutraceuticals (Blikra et al. 2024b). In addition, PEF treatment reduces the saltiness and umami intensity of the solid kelp fraction. This effect may be undesirable in applications where seaweeds are used as flavour ingredients but beneficial in others where they serve primarily as textural components (Stévant et al., *in prep.*; see **next chapter**).

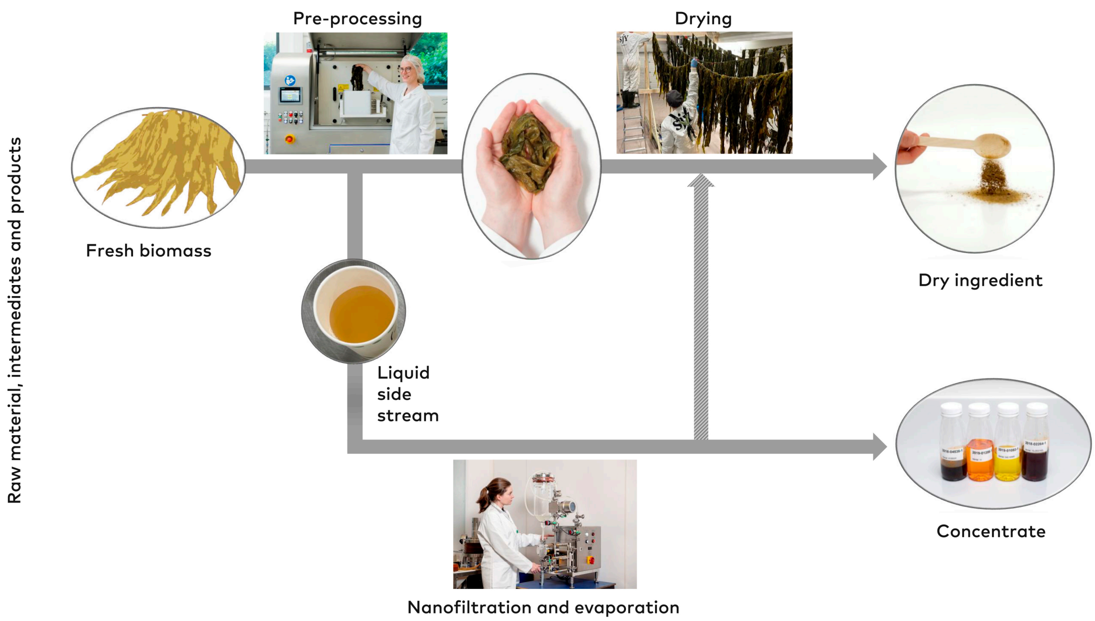

Figure 7: Plausible processing scheme for utilization of solid and liquid fractions after pre-processing steps, such as PEF processing. The liquids can be filtered to reduce unwanted compounds (arsenic, iodine, salt, water) before either reintroduction with the residual biomass (in case of 1 product), or be used as a product itself (biostimulant or precursor for other applications). Images: Marthe J. Blikra, Jan Inge Haga, Anne-May Johansen, Gorana Drobac, Helge Skodvin, © Nofima.

4.1.3. Ultrasound (US)

US technology generates sound waves with frequencies typically in the range of 20 kHz to 10 MHz. In food processing, the raw material is typically immersed in a liquid during the treatment. The effect of US technology depends on the parameters used, and the treatment must be optimised regarding the raw material and desired effect. In general, the application of US technology has three effects on seaweed: i) green extraction of high-value compounds, ii) reduction of PTEs, and iii) enhancement of subsequent drying.

Green extraction of high-value components

Application of US at high frequencies extracts significant amounts of dry matter from seaweeds, and US can therefore be suitable for extraction processes. For *A. esculenta*, roughly half of the dry matter was extracted after US treatment (Sund et al. 2025a). Another study found the US intensity to be a critical factor for the extraction effect, with 7% to 76% dry matter loss reported for *A. nodosum* depending on the intensity used (Kadam et al. 2015b). For *P. palmata* and *Porphyra* spp., an US-assisted method was optimised to extract compounds with high antioxidant activity (García-Oms et al. 2024). The antioxidant effect of the extracts was attributed to pigments and polyphenols, and their potential for high-value in food supplements was highlighted. Two similar studies found US processing to be efficient for extracting phenolic compounds with high molecular weights, fucose and uronic acids from *A. nodosum* (Kadam et al. 2015a; Kadam et al. 2015c). Nevertheless, US was not found to improve the extraction of dry matter, ash, protein, amino acids, or sugars from *P. palmata* (Maribu et al. 2025). In a study using *A. esculenta* as one of the raw materials, probe sonicators (i.e., ultrasonic homogenizer) were found to improve extraction compared to control treatments, whereas bath sonicators were ineffective (Inguanez et al. 2023).

Reduction of PTEs

The application of US can be used to reduce the content of some PTEs from seaweeds. A significant decrease in iodine and total and inorganic arsenic was found in *A. esculenta* during US treatment, compared to unprocessed seaweed. Noriega-Fernández et al. (2021) found a significant decrease in total arsenic content in *L. hyperborea* after US treatment compared to soaking. A significant reduction in inorganic (90%) and total arsenic (59%) was also found after a US treatment of *S. latissima* (Jönsson and Nordberg Karlsson 2024), however, similar to reductions found for soaking in freshwater at the same temperature (30 °C) without sonication. In contrast, no significant effect on iodine content was found after US treatment of *P. palmata* (Maribu et al. 2025). An increase in Cd content was found in *A. esculenta* and *S. latissima*, as a result of the extraction of other components (Sund et al. 2025a; Jönsson and Nordberg Karlsson 2024). Similarly, the protein content in the residual biomass increased after US for *A. esculenta* and *P. palmata* (Maribu et al. 2025; Sund et al. 2025a).

Enhancement of subsequent drying

In addition to altering the chemical composition by extracting dry matter to a liquid phase, US can also be applied to enhance drying processes of the residual biomass (the solids). For *A. nodosum*, pre-treatment with US significantly reduced the drying time compared to without pre-treatment, using hot air convective drying and fluidized bed drying (Kadam et al. 2015b; Zhu et al. 2021b).

4.1.4. Steaming

Steaming of kelp

Steaming is known as a gentle method to preserve and sterilize foods while retaining nutrients and natural flavours in vegetables. Steam treatment has been tested as a pre-treatment of *S. latissima* prior to freezing. Steaming softened kelp tissue, reduced drip loss during freezing and thawing, and effectively preserved bioactive compounds, namely fucoxanthin and laminaran, most likely by inactivating enzymes responsible for the degradation of these compounds during frozen storage (Stévant et al. 2024). Steam treatment also promotes good retention of minerals and flavours (saltiness and umami) compared to blanching

(Krook et al. 2023). However, some nutrient losses may occur if the kelp is cooled directly in ice water after steaming, due to leaching into the water (Lafeuille et al. 2023b). Because iodine from kelps can be released into the atmosphere under oxidative stress (Küpper et al. 2008), attempts have been made to reduce its levels through evaporation. However, approaches such as steam exposure and rotary evaporation resulted in only marginal reductions (Stévant et al. 2021).

4.1.5. Mechanical dewatering (MD)

MD is a process in which the raw material is pressed, and water is removed through mechanical means. Pre-treatments such as PEF have been suggested as effective ways to enhance dewatering efficiency by disrupting cell structures and making intracellular water more available for removal. This was demonstrated in an experimental trial using *S. latissima* in Figure 8. The samples pre-treated with PEF and MD prior to drying had a lower initial weight at the onset of drying, and preliminary results suggest that these samples exhibited a faster drying rate Figure 9.

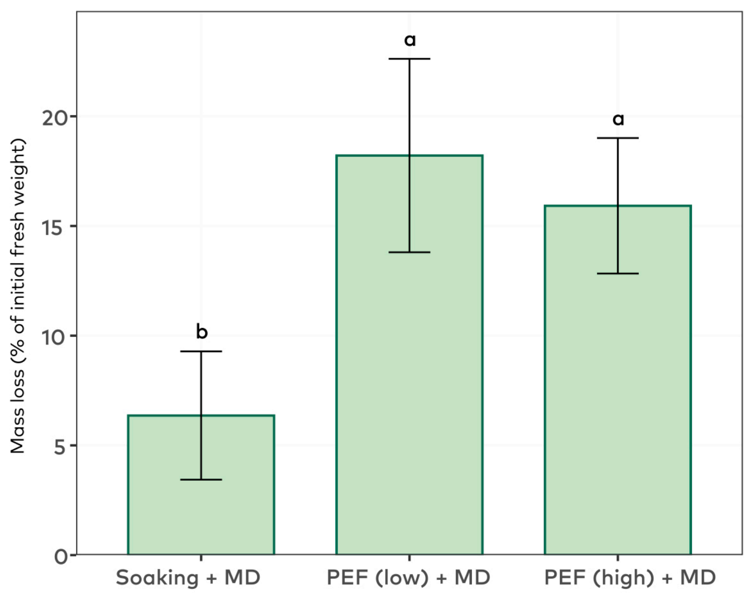

Figure 8: Mass loss from pre-treatments of *Saccharina latissima* (Blikra et al., unpubl. data). 500 g of kelp biomass was pre-processed either by pulsed electric field (PEF) at low/high pulse count and soaking in 5 L freshwater at 20 °C for 1 min (control treatment), as described in Blikra et al. (2022b). Subsequent mechanical dewatering (MD) was carried out by compression in a cylinder by a hydraulic operated piston. Each sample was placed in the customized sieve and pressurized until no further water could be extracted from the seaweed. The mass loss is calculated from the recorded initial weight of the treated samples compared to the recorded weight after MD. Values are given as mean ± st. dev. (n = 3). Different letters represent statistically significant differences between treatments (analysis of variance).

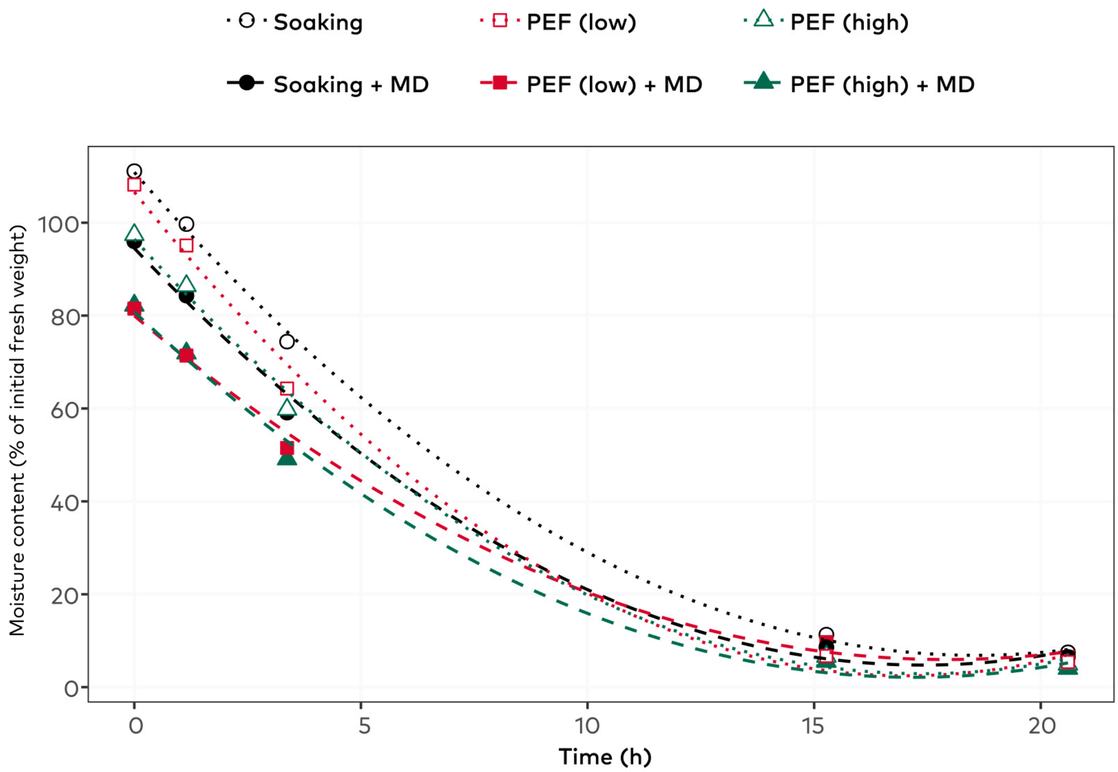

Figure 9: Experimental drying curves of *Saccharina latissima* dried at 25 °C following different pre-treatments (Blikra et al., unpubl. data). 500 g of kelp biomass was pre-processed either by pulsed electric field (PEF) at low/high pulse count and soaking in 5 L freshwater at 20 °C for 1 min (control, treatment), as described in Blikra et al. (2022b). Subsequent mechanical dewatering (MD) was carried out by compression in a cylinder by a hydraulic operated piston. Each data point represents average values from replicate treatments (*n* = 3).

4.1.6. High pressure processing (HPP)

HPP is a non-thermal preservation technology that applies extremely high pressures to inactivate microorganisms and extend shelf life without heat. Pressure is transmitted instantaneously and uniformly throughout the product, independent of its size or geometry. Typical conditions range from 400 to 600 MPa (1 MPa = 10 bar) with holding times of 1–5 minutes for shelf-life extension. The main advantage of HPP is its ability to preserve sensory attributes such as taste, colour, and texture, while minimizing nutrient loss and preventing oxidation or thermal degradation. Since seaweed spoilage is largely driven by microbial growth, HPP has been explored as a preservation method in several studies. The main limitation of HPP at industrial scale is its high energy demand and the substantial costs associated with equipment and maintenance (Nabi et al. 2021).

Effects on quality

Jönsson et al. (2023a) reported that HPP of *S. latissima* effectively preserved colour and nutrients but softened texture. In another study, del Olmo et al. (2020) found that HPP at 400 and 600 MPa for 5 minutes significantly reduced bacterial counts and extended the shelf life of five seaweed species, including *Ulva lactuca*, to over 180 days at 4 °C in sealed packaging. O' Connor et al. (2020) evaluated HPP as a pre-treatment for protein extraction in two brown and two red seaweed species. While HPP and autoclaving obtained similar protein yields, HPP resulted in lower protein recovery for red species but showed promising results for brown species. Jönsson and Nordberg Karlsson (2024) further assessed HPP followed by rinsing for reducing potentially toxic elements (PTEs) in four seaweed species. Iodine concentrations were reduced below the French recommendation of 2,000 mg kg^{-1} DW, whereas cadmium levels increased across most tested methods, likely due to its strong binding affinity to alginate and fucoidans, leading to up-concentration during processing.

4.2. Stabilisation methods

4.2.1. Drying

Drying is a common method for stabilising wet biomass

Moisture removal reduces the water activity (a_w), thus preserving the product by avoiding microbial growth and limiting the rate of chemical reactions. In addition, drying substantially reduces the weight and volume of the material, lowering packaging, storage and transportation costs. A large share of seaweed-based food products available in Europe is sold in its dried form owing to their long shelf-life and convenience for consumers. In Europe, seaweeds are typically dried using hot-air convection systems such as ovens and cabinets, drying chambers or tunnels. However, drying is highly energy-intensive and has been identified as a major contributor to the overall environmental impact of the seaweed production value chain (van Oirschot et al. 2017; Thomas et al. 2021) (See **Chapter 7**).

Drying temperature and product quality

The drying temperature strongly influences both the efficiency of the process and the quality of the final product. Higher temperatures (> 50 °C) increase drying rates but may cause degradation of heat-sensitive nutrients such as vitamins, antioxidants, and carotenoids (Silva et al. 2019; Badmus et al. 2019). Elevated temperatures also alter the physico-chemical properties of the material, including oil-binding properties, swelling capacity and hydration properties, as observed in *S. latissima* (Sappati et al. 2017; Stévant et al. 2018b). These effects are mainly attributed to product shrinkage, which may reduce the textural quality of seaweed-based food ingredients. Conversely, drying at lower temperatures is known to better preserve heat-sensitive compounds but also extends the processing time, which may increase exposure to oxidative stress and promote degradation of antioxidants (Gupta et al. 2011).

Drying kinetics and product stability

The drying rate of seaweeds, like other foods, is not constant and follows two main phases. During the constant-rate period, free water evaporates steadily from the product surface. Once a critical moisture content (MC) is reached, the process enters the falling-rate period, where evaporation slows due to limited internal moisture diffusion. In practice, this means that reducing the MC from 15% to 10% may take a longer time and require more energy than from 80% to 50%. Drying effectively inhibits microbial growth by reducing the water activity (a_w) to 0.6 or below, which prevents the proliferation of yeasts and moulds, while bacteria are inhibited at much higher a_w levels (Løvdal et al. 2021). Although most commercially available dried seaweed products contain approximately 10% moisture, experimental data show that *A. esculenta* and *S. latissima* remain microbiologically stable at MC levels between 15% and 25% (**Figure 10**). This finding is consistent with results from Sappati et al. (2017), who reported a_w values around 0.6 for *S. latissima* within this range of MC. Stévant et al. (2020) reported the storage of *P. palmata* in semi-dry form containing 18-22% moisture, corresponding to a_w ranging from 0.60 to 0.65. No yeasts or moulds were detected in these samples after four months of storage. Experimental data from Uribe et al. (2018) suggest that *Ulva* spp. can remain stable at lower moisture content levels (around 10%), although additional studies are needed to confirm this observation.

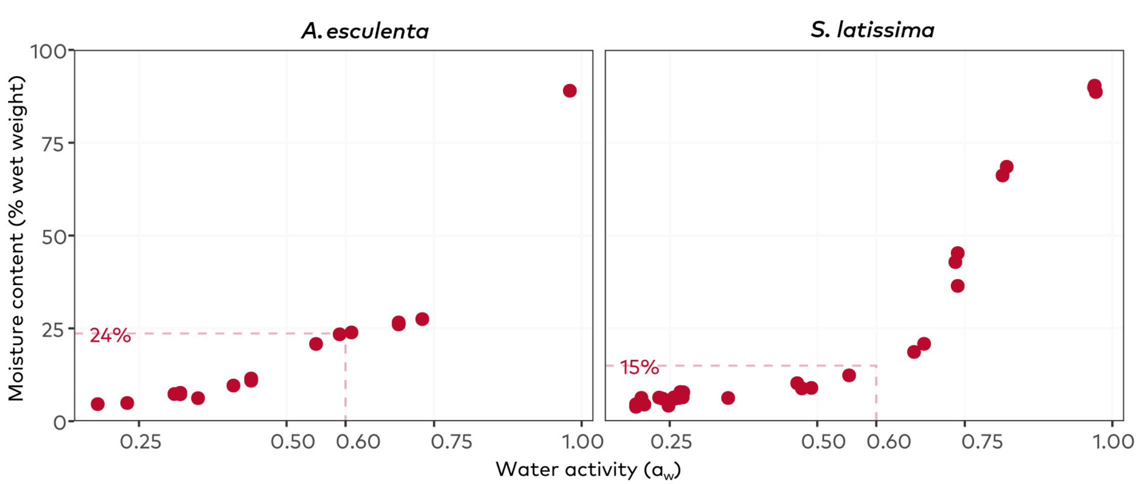

Figure 10: Moisture sorption isotherm of air-dried *Alaria esculenta* and *Saccharina latissima* determined at 40 °C (Stévant et al. unpubl. data) from experimental air-drying treatments described in Stévant et al. (2018b).

Product stability also depends on factors such as storage temperature and pre-processing methods. While seaweeds with higher MCs may remain microbiologically safe, elevated moisture typically increases the rate of enzymatic and non-enzymatic reactions responsible for the degradation of phytochemical compounds. Achieving a low MC is therefore critical when seaweeds are intended as sources of bioactive compounds sensitive to degradation, such as vitamins, polyphenols and pigments (Gupta et al. 2011; Munier et al. 2013; Lage-Yusty et al. 2014). For example, Harrysson et al. (2021) reported loss of vitamin C and lipid oxidation during storage of dried *Ulva fenestrata* and *Porphyra umbilicalis*. Conversely, in some applications, controlled reactions within products stored at higher MCs may promote the development of desirable flavour compounds and may be exploited to enhance the sensory properties of edible seaweeds (see **Chapter 5**). Nevertheless, the actual shelf-life depends strongly on factors such as packaging, storage humidity, temperature, and light exposure.

Freeze-drying

Freeze-drying is regarded as a premium method for drying seaweeds, as it effectively preserves sensitive compounds and structural integrity, preventing product shrinkage while maintaining porosity and rehydration properties in the seaweed (Stévant et al. 2018b; Badmus et al. 2019; Wirenfeldt et al. 2024). However, the technique is both capital- and energy-intensive, and the high cost per kilogram of wet biomass, together with limited scalability without major investments, represents a major barrier to large-scale processing. Consequently, freeze-drying may be applied primarily to premium products with high market value, such as nutraceutical products (Badmus et al. 2019; Stévant and Rebours 2021).

Microwave vacuum drying (MVD) is an emerging drying technology that combines microwave heating with reduced pressure, allowing water to evaporate at lower temperatures than during atmospheric drying. Unlike convective air-drying, where heat is transferred from the surface inward, MVD generates heat volumetrically within the biomass, with energy deposition occurring primarily where water is present. This accelerates moisture removal and reduce exposure time to thermal and oxidative stress, making MVD a potential alternative to freeze-drying when high quality is required but processing time is limited. In a drying comparison study on *Ulva* sp. and *F. vesiculosus*, MVD produced products generally closer in quality to freeze-dried material for *Ulva* sp., while *F. vesiculosus* showed more pronounced differences between drying methods, indicating that method selection should be guided by the targeted attributes for each species (Wirenfeldt et al. 2024). Drying method influenced a_w and rehydration-related properties (water absorption and water holding capacity), though effects depended on species. Method-specific differences in lipids and pigments were observed in some cases, reinforcing that MVD is not a "one-size-fits-all" solution but a technology that can be selected based on prioritised quality attributes (Wirenfeldt et al. 2024). Overall, MVD can be positioned as (i) a quality-focused alternative to conventional hot-air drying, (ii) a faster option than freeze-drying in certain configurations, and (iii) part of hybrid drying strategies where upstream dewatering or structure-modifying pre-treatments reduce the moisture load and improve process efficiency

Alternative drying technologies

Large-scale drying of seaweeds at low temperatures may require technical adaptation of drying systems to optimize product quality while reducing energy consumption. Potential strategies include increasing air velocity, dehumidifying the inlet air (e.g. using heat pump technology; Sappati et al. (2018)), and fluidising the material to enhance surface contact with the drying medium. Anagnostara et al. (*in prep.*) evaluated *S. latissima* drying vertically (hanging on ropes) compared to lying horizontally on grids in a closed room with dehumidifier at ambient temperature (9.3 to 12 °C). Despite the difference in drying time i.e., 13 h versus 18 h respectively, no differences were observed in antioxidant content and activity, as well as lipids or pigments contents. Pre-treatments like PEF or mechanical dewatering may also increase the efficiency of the drying process by reducing the initial moisture load (Prabhu et al. 2020). Alternative technologies, including superheated steam drying, have shown improved efficiency compared to conventional convective air-drying. This technique uses recirculated superheated steam as a drying medium, which supplies heat to the product while removing evaporated water. Owing to its higher thermal conductivity, superheated steam enables faster drying rates while minimizing nutrient loss from oxidation and reducing mechanical stress such as shrinkage (Sehrawat et al. 2016). Microwave drying is another technology gaining attention in the food processing industry. It relies on electromagnetic waves that penetrate the product, generating internal heat to gently remove the moisture, provided that the material is heated evenly (Santhoshkumar et al. 2023). Both superheated steam and microwave drying are scalable technologies offering reduced energy demand and shorter processing times compared with conventional air-drying methods. However, their implementation involves relatively high investment costs. **Table 10** provides an overview of alternative technologies, their applications, and associated energy demands. Large amounts of surplus energy may be available along the coast of Nordic countries (e.g., manufacturing of petroleum products, waste incineration) and may be implemented as an energy source for large-scale seaweed processing (Stévant and Rebours 2021).

Table 10: Overview of drying technologies and associated energy demand (Adapted from Rode et al. (2025)). Abbreviation: specific energy consumption (SEC).

Technology	Energy consumption	SEC (kWh kg^{-1} H_2O)	Description
Freeze-drying	Very high	Up to 22	Suited for high-value products
Forced convection drying methods			
Hot air belt dryer	High	n.d.	Possible thermal degradations
Hot air cabinets	High	n.d.	Flexible but often limited capacity
Hot air drum of mill dryer	High	1.2	Possible thermal degradations
Low temp. dehumidified air drying	Moderate	n.d.	Minimises heat damage
Superheated steam mill dryer	Moderate	0.75	Possible thermal degradation. No oxidation.
Spray drying	High	1.3–3.2	Suitable for liquids and slurries
Refractance window drying ™	High	2.3–3.2	Suitable for liquids and slurries
Other methods			
Microwave drying	Moderate	0.6–2.2	Often used as a first drying step
Microwave vacuum drying	High	8.1	Very quick. Avoids heat damage.
Radio frequency drying	Moderate	n.d.	Usually, final drying step
Infrared drying	Very high	14.5	Limited to thin layer products
Outdoor/solar drying	Low	n.d.	Weather dependant

n.d.: no data.

4.2.2. Lactic acid bacteria (LAB)-induced fermentation

LAB-induced fermentation represents a promising approach for the large-scale stabilisation of harvested seaweed, offering a low-energy and low-technology alternative to conventional preservation methods (Stévant and Rebours 2021). Fermentation can serve as a primary stabilisation step for fresh biomass—either as a final product route (e.g., fermented ingredients) or as interim storage before downstream processing (e.g., drying). Most research and development efforts on seaweed fermentation have so far focused on kelp species. However, successful pilot-scale fermentations have also been reported for red seaweeds, e.g., *Porphyra/Pyropia* spp., demonstrating the potential of this approach for specific food applications (Uchida and Miyoshi 2013). To date, only a few commercial products based on fermented seaweeds have been developed in Europe. Under anaerobic conditions, LAB convert available fermentable sugars into lactic acid, thereby lowering the pH (typically below 4.0) and inhibiting the growth of spoilage microorganisms such as *Clostridia* and moulds. While this process is well established for terrestrial crops and certain food products, its application to seaweeds is relatively recent and is still at a development stage. The structural complexity of seaweed polysaccharides such as alginates, carrageenan, and agar, which are not readily fermentable by most LAB, presents a major challenge. In contrast to vegetables and dairy products, which naturally contain fermentable carbohydrates and LAB, fresh seaweeds generally contain low levels of simple sugars and initial number of LAB, low dry matter content and are characterised by a relatively high buffering capacity (i.e., high resistance to pH change) (Herrmann et al. 2015; Cabrita et al. 2017). Studies have shown that mannitol and, to a lesser extent, glucose in kelps are the main carbon sources for LAB fermentation (Allahgholi et al. 2023; Stévant et al. 2025b). Glucan oligosaccharides from laminaran degradation in kelps may also be used as substrate (Allahgholi et al. 2023). Among edible seaweed species, the kelps *S. latissima* and *A. esculenta* have shown promising fermentation potential, with spontaneous lactic acid production observed under anaerobic conditions (Herrmann et al. 2015; Sørensen et al. 2021; Krook et al. 2024). However, the variability of native microbial populations, limited availability of fermentable substrates such as mannitol and laminaran, and the lack of optimized starter cultures hinder process control and reproducibility. To overcome these limitations, strategies such as enzymatic saccharification (Uchida and Miyoshi 2013), heat treatments (Bruhn et al. 2019), supplementation with fermentable sugars like molasses (Larsen et al. 2021) and developing adapted starter cultures (see below), have been proposed, but have not yet been implemented commercially.

pH threshold

A critical parameter for the controlled fermentation of seaweeds is a rapid pH decrease to below safe thresholds. Based on known limits for the growth of known pathogens in relation to temperature, pH, a_w and water-phase NaCl, Løvdal et al.

(2021) recommended a pH below 4.3, where most pathogens of relevance for seaweeds (*Listeria* spp., *Clostridium* spp., *Bacillus* spp., and *Vibrio* spp.) are inactivated at refrigerated temperature (4 °C). The authors recommend a pH below 3.8 for storage at ambient temperatures to prevent the growth of *Salmonella* spp., *Staphylococcus aureus* and pathogenic *E. coli*. There are currently no established guidelines for the rate of acidification in fermented seaweeds. The Danish Veterinary and Food Administration (DVFA) recommends that the pH of fermented vegetables should reach below 4.5 within 24h and 4.0 within 48h of storage (DVFA 2025) which has been used as a target by Nordic kelp producers. In a preliminary challenge test of *S. latissima* with *B. cereus*, no growth of the pathogen was observed on fermented samples after 72h, despite pH levels above the threshold (4.5 to 5.1; Stévant et al. 2025b). These results suggested that both acidification and competition with the inoculated starter culture and native microflora prevented the growth of the pathogen. More comprehensive challenge tests involving a wider range of foodborne pathogens are needed to develop evidence-based guidelines for the safe fermentation of seaweeds. Pre-treatments such as grinding or chopping of the raw material, as well as PEF treatment, can enhance substrate availability to the fermenting microbiota, thereby promoting faster acidification.

Starter cultures

To date, starter cultures used for kelp fermentation have mainly relied on commercial strains originally developed for agricultural applications. Efficient LAB strains for seaweed fermentation must be capable of rapid acidification, utilizing mannitol as the primary available carbon source, and tolerating saline conditions. Zioga et al. (2025) proposed a high-throughput screening approach and identified *Lactiplantibacillus plantarum*, *Lacticaseibacillus paracasei*, and *Lacticaseibacillus rhamnosus* from the National Food Institute Culture Collection in Denmark, as promising candidates based on their ability to efficiently convert mannitol into organic acids. In another study, Stévant et al. (2025b) demonstrated that fermented kelp fluid, obtained from a previous spontaneous fermentation of *S. latissima*, promoted rapid acidification of fresh kelp batches when used as starter culture. This fermented fluid contained predominantly LAB (though not taxonomically identified). Most LAB strains with potential for kelp fermentation perform optimally at around 30 °C, highlighting the importance of temperature control during processing. Strains capable of efficient fermentation at lower, ambient temperatures (10–15 °C) are currently under investigation. Both a native marine strain and a LAB strain were identified with potential use for kelp fermentation at ambient temperatures (Storesund, Duinker et al., *in prep.*). Future research should prioritize extensive screening of LAB and the development of mixed-strain starter cultures combining complementary phenotypic traits to ensure robust, predictable, and efficient fermentation of kelps, which are inherently complex substrates. In addition, technical solutions should be developed to ensure strictly anaerobic, optimal, and safe fermentation conditions at commercial scale, supporting both process stability and product consistency and safety.

Quality

As commonly observed during the fermentation of biomass with relatively low dry matter content, kelp fermentation results in the formation of a substantial liquid fraction, representing approximately 20-40% of the original wet weight (Stévant et al. 2025b). This fraction consists mainly of water and dissolved minerals such as sodium, potassium, magnesium and trace elements like iodine. Furthermore, fermentation has been shown to reduce the concentration of certain potentially toxic elements, including cadmium and mercury in *S. latissima*, as these leach into the liquid phase (Bruhn et al. 2019). Fermentation also promotes the degradation of complex polysaccharides, such as alginates and fucoidan, leading to the formation of oligosaccharides (Krishna Perumal et al. 2023; Nøkling-Eide et al. 2023). Recent studies indicate that kelp-derived polysaccharides, and their degradation products, may exert prebiotic effects by modulating gut microbiota, thereby supporting host health (Lopez-Santamarina et al. 2020; Zang et al. 2023). Further research is needed to determine how kelp processing, such as fermentation, influences the prebiotic potential of kelp-based ingredients, in order to support functional claims and promote their potential use as nutraceuticals. Regarding the effects of kelp fermentation on product flavours, available results indicate that the process tends to reduce perceived saltiness and umami intensity, while also diminishing marine flavours and odours, which could be beneficial for a more widespread use in mainstream food products (Bruhn et al. 2019; Zhu et al. 2021a; Stévant et al. *in prep.*).

4.2.3. Acid preservation

Direct acidification by the addition of organic acids has been investigated as a low-cost and energy-efficient stabilisation method for cultivated kelp biomass. This approach has also been implemented commercially as a scalable and more straightforward way to acidify kelp and overcome the variability and unpredictability associated with LAB-induced fermentation. Direct acidification of *S. latissima* and *A. esculenta* using lactic, citric or formic acid results in a rapid and stable decrease in pH (below 4.3), maintaining stability over extended storage periods at room temperature (approx. 20 °C) (Sandbakken et al. 2018; Nøkling-Eide et al. 2023; Hrólfsdóttir et al. 2024; Krook et al. 2024). Industry experience indicates that, despite good results at laboratory scale, controlling the growth of unwanted microbes remains challenging on a commercial scale. Achieving complete anaerobic storage at large scale remains the main bottleneck. Industrial trials using IBC-containers and Big Bags (1,000 L) have so far shown mixed results.

Quality

Lower concentrations (3 g acid per kg fresh kelp) of organic acids (citric and lactic acid) were associated with higher retention of nutrients, including minerals and water-soluble carbohydrates, compared to higher acid doses (Krook et al. 2024). This is likely due to increased hydrolysis of structural polysaccharides at higher acid concentrations, leading to greater losses of intracellular content. Alginate depolymerization has been reported in *S. latissima* and *A. esculenta*, although this effect can be mitigated by lower storage temperatures (4 °C) and shorter storage times (Nøkling-Eide et al. 2023). Cellulose appears unaffected by acid preservation, while hydrolysis of laminaran to glucose has been observed at pH levels between 3.7 to 4.5 (Sandbakken et al. 2018). Partial loss of fucoidan to the liquid fraction has also been reported (Krook et al. 2024), and polyphenol content as well as antioxidant activity tend to decrease with storage (Hrólfsdóttir et al. 2024).

4.2.4. Refrigerated storage

Shelf-life of fresh seaweeds

The typical shelf life of edible seaweeds under refrigerated storage (≤ 4 °C) ranges from 3 to 14 days, depending on species and pre-treatments (Liot et al. 1993; Nayyar and Skonberg 2019; Wirenfeldt et al. 2022). Changes in aroma, texture, and colour are closely linked to microbial growth and serve as reliable indicators of spoilage during storage. Pre-treatments such as blanching or HPP, which reduce the initial microbial load, have been shown to extend the shelf life of refrigerated seaweeds (del Olmo et al. 2020; Wirenfeldt et al. 2022). Fresh post-harvest storage of kelp can also be prolonged up to approx. 14 days using refrigerated seawater, provided that stocking density, water flow, and circulation are properly controlled to maintain uniform cooling throughout the biomass (Stévant et al. 2018a).

4.2.5. Freezing

Freezing is one of the most widely used methods for food preservation, as it inhibits microbial growth and slows down biochemical reactions responsible for food deterioration. Large-scale freezing technologies, such as impingement and vertical plate freezing, are well established in the food industry and have also been implemented in commercial kelp production (Blikra et al. 2024a). The main advantages of freezing are rapid stabilisation capacity and the ability to maintain high product quality relative to the original raw material. However, freezing and frozen storage requires space and substantial amounts of energy, which increases production costs and reduces the sustainability of the production (Thomas et al. 2021).

Quality and pre-treatments

Studies on the freezing and thawing of *S. latissima* and *A. esculenta* have reported considerable drip loss upon thawing, reaching up to 57% of the original wet weight. This liquid contains mainly minerals (sodium, potassium, and some iodine), as well as free amino acids and mannitol (Sund et al. 2024; Stévant et al. 2024). Rapid freezing was shown to reduce drip loss in *A. esculenta*, while differences between slow and quick thawing procedures had little impact (Sund et al. 2024). Steaming before freezing effectively reduced drip loss upon thawing of *S. latissima* (Stévant et al. 2024). The same study provided evidence that enzymatic reactions occur during frozen storage and contribute to the degradation of certain compounds, notably fucoxanthin and laminaran. Steaming was found to inactivate enzymatic activity and thereby promoted the preservation of these bioactive compounds. Combining steaming with subsequent freezing has also been identified as a suitable preservation method, yielding product with desirable taste and texture (Blikra et al. 2024a).

4.2.6. Dry salting, brining and pickling

Dry salting, brining, and pickling are traditional preservation methods used to extend the shelf-life of foods. Dry salting is the process of mixing food with dry sodium salt and allowing the resultant brine from the dissolution of the salt in the water extracted from the food, to drain away. Brining consists of immersing the food in a salt solution at a concentration that limits the development of spoilage microorganisms. Pickling or pickle curing in seafood processing typically refers to the process whereby food is mixed with salt and stored under the brine formed by the extracted water. In other foods, it involves the addition of acid (typically vinegar), which is here referred to as acid brining. Other than its preservation role, the addition of salt has been shown to immediately reduce the volume of seaweed (Caroline Østergaard Klein, pers. observation).

Shelf-life

When properly applied, salt-based preservation methods can extend the shelf life of fresh and/or pre-processed (e.g., blanched) seaweed from days to weeks or months. However, signs of deterioration, such as colour changes and tissue softening due to alginate degradation from bacterial activity, can occur if the conditions (salt-to-water ratio, temperature) are suboptimal. Successful preservation of kelps (*S. japonica*, *S. latissima*) for up to 30 days has been reported when 10–30% salt was added and the product was stored at 4 °C (Wei et al. 2021; Arya et al. 2024), as well as when at least 30% salt was added and the product was stored at ambient temperature (25 °C) (Wei et al. 2021). For *S. latissima*, recent experience shows that salt-pickling with ≥ 20% salt (up to 50%) can extend refrigerated (4 °C) shelf life as long as one year based on the microbial level and off-odour assessment (Klein et al., under review). A similar shelf-life can be achieved with lower salt levels when salt (5%) is combined with acid brining (pH 4.5) and refrigerated. However, mould growth may occur during storage unless sorbic acid is included in the brine, as acetic acid alone is insufficient to prevent spoilage (Klein et al., *in prep.*). A recent study on different brining conditions for *U. fenestrata* showed that brining with 25% salt or 50% sugar ensured microbial stability of the seaweed during refrigerated storage at 4 °C (Vall-llosera et al. 2024). Although salting processes should be optimized for each species, combining multiple hurdles towards spoilage, such as low temperature, appropriate salt concentration, pH control where relevant, and hygienic handling, will ensure food safety.

Quality

Water-soluble nutrient including minerals (especially potassium and iodine), polyphenols, free amino acids, and presumably some vitamins will leach into the drip water or brine, as well as during desalting to remove excess salt prior to use, resulting in some nutrient loss (Stévant et al. 2024). Dry salting tends to preserve the brown colour and firm texture of fresh *S. latissima* initially, although prolonged storage can cause tissue softening and colour changes (Arya et al. 2024; Stévant et al. 2024). Depending on the extent of salt removal upon desalting, saltiness is likely to dominate the flavour profile of salt-preserved seaweed and mask other flavour attributes. Acid brining, on the other hand, increases the sourness of the final ingredient (Østergaard Klein et al., *in prep.*). Vall-llosera et al. (2024) reported that preservation of *U. fenestrata* in a 25% (w/w) sodium chloride brine at 4 °C effectively maintained the original colour and texture of the seaweed. However, this treatment resulted in substantial nutritional losses, including reductions of approximately 70% in protein content, 42% in total fatty acids, and 57% in PUFAs.

4.3. Conclusions

Efficient post-harvest handling and stabilisation are critical for unlocking seaweeds as safe, nutritious and high-quality food ingredients. Because seaweed biomass deteriorates rapidly, early stabilisation is essential to protect food safety, sensory quality, and economic value. The evidence reviewed shows that both conventional and emerging technologies can improve food safety (notably iodine control and microbial stability), quality retention and process efficiency when adapted to the seaweed species and end-use. Processing routes should be **tailored to product goals**: gentle treatments better preserve water-soluble nutrients and flavour when seaweeds are used as flavour ingredients, whereas more intensive fractionating approaches can be advantageous when targeting fibre-rich functional or textural ingredients. **Pre-processing** options such as short warm-seawater treatments, as well as emerging technologies (PEF, US, HPP), show promise for improving iodine management and downstream efficiency, but require further industrial validation and cost optimisation. **Low-energy stabilisation** through LAB fermentation or direct organic acidification offers scalable alternatives to freezing/drying, yet both approaches need improved process control and clearer safety guidance. Finally, since drying and freezing dominate energy use in seaweed value chains, future competitiveness depends on hybrid process design, low-temperature/efficient drying technologies (e.g., microwave-vacuum drying) and renewable energy integration. Achieving industrial feasibility ultimately requires balancing product quality with energy use, operational complexity and environmental impact. Continued innovation, including tailored pre-treatments, low-energy stabilisation, side stream valorisation and centralised processing infrastructures, will be essential to support a sustainable and competitive scale-up of the European seaweed sector.

- **Post-harvest handling**: Fresh seaweeds deteriorate rapidly due to high moisture content. Early and efficient stabilisation is therefore essential to ensure food safety, preserve nutritional and sensory quality and prevent economic losses along the value chain.
- **Tailored processing routes to product goals**: Processing routes should be matched to the intended product application. Gentle processing is preferred when seaweeds are used as flavour ingredients, as it promotes retention of water-soluble nutrients and flavour compounds. More intensive processing, maximising extraction of soluble components, may be chosen when seaweed fibres are targeted as functional or textural ingredients.
- **Pre-processing:** Short warm-seawater treatments (40–50 °C, 1–4 min) provide substantial iodine reduction while retaining more minerals and flavours than freshwater blanching. Emerging technologies such as pulsed electric field (PEF), ultrasound (US) and high pressure processing (HPP) can further reduce iodine, enhance extraction of bioactive compounds and improve the efficiency of downstream processing. These methods require industrial upscaling and cost optimisation.
- **Low-energy stabilisation:** LAB-induced fermentation offers a low-energy preservation route but requires adapted starter cultures, sufficient substrate availability and clear safety guidelines (e.g., pH kinetics targets). Direct acidification with organic acids enables rapid, predicable reduction of pH and shelf-stable products but requires improved microbial control at industrial scale. Polysaccharide

breakdown products formed during fermentation and acid preservation may support gut health, but further research is needed to substantiate mechanisms and functional claims.

- **Drying:** Drying efficiency can be increased by combining pre-treatments (e.g., PEF, mechanical dewatering) with dehumidified air or heat-pump drying technologies, or by fluidisation of the raw material to reduce processing time and energy demand. Alternative drying technologies may enable more efficient drying, but investment costs often remain a barrier to commercial implementation.
- **Reducing environmental impacts**: Drying and freezing dominate energy use in seaweed value-chains. Implementing renewable energy, heat recovery systems and low-temperature drying technologies can substantially reduce the environmental footprint of seaweed processing.
- **Develop processing hubs:** Collaborative processing infrastructures, modular facilities and integrated biorefineries can reduce costs, improve resource efficiency and enable full biomass utilisation, including valorisation of side streams.

5. Sensory quality

Seaweed consumption in Asia is deeply rooted in culinary traditions and seaweeds are appreciated for their characteristic flavours, texture and functional roles in food. In contrast, interest in seaweed among European and Western consumers is primarily driven by perceived health benefits, climate-positive attributes, vegetarian and vegan trends, and strong preferences for organic, sustainable and fair-trade products (Buschmann et al. 2017; Birch et al. 2018). In Scandinavia, the renewal of the Nordic Cuisine led by avant-garde restaurants based on locally sourced natural ingredients has highlighted seaweeds as valuable components in high-end gastronomy. Several initiatives have demonstrated the potential of locally available species, including *S. latissima*, *A. esculenta, P. palmata* and *Ulva* spp., to be incorporated into traditional recipes and everyday culinary applications, contributing both flavours and textures (Mouritsen et al. 2012; Chapman et al. 2015). For broader commercial success, sensory quality is critical. Perceived appearance, odour, flavour and texture strongly influence consumer acceptance, and nutritional or health benefits alone are insufficient to compensate for unfavourable sensory properties (Rode et al. 2025). Despite increasing interest in seaweed-based foods, the diversity and specificity of sensory profiles across species and post-harvest treatments remain poorly understood by consumers and food manufacturers. This knowledge gap limits the wider incorporation of seaweeds into Western diets and underscores the importance of systematically characterising and managing sensory quality throughout processing and product development.

5.1. Sensory profiles

Sensory quality encompasses multiple attributes perceived during consumption, including appearance (e.g. colour and visual structure), odour, flavour, texture and mouthfeel. In seaweeds, these attributes are shaped by species-specific biochemical composition, harvest conditions and post-harvest processing. Sensory perception therefore reflects both intrinsic properties of the biomass and the effects of processing and storage. Understanding how these attributes interact is essential for designing seaweed ingredients that meet consumer expectations and perform reliably in food applications.

Seaweed flavours and odours

The growing appreciation of seaweed as a natural source of flavour has contributed to the recent rise in interest across Europe. Yet, most consumers remain unfamiliar with seaweeds, and their flavour profiles have been only partially defined and characterised for food product development. Early descriptions of individual species were provided by gastronomists and high-end chefs, often with scientific insight (Mortensen et al. 2004; Rhatigan 2009; Mouritsen 2013). Subsequent academic studies have aimed to systematically document the sensory characteristics of major edible species through objective assessments (Chapman et al. 2015; Dahlstedt et al. 2025 and references therein). Species-level differences can be substantial, comparable to those observed between distinct terrestrial vegetables or fruits. Indeed, seaweed species can differ as markedly as broccoli and bananas, making generalisations difficult. In addition, flavour and odour profiles vary with harvest season, geographic origin, physiological state, and post-harvest processing. The main cultivated edible seaweeds in Europe i.e., *S. latissima*, *A. esculenta*, *P. palmata* and *Ulva* spp. (Araújo et al. 2021) are generally characterised by salty and umami tastes combined with grassy and fresh marine notes of variable intensity (**Figure 11**).

Umami

In addition to salt, umami is the most prominent characteristic flavour of seaweeds and has received the greatest attention from both culinary and academic studies. Umami is a basic taste described as brothy, meaty and savoury, known for enhancing the intensity and complexity of other flavours (Mouritsen and Styrbæk 2014). First identified in Japanese kelp (*S. japonica*), umami taste is associated with the presence of the free amino acid glutamate. The umami response can also be enhanced by the presence of synergetic compounds to glutamate in food, particularly the free nucleotides inosine-5′-monophosphate (IMP) and guanosine-5′-monophosphate (GMP). However, recent studies have shown a weak correlation between umami intensity and glutamate levels in *A. esculenta* and *S. latissima* and identified specific volatile compounds and other free amino acids contributing umami in these species (Mouritsen et al. 2019a; Frøst et al. 2021; Stévant et al. *in prep.*). Umami is strongly linked to food preference and the use of monosodium glutamate (MSG, E-number E621; commonly produced by chemical synthesis or bacterial fermentation) is well established to enhance palatability of processed foods (Figueroa et al. 2021). The natural umami quality of edible seaweeds therefore offers considerable potential for their use as natural flavour-enhancing condiments across a wide range of food products and preparations, including meat, vegetables, bread, and even desserts (Mouritsen et al. 2012; Chapman et al. 2015).

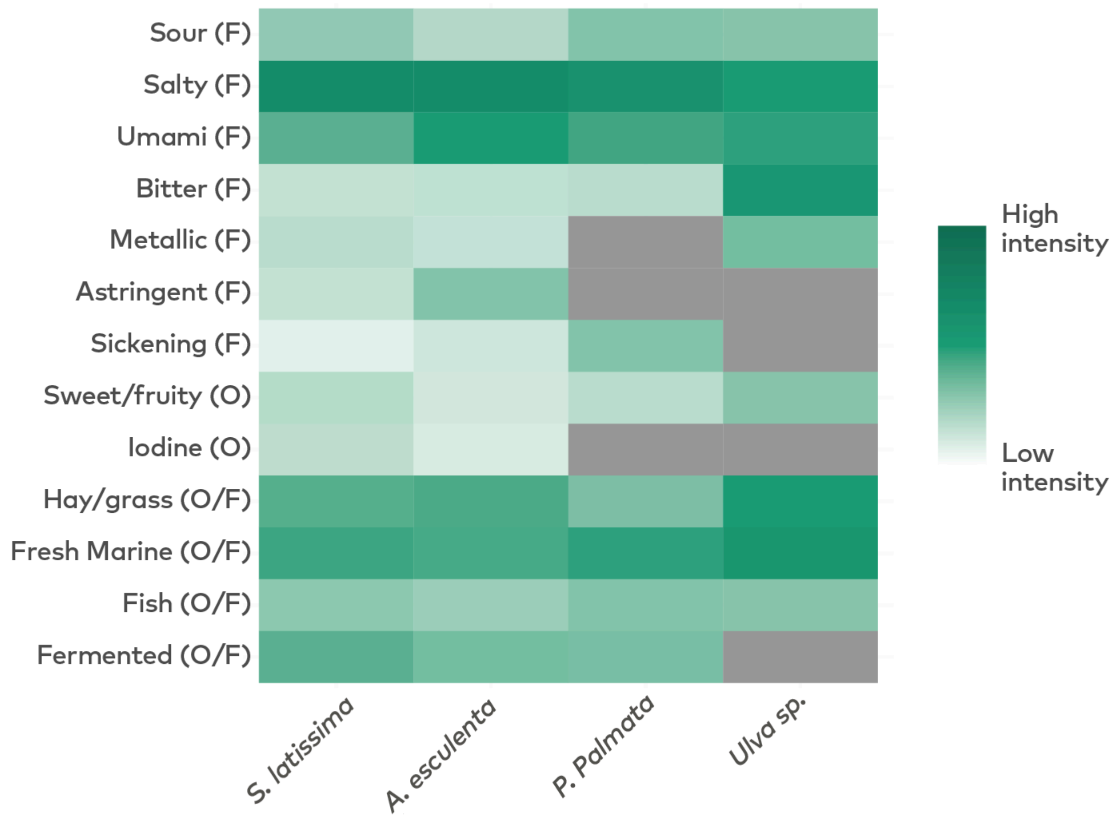

Figure 11: Sensory profile of dried *Saccharina latissima*, *Alaria esculenta*, *Palmaria palmata* and *Ulva* spp. based on scaled sensory scores for flavour (F) and odour (O) attributes from several Nordic studies. The scores were obtained from generic descriptive analysis (GDA) using trained sensory panels from Norway, Iceland, Denmark and Sweden. Seaweeds were wild-harvested or cultivated, and air-dried at max. 52 °C. Data from Stévant et al. (2018b); Stévant et al. (2020); Stévant et al. (2021), Jönsson et al. (2023b); Krook et al. (2024), Wirenfeldt et al. (2024) and unpublished data from the SusKelpFood project. Grey colour represents no data available.

Off-flavours and -odours.

Marine and fishy odours and flavours are present in the four species mentioned above (Figure 11) and are generally regarded as off-flavours associated with lower consumer acceptance as they can relate to odours from decomposing beach-cast on the shore (Mouritsen 2013; del Olmo et al. 2018). Bitterness, another common off-flavour, can be characteristic of *Ulva* spp. and may also originate from volatile compounds (Figueroa et al. 2022; Wirenfeldt et al. 2024). Various nitrogenous and volatile compounds with unpleasant odours are produced during seaweed spoilage and can serve as sensory indicators of shelf-life. Reported off-odours include "vinegar", "acetic acid", "rotten", "old hay", "chlorine", or "sulphur-like" notes in *S.*

latissima (Wirenfeldt et al. 2022) and "fishy" notes in *P. palmata* (Nayyar and Skonberg 2019). These off-notes corresponded with observable early signs of spoilage and biomass degradation.

Seaweed-based foods and consumer preference

Numerous studies from Europe showed that increasing seaweed content in food product above 5% often leads to reduced consumer liking (Dahlstedt et al. 2025 and references therein). This underscores the importance of careful species selection and post-harvest processing to achieve favourable sensory profiles. Product success further depends on appropriate pairing with other ingredients, where the flavour and odour interactions can create synergy and/or enhance umami. These considerations are closely linked to whether seaweed is intended to act as a dominant sensory component or as a subtle background ingredient in the final product.

5.2. Textural properties

Phycocolloids

Purified seaweed polysaccharides extracted through chemical processes, such as alginates from brown seaweeds or agar and carrageenan from red seaweeds, are widely used in foodstuffs as gelling, clarifying, emulsifying and stabilising agents. However, these compounds must be declared as food additives (E-numbers E401 to E407), a category that has drawn negative public attention due to the refining approach of the additive and health concerns linked to ultra-processed foods (Monteiro et al. 2025).

Seaweeds as texture ingredients

Using whole seaweeds in suitable forms (e.g., powders or flakes) can provide similar physicochemical and textural benefits than phycocolloids extracts, and retain a more natural image (Roohinejad et al. 2017). For example, the addition of powdered brown seaweeds at levels between 1% and 10% has been shown to enhance water- and oil-binding capacities in meat products such as pork and beef patties and frankfurters (Cofrades et al. 2008; López-López et al. 2009; Choi et al. 2012; Cox and Abu-Ghannam 2013). Whole seaweeds also allow exploitation of both their gelling and flavour properties. When off-flavours and/or potentially toxic elements (e.g., iodine) pose a challenge, processing methods that remove water-soluble flavour compounds (e.g., blanching, PEF; see Table 7 and Table 8) may be preferred, allowing more seaweed ingredient to be added to the food. Processed seaweed ingredients designed for use in hybrid meat products (e.g., burgers) are beginning to enter the market. Blends combining flavour-retained seaweed ingredients (e.g., umami-rich) with components rich in structural polysaccharides (texture ingredients), derived from different species and/or processing routes, could also be developed for tailored applications within the food industry.

5.3. Effects of post-harvest processes and storage on the sensory quality

The sensory quality of seaweeds is closely linked to their content of flavour-active compounds such as free amino acids, minerals and volatile compounds (Mouritsen et al. 2019a; Stévant et al. 2020; Figueroa et al. 2021), which may be affected by processing of the raw material. Several studies have investigated how processing influences the sensory quality of edible seaweeds, and the main effects of the different methods on *S. latissima*, *A. esculenta P. palmata* and *Ulva* spp. is summarised in **Table 11,** and further addressed below.

Pre-processes

Processes involving osmotic pressure (e.g., freshwater blanching, PEF) or those that induce the formation of a liquid phase (e.g., freezing/thawing, fermentation, acid preservation) generally reduce the content of small water-soluble components such as minerals and free amino acids. Short freshwater blanching has been shown to drastically decrease sodium, potassium and free glutamate and aspartate levels (Wirenfeldt et al. 2022; Stévant et al. 2024), which likely explains the markedly reduced perception of saltiness and umami following this treatment (Krook et al. 2023). Heat treatments such as blanching are also known to induce colour changes in kelps, typically from olive-brown to bright green (Blikra et al. 2018; Stévant et al. 2024). This bright green, vegetable-like appearance has been positively correlated with hedonic scores (Akomea-Frempong et al. 2021), suggesting that such colour changes may increase the visual appeal of seaweeds and lower the acceptance barrier among Western consumers.

Table 11: Effects of post-harvest processes on the sensory quality of *Alaria esculenta, Saccharina latissima, Palmaria palmata* and *Ulva* spp. reported in the literature.

Post-harvest process	Species	Effect on sensory properties	Reference
Blanching (95 °C, 15 min) followed by LAB-induced fermentation	*S. latissima*	Heat treatment significantly reduced saltiness and umami and gave the kelp a less "slimy" appearance. Fermentation further resulted in decreased intensity of marine aromas ("smell of sea"). No effect of heat-treatment and fermentation on firmness.	(Bruhn et al. 2019)
Freshwater-/seawater-blanching (45 °C, 2 min), Steaming (15 min)	*S. latissima*	Seawater-treated kelp was highest in saltiness, umami and "fresh sea aroma". Steaming retained umami flavour while freshwater-treated kelp was mild and dominated by "hay" and green notes.	Krook et al. (2023)
Blanching/heat treatments (boiling, vacuum and steam cooking)	*U. rigida*	Fresh marine aromas ("seaside" and "seaweed") decreased in heat-treated samples while "cooked fish", "salty dry fish" and "crustacean" aromas increased.	Sánchez-García et al. (2021)
LAB-induced fermentation, pulsed electric field (PEF), seawater-blanching (50 °C, 2 min)	*S. latissima, A. esculenta*	PEF treatment decreased umami flavour intensity and saltiness. Fermentation appeared to reduce the perceived umami intensity.	Stévant et al. *in prep.*
Convective air-drying (52 °C), microwave vacuum drying (-40 to 40 °C), freeze drying (-20 to 20 °C)	*Ulva* sp.	More intense marine aromas ("seaweed", "sea", "fresh fish") in freeze-dried samples. Air drying produced firmer, crispier and darker samples.	Wirenfeldt et al. (2024)
Convective air-drying (25, 40 and 70 °C), freeze drying	*S. latissima*	No major effect of drying temperature (25 vs. 70 °C) on aromas and flavour. Reduced swelling capacity in air-dried samples at high temperature	Stévant et al. (2018b)

Storage at 4 and 16 °C for 12 days	*U. rigida*	Aromas of "seaside" and "seaweed" decrease over time, and "boiled vegetable" odours became more pronounced.	Sánchez-García et al. (2019)
Storage in seawater (4 °C) for 15 days vs. frozen	*P. palmata*	Dulse stored in seawater retained fresh and marine aromas ("seaside", "iodised", "seaweed") while frozen dulse developed "green" aromas.	Le Pape et al. (2002)
Refrigerated storage (2 °C, 7 °C) for up to 2 weeks	*P. palmata*	"Fresh" aromas decreased during storage for unpleasant "fishy" aromas	Nayyar and Skonberg (2019)
Storage dry (6% moisture) and semi-dry (20% moisture) for 126 days	*P. palmata*	Marine and fishy flavours faded upon semi-dry storage, while sweet, rich and complex notes (incl. umami) arose. Semi-dried dulse was also more tender.	Stévant et al. (2020)
Storage dry (6% moisture) and semi-dry (15–18% moisture) for 97 days	*S. latissima*	Dry-stored kelp maintained fresh marine aromas while green notes ("hay", "green tea") developed upon semi-dry storage instead of marine aromas. No effect of storage condition on saltiness and umami.	Stévant (2019)
Storage in acid (lactic vs. citric acid) for 56 days	*S. latissima*	Citric acid storage resulted in a higher perceived sourness than lactic acid at comparable concentrations. No significant effects detected over storage time.	Krook et al. (2024)
Storage dry and fermented for 2 years	*A. esculenta*	No significant changes in sensory profile upon dry storage. Sourness tends to increase during storage of fermented kelp.	Larssen et al. *in prep.*
Brining (6% NaCl), pickling (sugar, salt and acetic acid or apple cider vinegar)	*U. fenestrata*	Bitterness and fishy flavours are reduced in all treatments. Brining enhanced seaweed odours, umami, and saltiness, while vinegar pickling introduced sweetness and distinctive vinegar-related flavours.	Björkman et al. (2026)

Drying and dry storage

Drying, by reducing water content to a minimum, can greatly affect the perceived flavour and texture of food materials. Michel et al. (1997) observed lower levels of volatile compounds in air-dried samples of *P. Palmaria* and *Ulva* sp. at 60 °C compared to fresh material, although the relative proportions between compounds remained similar, in line with relatively similar sensory profiles between fresh and dry material. In contrast, drying at 150 °C caused drastic changes in colour and volatile composition, with the formation of low-molecular-weight compounds at the expense of long-chain fatty acids and aldehydes, attributed to Maillard and oxidative reactions at high temperatures. Drying below 60 °C is generally recommended to preserve nutritional and bioactive compounds (Badmus et al. 2019), and no major sensory differences were detected between *S. latissima* dried at 25 °C and 70 °C (Stévant et al. 2018b). Several studies indicate that low-temperature drying, including freeze-drying, better preserves the integrity of odour- and flavour-active volatiles responsible for fresh marine and fishy aromas and flavours (Wirenfeldt et al. 2024; Dahlstedt et al. 2025). High drying temperatures negatively affect the physicochemical properties of kelp such as water- and oil-binding and swelling capacities due to product shrinkage and reduced porosity (Sappati et al. 2017; Stévant et al. 2018b). Similar temperature-related losses in hydration properties upon drying have been reported for *P. palmata* (Stévant 2019) and other edible seaweeds (Tello-Ireland et al. 2011; Chenlo et al. 2017), which may lower the quality of dried seaweed as a textural ingredient.

Different drying methods tested on *Ulva* spp. and *F. vesiculosus* were compared by (Wirenfeldt et al. 2024) and overall, freeze-drying preserved the mildest sensory profile, with lighter colour, lower bitterness, and more neutral odour, making it closest to the fresh reference for several attributes. Conventional hot-air drying (52 °C) resulted in darker colour, more pronounced bitterness, and stronger "marine" and "dried" notes, indicating greater thermal and oxidative impact on flavour and appearance. Microwave-vacuum drying (MVD) generally produced sensory characteristics intermediate between freeze-drying and hot-air drying, combining shorter processing times with better retention of colour and flavour than hot-air drying, although not always matching freeze-dried quality. Texture attributes (e.g., crispiness/firmness) shifted substantially with drying method; with convective drying yielding a crispier, firmer product depending on species. Importantly, the study shows that species respond differently. MVD performed particularly well for *Ulva* spp., yielding sensory properties close to freeze-dried samples, whereas larger differences between drying methods were observed for *F. vesiculosus* (Wirenfeldt et al. 2024). This highlights that drying method selection should be species- and product-specific, depending on the targeted sensory profile and application.

Fermentation

LAB-induced fermentation involves the conversion of fermentable sugars in seaweeds into lactic acid, resulting in a sourness in the final product. However, sourness may not appear as a dominant flavour when the fermented seaweed is subsequently dried (Stévant et al., *in prep.*). A recent shelf-life study of fermented *A. esculenta* stored in the fermenting fluid for up to two years showed an increase in sourness intensity with storage time (Larssen et al., *in prep.*). Fermentation of *S. latissima* was also reported to reduce marine-like aromas (Bruhn et al. 2019), likely due to the degradation of odour-active compounds responsible for these aromas and/or the emergence of other flavour-active compounds masking them. Similarly, fermentation of *S. japonica* with the yeast *Aspergillus oryzae* resulted in the removal of marine-type odours often perceived as off-flavours (Seo et al. 2012). Flavour profiles developed during seaweed fermentation depend strongly on the seaweed species, starter culture, and processing conditions, which influence the formation of flavour-active substances. This was illustrated by Uchida et al. (2017) when developing a sauce made of *Pyropia* sp. fermented following different protocols and incubated for two years, which yielded variable umami intensities. Although fermented seaweeds are not yet mainstream food ingredients, even in Asia, some commercial innovations are emerging. In France, for example, fermented brown seaweeds are promoted as locally sourced, low-footprint sea vegetables suitable as functional ingredients in the food industry or for direct consumption in salads and cooked dishes (www.algood.fr/). Ensuring product consistency in both safety and flavour will be key to establishing fermented seaweed ingredients in commercial food products.

Freezing

There is limited research systematically describing the effects of freezing on seaweed sensory properties. As outlined in the **Chapter 4**, freezing typically leads to substantial drip loss upon thawing, which is associated with texture softening and structural changes in kelps (Sund et al. 2024; Stévant et al. 2024). This liquid fraction from drip loss has been shown to contain flavour-active compounds such as free amino acids (Sund et al. 2024; Stévant et al. 2024). In a sensory study on *P. palmata*, panellists described frozen samples with odours such as "cut grass", "tea" or "hay", whereas fresh samples were characterised by marine notes (e.g. "seaside", "seaweed", "iodized"). These changes may result from cell lysis during freezing and thawing, leading to the release of enzymes such as lipoxygenases that generate green, grassy volatile compounds from fatty acids (Le Pape et al. 2002).

Flavour development

While numerous studies have focused on optimizing the extraction of high-value compounds from seaweeds, much less attention has been given to processes that modulate flavour to appeal to Western consumers. In Asia, established methods exist for flavour development in commonly used seaweeds. For instance, nori (*Pyropia* spp.) is washed, chopped, and mixed with water to form a slurry, which is then dried into sheets and roasted to develop its characteristic aroma, colour, and crisp texture. Likewise, Japanese *konbu* (*S. japonica*) undergoes sun-drying followed by storage in ageing cellars under controlled humidity and temperature for up to ten years, during which strong marine odours diminish, and rich, savoury umami flavours develop. In Western contexts, traditional practices focusing on flavour enhancement are scarce. One example comes from coastal Canada, where open-air drying of giant kelp (*Macrocystis pyrifera*) and bull kelp (*Nereocystis leutkeana*) allows ultraviolet radiation to break down bitter polyphenols (Mouritsen et al. 2019b). According to historical records of *P. palmata* harvests in Iceland, the flavour value of the seaweed increased after sun-drying and subsequent storage in closed barrels for weeks or months (Kristjánsson 1980). Sun-drying typically results in products with higher levels of moisture than when using forced air drying systems (Chan et al. 1997), promoting the activity of endogenous enzymes and other reactions (hydrolysis of proteins, carbohydrates, oxidation of lipids), leading to the formation of flavour compounds such as free amino acids, mono- and oligosaccharides and the formation of volatile compounds. This was confirmed experimentally by Stévant et al. (2020), who observed that lightly rehydrated *P. palmata* fronds (containing approx. 20% moisture) stored for weeks or months developed sweet, rich, and complex flavours with umami, honey, and liquorice notes, along with a tenderised texture. These changes were paired with increased levels and diversity of volatile compounds. Together, these examples illustrate that targeted processing and storage conditions can produce a diverse range of desirable sensory profiles in seaweeds.

5.4. Quality control methods for the industry

Quality standards

To improve the sensory quality of seaweed ingredients used in commercial foods and enhance their market success, harmonised and consistent production and quality assessment methods are essential. Such methods should be applicable across the seaweed industry and aligned with consumer acceptance. In other food sectors, industry-adjusted control systems for sensory quality are well established, e.g., quality standards for fish products and fish oils, or standards set by the International Olive Oil Council (IOOC). These frameworks help define product categories (as in the Codex Alimentarius) and support better product positioning on the market.

Sensory vocabulary

Developing a suitable sensory vocabulary that captures both positive and negative sensory properties, including flavour, texture, and colour, is a key step toward evaluating overall seaweed quality, whether the product is used for flavouring or as a texturizing ingredient. A sensory wheel for edible seaweeds and microalgae, comprising descriptive terms for relevant sensory attributes, was proposed by Francezon et al. (2021), inspired by similar work on marine oils (Larssen et al. 2018). Creating species- or group-specific (e.g., kelps) sensory frameworks can provide accurate, representative descriptions of seaweed product quality. Such tools can support sensory quality control, ensure product consistency, and guide process optimization in seaweed production for food use.

5.5. Conclusions

Sensory quality including appearance, odour, flavour and texture **is central to consumer acceptance and the commercial success of seaweed-based foods**. While edible seaweeds offer substantial potential as natural flavour enhancer, texturising ingredients, and visually distinctive food components, their sensory properties are highly dependent on species, processing, and storage conditions. Nutritional and sustainability benefits alone are insufficient to compensate for unfavourable sensory attributes. A clear understanding of how sensory quality is shaped along the value chain is therefore essential to enable wider integration into Western food products.

Seaweeds are naturally rich in **umami-active compounds and minerals**, making them attractive as flavour ingredients capable of enhancing savoury intensity and reducing reliance on synthetic flavour additives. At the same time, strong marine, fishy or bitter notes may limit acceptance if not appropriately managed. Post-harvest processing plays a decisive role in shaping these sensory attributes. Heat treatments, drying, fermentation, freezing and storage each influence flavour intensity, aroma composition, colour and texture in distinct ways, offering opportunities to either retain fresh marine characteristics or develop more complex, mild or mature flavour profiles.

Beyond flavour, seaweeds can function as minimally processed **textural ingredients**, providing gelling, thickening and water-binding properties without the need for extracted hydrocolloids. This aligns well with clean-label and sustainability-driven formulation strategies. However, achieving consistent quality requires careful selection of species, processing routes and storage conditions, supported by appropriate quality control tools.

Overall, **targeted processing and informed sensory management** enable seaweeds to move from niche ingredients to versatile components in mainstream food products. Developing shared sensory vocabularies, quality frameworks and application-oriented processing strategies will be key to unlocking the full sensory and commercial potential of seaweeds in European food systems.

- **Sensory quality drives acceptance:** Appearance, flavour, odour and texture are decisive for consumer acceptance of seaweed-based foods; health and sustainability benefits alone are not sufficient.
- **Seaweeds as flavour ingredients:** Edible seaweeds are rich sources of natural umami and minerals, offering opportunities to enhance savoury flavour and reduce reliance on synthetic flavour additives.
- **Managing off-flavours:** Marine, fishy or bitter notes can limit consumer acceptance. Species selection and tailored processing are essential to achieve balanced and application-specific flavour profiles.
- **Seaweeds as textural ingredients:** Whole or minimally processed seaweeds can provide gelling, thickening and water binding functionality, supporting "clean-label" formulations without extracted hydrocolloids.
- **Processing shapes sensory outcomes:** Blanching reduces saltiness and umami; low temperature drying preserves fresh marine aromas and texture; fermentation reduces marine notes and introduces sourness and complexity; freezing tends to shift aromas towards green and grassy notes.
- **Opportunities for flavour development:** Traditional Asian practices such as roasting and ageing demonstrate how targeted processing can purposefully develop desirable flavour profiles, offering inspiration for innovation in Western seaweed-based foods.
- **Quality control is essential**: Harmonised sensory vocabulary and quality framework are needed to ensure product consistency, guide processing decisions and support market positioning of seaweed ingredients.

6. Consumer acceptance and food product development

Consumer acceptance is a critical determinant of whether seaweed-based foods can move beyond niche markets and achieve broader uptake in Western diets**.** While earlier chapters have addressed nutrients (**Chapter 2**), food safety (**Chapter 3**), post-harvest processing (**Chapter 4**), and sensory quality (**Chapter 5**), successful market introduction ultimately depends on how consumers perceive, accept, and are willing to purchase and consume seaweed-containing products. **Chapter 6** therefore focuses on consumer attitudes, preferences, and behavioural drivers related to seaweed as food, with particular emphasis on Western and Nordic contexts. Drawing on both international literature and empirical findings from the SusKelpFood project, the chapter examines current consumption patterns, hedonic responses, perceived barriers and drivers, and consumer segmentation to inform product development, communication strategies, and market positioning.

Western consumers and seaweeds

As opposed to Asian cultures, seaweeds have not been traditionally consumed in Europe. In Western societies, consumer acceptance of seaweed-based foods is shaped by perceived health and nutritional benefits, sensory qualities, ethical and environmental values, as well as prior familiarity (Birch et al. 2019; Govaerts and Olsen 2023; Onwezen et al. 2021) Major obstacles to a broader use of seaweeds in Western diets include limited consumer knowledge, low accessibility of seaweed-based foods, high prices, food neophobia and food safety concerns (Birch et al. 2019; Tenorio-Rodríguez et al. 2025; Young et al. 2022). Acceptance of seaweed-based foods tends to be higher among younger individuals, health-conscious and adventurous consumers, and is further associated with biospheric values (i.e., greater care for nature and the environment) (Birch et al. 2019; Govaerts and Olsen 2023) As discussed in the previous chapter, seaweeds possess intrinsic sensory properties that can be modulated through processing and can enhance the flavour, texture, and colour of the foods to which they are incorporated. The sensory appeal of seaweed-based products is identified as a driver for consumer acceptance of seaweeds as untraditional food items, potentially mitigating food neophobia (Embling et al. 2022).

Cultural adaptation

In Western countries, promoting seaweeds may require broad cultural interventions such as school-based food education, positive media framing, supermarket visibility, and integration into familiar food products (Pickering et al. 2025). Although adventurous consumers are often quicker to adopt new foods, consumer acceptance of seaweed must be understood within specific cultural contexts and priorities. For instance, survey data from Australian consumers emphasize the need for increased promotion (general advertisement, nutritional benefits), greater product diversity, and reduced single-use plastic packaging (Young et al. 2022), whereas a study of Mexican consumers stresses the importance of education, communication, and culinary integration strategies to support adoption (Tenorio-Rodríguez et al. 2025). Together, these insights underscore the need for tailored marketing and cultural adaptation strategies to expand seaweed adoption in Western markets, which are not homogeneous but shaped by distinct regional, national and local food cultures and preferences.

The present section summarizes recent findings from the SusKelpFood project, which investigated **Norwegian consumer preferences and motivations regarding seaweed as food** through surveys, focus group interviews, and product trials. The aim was to provide a deeper understanding of consumer perceptions and attitudes in a Nordic context, to identify and characterize homogenous consumer segments, and to assess both acceptance and willingness to pay for seaweed-based foods.

6.1. Seaweed consumption and hedonic liking of seaweed food among Norwegians

Seaweed consumption in Norway

As part of a large questionnaire addressing both general food-related factors (e.g. neophobia) and seaweed-specific aspects, the frequency of seaweed consumption among a representative sample of Norwegian consumers (*n* = 1,001) was recorded using a seven-point scale ranging from "never" to "very often" (**Figure 12**). A clear majority reported either never consuming seaweed (60%) or doing so only very seldom (10%). Only 10% indicated that they had consumed seaweed several times or more over the past six months. When sushi consumption was excluded, reported consumption declined slightly, suggesting that sushi is the primary context in which consumers encounter seaweed. Overall, seaweed remains a niche food product in Norway.

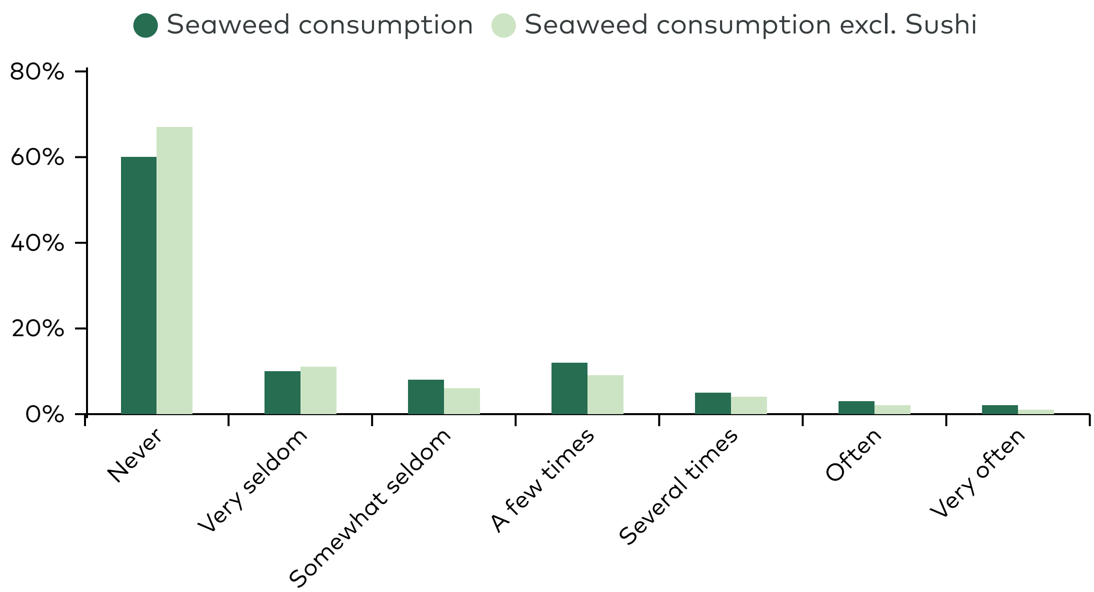

Figure 12: Frequency of seaweed consumption among Norwegian consumers (*n* = 1,001), based on survey data. The orange bars represent overall consumption, while the green bars show consumption excluding sushi. The average age of participants was 48.3 (range: 18–85), with a gender distribution of 49% men and 51% women. A majority (55.7%) reported having higher education (university or university college). The respondents were grouped across five regions of residence: Oslo (13.5%), Innlandet/Viken (30.9%), Agder/Sør-Østlandet (13.8%), Vestlandet (25.7%), Trøndelag/Northern Norway (16.2%).

Hedonic consumer response

In addition to the survey, product trials were conducted across three locations during six tasting events, involving a total of 238 participants. Alongside hedonic evaluations of two seaweed-containing food items (a fish soup and a Nordic kelp salad, both containing *A. esculenta*), participants were asked about their seaweed consumption frequency, willingness to consume seaweed-based products, and a range of attitudinal measures related to seaweed as food. Importantly, participants (recruited as passersby) were invited to take part in the product trials and were informed only that the dishes contained seaweed and relevant allergens (e.g., fish, gluten); the exact recipe was not disclosed. Consumer ratings of the fish soup with kelp were centred around the midpoint of the scale, with 31% of participants rating it 5 on the 1–9 hedonic scale (**Figure 13**), indicating a moderate level of liking. This may be partly explained by the fact that option 5 was preselected by default. Despite this, 46% of respondents rated the soup above the midpoint (scores 6 to 9), while only 22% rated it below (scores 1 to 4). This distribution suggests that the fish soup was perceived as moderately appealing, with relatively few respondents expressing strong positive or negative opinions. In contrast, the kelp salad received more favourable ratings (**Figure 13**). Although 26% of respondents gave it low scores (1 to 4), nearly two-thirds (64%) rated it at the higher end of the scale (6 to 9), indicating a generally positive reception. Overall, the comparison suggests that the kelp salad was better received than the fish soup, with a larger proportion of participants expressing a clear preference for the former.

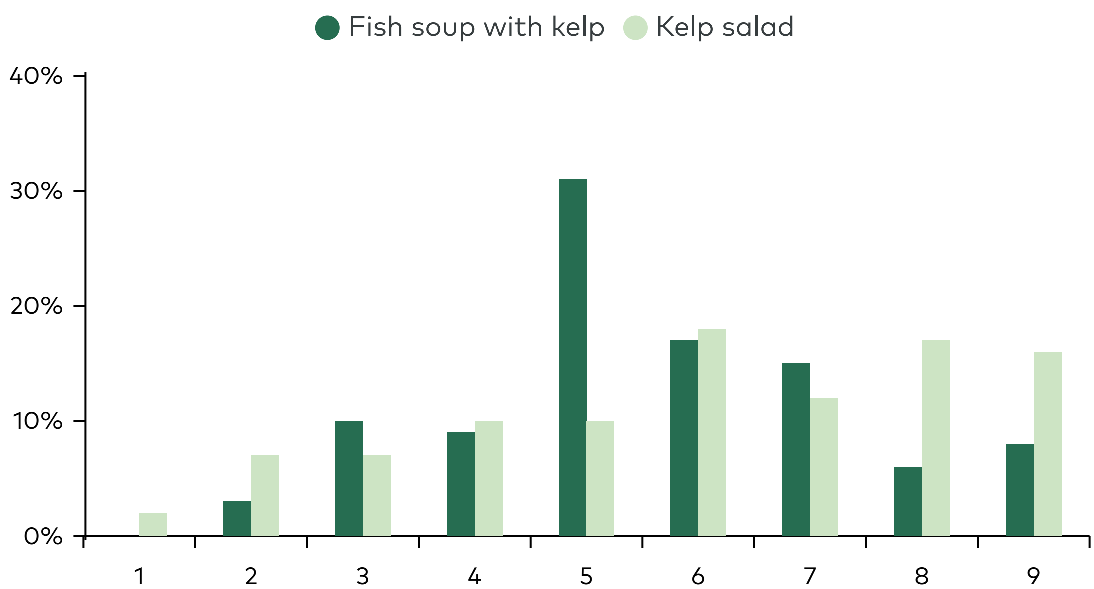

Figure 13: Hedonic ratings of fish soup (n = 150) and kelp salad (n = 88), both containing *Alaria esculenta*, based on evaluations from Norwegian consumers. Tasting events were held in spring 2024 at three locations: Orkla Foods headquarters' canteen in Oslo, the canteen at Måltidets hus (a shared facility for food research, development, and industry) in Stavanger, and the canteen of the Norwegian Maritime Competence Centre in Ålesund. The participants included 46% women and 53% men, with 51% under the age of 45 and 49% aged 45 or older.

Consumer attitude

A substantial majority of consumers in the product trials expressed a strong willingness to consume seaweed-based foods, with 78% agreeing or strongly agreeing with the statement, "I am very willing to eat food containing seaweed" (**Figure 14**). This aligns with similar findings on Italian consumers' willingness to consume seaweed (Palmieri and Forleo 2020). At the same time, the results highlight the importance of how seaweed is positioned in food products, whether it is explicitly highlighted or used as a background ingredient (see **Chapter 4**). Conversely, despite this positive attitude, 74% of participants reported that they never or seldom consume seaweed products, suggesting that limited availability, accessibility, or both may constrain actual consumption. These results align with the survey findings presented in **Figure 12**, where a combined 70% of respondents reported *never* or *very seldom* consuming seaweed and only 5% reported *often* or *very often*.

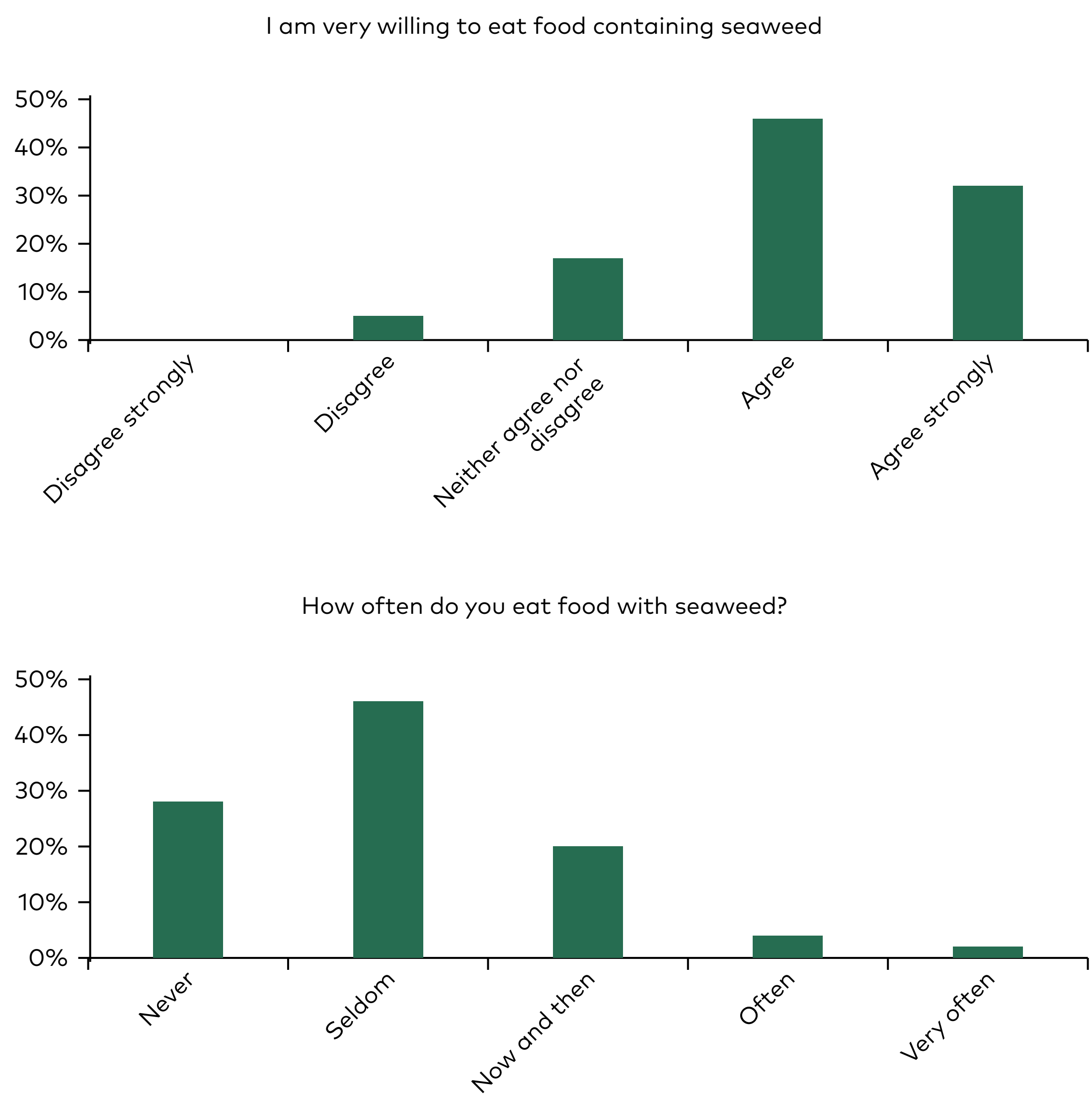

Figure 14: Consumers' willingness to eat food containing seaweed (left) and their actual consumption (right). Data are based on a survey of Norwegian consumers assessing willingness to eat (n = 237) and actual consumption (n = 238) of seaweed-containing food products. These results were collected alongside the hedonic ratings presented in **Figure 13**.

6.2. Food innovativeness and the adoption of seaweed: insights from focus groups

Consumer focus group interviews

As part of the SusKelpFood project, Alm et al. (2024) investigated whether food-innovative consumers exhibit distinct attitudes and informational needs compared to less food-innovative consumers. The study was based on six focus group interviews, and participants across all six groups were subsequently classified into two consumer segments according to their level of food innovativeness (see e.g., Huotilainen et al. 2006). These two segments were then used as the analytical basis for comparing perceptions, concerns, and expectations related to seaweed as food. Across both consumer segments, the focus group discussions explored psychological barriers and perceived opportunities associated with introducing seaweed into Norwegian diets. Overall, participants in both segments viewed seaweed as a sustainable and underutilized resource that should be more widely integrated into everyday meals. Nonetheless, participants expressed concerns about the ecological impact of both wild harvesting and seaweed cultivation, particularly regarding potential consequences for marine ecosystems dependent on kelp forests. This underscored a shared and strong demand across the two segments for transparent and accessible information about the sustainability of seaweed production to ensure its compatibility with environmentally conscious eating habits.

Consumers' opinion

Participants in both consumer segments showed a marked preference for locally produced Norwegian seaweed, citing its lower environmental footprint and higher food safety standards due to stringent national regulations. Seaweed was widely regarded as a nutritious food, rich in minerals and vitamins, and comparable to vegetables. Nevertheless, its iodine content raised health concerns in five of the six focus group interviews, leading to scepticism about its overall health benefits. Seaweed was considered most suitable for dinner dishes, especially seafood-based meals such as fish burgers and soups. Its association with Asian cuisine made it a natural complement to noodle and vegetable dishes, and participants highlighted its compatibility with vegetarian and vegan diets to introduce "seafood" flavours.

Drivers and barriers to seaweed consumption

There was widespread curiosity about seaweed taste and its influence on dish flavour. While many anticipated a salty profile due to its marine origin, participants were open to using seaweed as a seasoning. They expressed interest in tasting opportunities, such as in-store samples or food festivals, before committing to purchases. Additionally, they sought independent, science-based information on iodine levels and other nutrients like protein and fibre to ensure safe consumption.

Participants also expressed a desire for practical guidance on how to cook with seaweed. They indicated openness to trying seaweed dishes in restaurants, where they trusted the expertise of professional chefs. However, some hesitated to pay for unfamiliar dishes, reflecting a lack of confidence in their own cooking skills. This barrier may be mitigated through interventions such as culinary workshops, which have been shown to enhance cooking skills and facilitate the integration of seaweeds into dietary habits (Lafeuille et al. 2024).

Innovative vs. conservative consumers

Differences between the two consumer segments (i.e., food-innovative consumers vs. less food-innovative consumers) were relatively minor. Both segments expressed interest in learning more about seaweed, tasting it, and incorporating it into their diets. However, food-innovative consumers demonstrated greater awareness and actively sought information, particularly concerning potential risks such as PTEs and iodine. They also exhibited a more adventurous culinary approach, incorporating seaweed into a wider variety of dishes, including desserts, and favouring its use as a primary ingredient rather than a subtle flavour enhancer. This behaviour reflects their greater openness to experimentation and aligns with established characteristics of consumers who are more receptive to novel food products.

The results presented above suggest that consumer acceptance of seaweed-based foods depends strongly on individual differences in food-related values, openness to innovation and perceived behavioural control. Treating consumers as a single group therefore risks overlooking important opportunities and barriers to adoption. Segmenting consumers based on shared attitudes and behaviours provides a more targeted framework for understanding market potential and for designing differentiated product and communication strategies.

6.3. Consumer segments

Consumer segmentation is the process of dividing a market into distinct groups that share common characteristics, such as demographics, behaviours, or psychographics, to enable more targeted and effective marketing strategies. By doing so, businesses can better understand and address the specific needs and preferences of each segment (Wedel and Kamakura 2000). In the food domain, the food-related lifestyle (FRL) approach conceptualises lifestyle as a cognitive link between an individual's core life values and their perceptions of, and behaviours toward, food. It explains how people differ in perceiving food and drink as a means of expressing or fulfilling their underlying values. The FRL framework has been employed in over 100 studies to segment, explain, and predict food-related behaviours (Brunsø et al. 2021). Applying the FRL framework to a nationally representative survey of Norwegian adults (n = 1,001) revealed three homogenous consumer segments with varying motivations for seaweed consumption: **conservatives** (16%), **moderates** (45%), and **adventurous** (39%). These segments closely resemble those identified by Brunsø et al. (2021) and Stancu et al. (2022), both in naming and in defining characteristics.

Conservatives are characterized by high food involvement but low food innovation and the lowest sense of food responsibility. They exhibit low intentions to consume seaweed, weak attitudes toward it, minimal perceived social pressure, and a low sense of behavioural control (i.e., perception of how easy or difficult it is to perform a behaviour; Ajzen 1991). Consequently, this group reports the lowest actual seaweed consumption. Demographically, conservatives are predominantly men, with 55% lacking a university or university college education, and 34% are active empty nesters.

Moderates, the largest segment, score around the average on all three core dimensions: food involvement, food innovativeness, and food responsibility. While their reported seaweed consumption is similar to that of the adventurous group (see next paragraph), they generally fall below the scale's midpoint on attitudinal and behavioural measures related to seaweed. This group is relatively well-educated, with 56% holding university degrees, and men (52%) slightly outnumber women. This segment includes a diverse mix of life stages, particularly pre-family individuals (28%) and senior citizens or inactive empty nesters (21%).

Adventurous consumers (i.e., early adopters) stand out with the highest scores on all core dimensions, particularly food innovation. They show the strongest intentions to consume seaweed, the most positive attitudes, and the greatest perceived behavioural control, which is reflected in their higher actual consumption. Demographically, they are mostly female (57%), well-educated (60% with university or university college education), and younger, with 27% in the pre-family stage and only 16% being senior citizens or inactive empty nesters.

6.4. Cross-country comparison of consumer segments

High-potential seaweed consumers

Across multiple studies and countries, three consumer segments emerge as the most receptive to seaweed-based foods: progressive consumers (UK; Govaerts and Olsen 2024), food enthusiasts (Australia, UK, Croatia; Maksan et al. 2025), and adventurous consumers (Norway; Alm et al. *in prep.*). These groups share key traits that make them ideal targets for product development and marketing. They exhibit high levels of food innovativeness, food involvement, and a stronger sense of food responsibility. Progressive consumers in the UK also score highly on biospheric values, reflecting a deep concern for sustainability and environmental impact. Food enthusiasts report greater experience and frequency of seaweed consumption, especially in the UK and Croatia.

Consumer segment profiles

Demographically, these three segments include consumers who are typically younger, well-educated, and predominantly female. Food enthusiasts also include a higher proportion of vegetarians, pescatarians, and fish-preferring consumers, aligning well with the nutritional and environmental profile of seaweed. In contrast, conservative consumers across these countries are less engaged as observed from the Norwegian survey described in the previous section. They show weak attitudes towards food innovation, and minimal behavioural control regarding seaweed consumption, resulting in the lowest actual usage. This group tends to be older, less educated, and more likely to prefer red meat or poultry (Maksan et al. 2025). Targeting progressive, adventurous, and food enthusiast segments through tailored messaging and innovative product formats could significantly boost consumer acceptance and market growth for seaweed-based foods.

6.5. Conclusions

Consumer acceptance represents a decisive link between the technical feasibility of seaweed-based foods and their successful market uptake. While seaweed remains a niche food category in Norway and other Western countries, this chapter demonstrates that overall consumer perceptions are largely positive. Low consumption levels appear to reflect structural and practical barriers, such as limited availability, high prices, lack of familiarity, and insufficient guidance, rather than fundamental rejection of seaweed as a food ingredient.

Empirical findings from surveys, product trials and focus groups show that consumers are generally receptive to seaweed-based foods when sensory quality is acceptable and when products are embedded in familiar culinary contexts. In particular, **younger, well-educated and food-innovative consumers display stronger intentions to consume seaweed,** higher willingness to pay, and greater openness to culinary experimentation. These early adopters actively seek transparent, science-based information on food safety aspects, including iodine and potentially toxic elements, underscoring the importance of clear communication alongside product development. Explicitly, highlighting seaweed may appeal to adventurous consumers, whereas using seaweed as a background or functional ingredient can lower acceptance barriers among more conservative segments, especially in products with higher inclusion levels. This directly complement the processing and sensory insights presented in **Chapters 4** and **5**, emphasizing that product design, processing choices and communication strategies must be aligned.

Overall, the chapter shows that expanding seaweed consumption in Western diets requires more than technological optimisation. Market success depends on combining sensory quality, food safety assurance, and sustainability credentials with targeted product formats, accessible information and segment-specific communication. Addressing these factors in an integrated manner will be essential to translate the nutritional and functional potential of seaweeds into sustained consumer uptake and commercial viability.

- **Positive attitudes, low consumption:** Western consumers generally view seaweed positively, but actual consumption remains limited due to low availability, high prices, limited familiarity and practical barriers.
- **High-potential consumer segments:** Younger, well-educated and food-innovative consumers show the strongest acceptance, willingness to pay and openness to experimentation with seaweed-based foods.
- **Clear and accessible information:** Consumers seek clear, easy-to-understand information about seaweed's health benefits, culinary uses, and preparation methods, but also science-based information on iodine, food safety and sustainability to support informed choices. Suggested formats included brochures, recipes, and online resources.
- **Practical everyday use:** Simple product formats and recipes on versatile ways to incorporate seaweed into familiar meals, such as salads, soups, and fish dishes, making it more approachable in daily cooking.
- **Sensory quality is decisive:** Flavour and texture were identified as critical factors. Participants encouraged producers to prioritise flavour and mouthfeel, possibly by combining seaweed with other appealing ingredients.
- **Product innovation:** There was a strong support for innovation in seaweed products. Participants called for new formats and flavour combinations in seaweed-derived food products, to attract a broader consumer base.
- **Market success requires integration:** Broader adoption depends on coordinated efforts in product innovation, pricing, availability, education, marketing and collaboration with chefs, nutritionists and food professionals.

7. Sustainability and value chain analysis

This chapter places seaweed production and use within **a broader sustainability and value-chain perspective**. Building on the preceding chapters, which addressed nutrients, food safety, processing technologies, sensory quality and consumer acceptance, this chapter examines how seaweed cultivation and utilisation align with European sustainability objectives, environmental policy frameworks, and emerging blue-bioeconomy strategies. It synthesises current evidence on environmental performance, nutrient and carbon dynamics, and life cycle impacts, and discusses how these factors influence the long-term viability and credibility of the European seaweed sector. Attention is given to the distinction between conceptual environmental potential and verifiable, measurable sustainability outcomes across the value chain.

7.1. European framework for sustainable blue growth and seaweed cultivation

EU sustainable targets

The EU aims to achieve sustainable and inclusive growth through the European Green Deal (European Commission 2019), which outlines measures to mobilize public and private investment toward climate and environmental goals. The overarching target is climate neutrality by 2050 (European Commission 2018), with legally binding interim goals such as a 55% reduction in greenhouse gas emissions by 2030 (EU 2021/1119). Similarly, the revised Urban Wastewater Treatment Directive (EU 2024/3019) requires member states to cut emissions of total phosphorus and nitrogen by 75% by 2025, and by up to 87.5% and 82.5%, respectively, by 2045.

Seaweeds and the blue bioeconomy

To mitigate climate change and reduce pressure on terrestrial food production, the EU increasingly recognizes the role of the oceans and promotes a transition from "blue growth" to a sustainable blue economy (European Commission 2021a). Within this framework, seaweeds are identified as renewable biomass sources that can provide environmental and health benefits (European Commission 2022). The European Commission actively supports seaweed cultivation through the Sustainable Development of Aquaculture Strategy (European Commission 2021c), the Organic Production Action Plan (European Commission 2021b), and funding mechanisms such as the European Maritime, Fisheries and Aquaculture Fund

(EMFAF) under the BlueInvest initiative, which has supported nearly 100 algae-focused companies (Carboni et al. 2025). Despite this momentum, European seaweed cultivation remains a nascent industry, mainly focused on at-sea farming of kelps (e.g. *S. latissima*, *A. esculenta*), with smaller pilot-scale efforts on *Ulva spp.* and *P. palmata* in land-based or IMTA systems (Barbier et al. 2020; Araújo et al. 2021). In 2022, European seaweed aquaculture produced approximately 1,040 t (wet weight) with a value of €6.3 million, of which some Nordic countries (i.e., Norway, Faroe Island, Denmark) contributed for 33% (Rebours and Sánchez López 2023).

EU water and nutrient policies

Recent EU policy discussions increasingly emphasise on carbon storage and alternative protein production from seaweed. In contrast, the potential of seaweed cultivation as a marine mitigation measure for nutrient recovery, particularly nitrogen (N) and phosphorus (P), remains insufficiently recognised. Existing key regulatory frameworks such as the Water Framework Directive (European Parliament and EU Council 2000), Nitrates Directive (European Parliament and EU Council 1991), and Marine Strategy Framework Directive (European Parliament and EU Council 2008) primarily conceptualise seaweed as indicators of eutrophication or symptoms of eutrophication rather than as active tools for nutrient removal. Large-scale field evidence now demonstrates that cultivated seaweeds can contribute measurably to nutrient uptake and removal, albeit at site-specific efficiencies and with clear spatial limitations (Bruhn et al. 2025). Although the revised Urban Wastewater Treatment Directive strengthens nutrient removal requirements, it does not yet integrate marine biomass production, such as seaweed farming, into broader nutrient management or mitigation strategies. This represents a missed opportunity to link water policy objectives with emerging blue-bioeconomy solutions.

Environmental value of the seaweed sector

Within the framework of the Circular Economy Action Plan (European commission 2020) and the emerging EU Circular Economy Act, seaweeds have been increasingly highlighted as a nature-based solution with potential to support nutrient recovery, recycling and more resource-efficient food systems. Seaweed cultivation is frequently associated with multiple environmental co-benefits, including uptake of dissolved nutrients, low input requirements, and compatibility with integrated multi-trophic systems. However, while the conceptual potential of the sector is well recognised, robust and comparable scientific evidence quantifying its net contributions, particularly with respect to long-term carbon sequestration and nitrogen and phosphorus removal at relevant spatial scales, remains limited and highly context dependent. Recent assessments emphasise that environmental benefits from seaweed cultivation depend strongly on species, cultivation density, site characteristics, hydrodynamics, and the fate of harvested biomass, and therefore cannot be assumed uniformly across production systems (Bruhn et al.

2025). Demonstrating measurable, verifiable and site-specific environmental outcomes will be essential if the seaweed sector is to credibly position itself within EU sustainability frameworks. In this regard, improved monitoring, harmonised metrics and transparent reporting of nutrient removal and carbon flows will be key to aligning seaweed production with the environmental sustainability criteria of the EU Taxonomy for sustainable activities (European Parliament and EU Council 2020). While EU policy frameworks increasingly frame seaweed cultivation as a potential contributor to climate and nutrient objectives, the extent to which these ambitions can be realised depends on the underlying biogeochemical functioning of seaweed systems. Understanding the carbon and nutrient dynamics of cultivated seaweeds is therefore essential to assess their realistic mitigation potential.

7.2. Carbon and nitrogen removal potential of seaweed

The potential of seaweed cultivation to contribute to nutrient removal and climate mitigation is closely linked to its carbon and nitrogen dynamics, which vary across species, cultivation systems and environmental conditions.

The carbon-to-nitrogen (C:N) ratio of seaweeds has been used as an indicator of nutrient level in many studies (Chapman and Craigie 1977) and reflect nutrient conditions and climate adaptation throughout the growing period. C:N ratios are also fundamental for understanding many oceanic biogeochemical processes, such as nutrient flux and climate regulation (Sheppard et al. 2023). Kelp species can utilize ammonia instead of nitrate, making these seaweed good candidates for integration into an integrated multitrophic aquaculture system where predominantly ammonia-rich effluents are released from fed aquaculture (Handå et al. 2013; Wang et al. 2014). Similarly, the potential of the cosmopolitan and euryhaline genus *Ulva* has also been well documented for bioremediation of nutrients with high efficiency for uptake (from 40% up to 90%) resulting high biomass yield (40–100 g of DW m^{-2} day^{-1}) (Neori et al. 2004; Bruhn et al. 2011; Nielsen et al. 2012; Lubsch and Timmermans 2019) with preferences for ammonium (Vandermeulen and Gordin 1990; Hernández et al. 2002). Furthermore, seaweed systems, both natural ecosystems and aquaculture, have been considered potential contributors to carbon dioxide removal (CDR) and climate mitigation (Duarte and Cebrián 1996). This expectation results partly from the hypothesis that seaweed productivity exceeds that of terrestrial plants (Froehlich et al. 2019; Yong et al. 2022). However, there is still non-consensus on whether seaweed systems act as net carbon sinks or sources. Evidence shows that natural ecosystems often exhibit high carbon fluxes and are generally net autotrophic, comparable to or exceeding other vegetated coastal habitats (Filbee-Dexter et al. 2023). Yet, other studies indicate that they can be net heterotrophic, functioning as CO_2 sources when their productivity depends on organic carbon from external sources (Gallagher et al. 2022).

Carbon dynamics

In aquaculture, seaweeds may also act as temporary carbon stores rather than long-term sinks, since biomass is typically consumed as food or feed, leading to rapid carbon remineralisation (Fujita et al. 2023). Consequently, Hurd et al. (2022) advocate for a "forensic analysis" of carbon flows in seaweed systems to quantify organic carbon fluxes and storage. This is particularly important because seaweeds have short production–consumption cycles and can release substantial amounts of dissolved and particulate organic carbon, as well as very short-lived halocarbons, e.g., bromoform ($CHBr_3$), methyl iodide (CH_3I) and diiodomethane (CH_2I_2), which can alter the ozone layer and biogeochemical cycles (Stemmler et al. 2015; Keng et al. 2020). Understanding their sources, quantifying emissions, and addressing existing knowledge gaps is therefore essential in the context of expanding seaweed aquaculture in a changing climate (Keng et al. 2020).

Although seaweeds can assimilate carbon and nutrients during growth, the environmental significance of this uptake depends on how biomass is harvested, processed and used. Evaluating the sustainability of seaweed-based products therefore requires a full value-chain perspective, which is commonly addressed through life cycle assessment (LCA).

7.3. Sustainable value-chain design

Life Cycle Assessments (LCAs) play a central role in corporate sustainability, policy development, and assessing seaweeds' contribution to the wider bioeconomy. Current global seaweed cultivation practices are associated with low emissions, typically 0.02–0.08 kg CO_2-eq. per kg wet seaweed, with key environmental hotspots arising during processing (particularly drying), transport, and the use of farm infrastructure such as ropes (Seghetta et al. 2016; Waqas et al. 2024; Thomas et al. 2024). Seaweed farming is therefore considered among the lowest greenhouse gas (GHG) "blue foods" (Gephart et al. 2021). However, thermal drying and freezing remain major contributors to impacts (van Oirschot et al. 2017; Thomas et al. 2021). Environmental performance is strongly influenced by the energy source used for drying (Error! Reference source not found.) as well as by farm scale, which affects the relative contribution of drying, transport, and storage (Koesling et al. 2021). Packaging and transport typically add 5–20 kg CO_2 eq. per tonne of fresh seaweed. Lower values correspond to short transport distances, efficient logistics, and lightweight packaging, while higher values are associated with long-distance road transport across Europe, refrigerated distribution, or more material-intensive packaging solutions (Seghetta et al. 2017; Thomas et al. 2021).

Evaluating carbon storage

Non-harvested seaweed may contribute to a long-term carbon storage in the deep sea and sediments (Krause-Jensen and Duarte 2016). However, once seaweed is harvested for commercial use, the stored carbon is eventually released during product use. Food and feed have typically short lifespans. The end-of-life treatment further influences the climate impact by determining the sink (e.g. soil, marine sediment, air) and the gas composition (e.g. CO_2, CH_4). When evaluating seaweed as a food or feed ingredient, Hasselström and Thomas (2022) recommend limiting system boundaries to the factory gate or supermarket and excluding end-of-life impacts, assuming downstream carbon, nitrogen and phosphorus dynamics are comparable to those of other food products.

Table 12: Global warming and freshwater eutrophication potentials when using different sources of energy to produce 1 kg protein from *Saccharina latissima* (adapted from Koesling et al. (2021)). Abbreviations: Norway (NO), European Union (EU).

	Fossil gas	Surplus energy	Incineration energy	NO electricity	EU electricity
Global warming Potential (kg CO_2-eq)	32.1	15.7	139.2	17.9	44.0
Freshwater Eutrophication (kg P-eq.)	7.9×10^{-2}	7.3×10^{-3}	1.6×10^{-2}	7.5×10^{-3}	1.4×10^{-2}

Knowledge gaps

Applying LCA to seaweed systems presents several challenges, including high variability, limited data, and methodological choices that strongly influence outcomes and hinder comparability. Addressing these issues is essential for meaningful interpretation and effective use of LCA results. Key knowledge gaps and methodological limitations in seaweed LCA research include:

- lack of standardized methods to compare diverse production systems,
- large variety of functional units,
- limited ability to assess holistically cultivation impacts on local ecosystems,

- missing impact categories for pressures such as microplastic or nanoparticle pollution, sea-use changes, spatially limited eutrophication, and consequences on the marine biodiversity (Thomas et al. 2024),
- insufficient data and database coverage, especially for comparing seaweed with other blue foods (Gephart et al. 2021) or terrestrial alternatives in substitution scenarios,
- differences and uncertainties in climate-change modelling approaches, including timing of emissions (Brandão et al. 2013).

Therefore, to enable meaningful comparison of recent LCA studies on *S. latissima*, Thomas et al. (2024) compiled existing life cycle inventory data and recalculated key impacts (global warming and eutrophication) using a harmonised methodology.

7.4. Broader sustainability dimensions of the seaweed sector

While life cycle assessments and nutrient, carbon accounting provide essential insights into the environmental performance of seaweed production systems, they capture only part of the sustainability profile of the sector. In line with emerging EU sustainability and environmental accounting frameworks, broader dimensions, including impacts on biodiversity, economic resilience of value chains, and social and regional contributions, must also be considered. These dimensions are increasingly reflected in policy instruments such as ecosystem accounting, biodiversity strategies and circular economy frameworks, and are critical for evaluating how seaweed cultivation can contribute to a sustainable European bioeconomy. The present section therefore places seaweed production in a wider sustainability context, linking the evidence presented earlier in this chapter to biodiversity, economic and social assessment perspectives.

Biodiversity considerations

Seaweed cultivation interacts with marine ecosystems in ways that are increasingly relevant to EU biodiversity policy objectives. Under the EU Biodiversity Strategy and the forthcoming Biodiversity Act, there is a growing emphasis on assessing not only pressures on ecosystems but also nature-based solutions that may support ecosystem functioning. Cultivated seaweed farms may provide habitat structure, refuge and feeding opportunities for marine organisms, potentially contributing to local biodiversity enhancement. At the same time, farm installations can modify light availability, hydrodynamics and benthic conditions, with effects that are strongly site- and scale-dependent. To align seaweed cultivation with EU biodiversity objectives, impacts should be evaluated within established assessment frameworks such as **MAES** (Mapping and Assessment of Ecosystems and their Services) and reported through platforms such as **BISE** (Biodiversity Information

System for Europe). These frameworks provide a basis for integrating seaweed cultivation into ecosystem assessments by linking ecological status, pressures and ecosystem services at relevant spatial scales. Applying such tools would allow biodiversity effects of seaweed farming, both positive and negative, to be systematically documented and compared across regions, supporting evidence-based spatial planning and adaptive management.

Economic sustainability of the seaweed value chain

Economic sustainability is a prerequisite for the long-term viability of the seaweed sector and for its contribution to EU circular bioeconomy objectives. As demonstrated by the LCAs and value-chain analyses discussed earlier in this chapter, seaweed cultivation is characterised by relatively low input requirements at the farming stage, while post-harvest processing, particularly drying, freezing and logistics, represents a dominant cost and environmental hotspot. Embedding seaweed production within circular economy frameworks, as promoted by the European Green Deal and Circular Economy Action Plan, requires optimisation across the full value chain. This includes processing infrastructure hubs, energy-efficient technologies, valorisation of side streams and development of higher-value food and ingredient applications. Assessing economic sustainability alongside environmental performance is consistent with integrated accounting approaches such as the System of Environmental-Economic Accounting (SEEA; seea.un.org), which emphasises linking physical resource flows with economic value creation. Applying such approaches to seaweed systems would support more transparent evaluation of trade-offs between cost, resource efficiency and environmental performance.

Social and economic contributions

Beyond environmental and economic metrics, the seaweed sector may contribute to social sustainability, particularly in coastal and rural regions. Potential benefits include job creation, diversification of maritime livelihoods and regional value creation. However, as highlighted by the broader sustainability discussion in this chapter, these contributions are not automatic and depend on governance structures, ownership models, access to infrastructure and integration with existing coastal activities. To systematically capture these contributions, social and ecosystem-service dimensions of seaweed cultivation can be assessed using the Common International Classification of Ecosystem Services (CICES, version 5.2), which is increasingly applied within EU environmental accounting and policy contexts. CICES provides a structured framework to classify provisioning, regulating and cultural ecosystem services, including those relevant to food production, nutrient regulation and socio-economic benefits. Aligning seaweed assessments with CICES and SEEA-based approaches would allow social and economic contributions to be evaluated alongside environmental performance, supporting more holistic sustainability reporting and policy integration.

7.5. Conclusions and recommendations

Seaweed farming has the potential to support climate mitigation as well as nutrient management through several different pathways. However, not all of these pathways are currently quantifiable within existing policy and accounting frameworks. For food or feed applications, carbon storage is inherently short-lived highlighting the importance of **clearly distinguishing between temporary carbon uptake and long-term climate mitigation claims**. To enable the seaweed sector to contribute meaningfully to a biobased economy, there is a need to bridge knowledge gaps related to the substitution of fossil-based or high-impact products (e.g., energy, biopolymers) and to maximise the duration of biogenic carbon storage in long-lasting products (e.g., building materials). Strengthening this evidence base is essential to drive climate-beneficial innovation and support long-term carbon storage. Future sustainability gains are therefore likely to depend on how seaweed-derived biomass substitutes higher-impact products and how value chains are designed to maximise environmental performance.

A first estimate of the carbon sequestration and nutrient (N, P) recovery potential of Norwegian seaweed farms (Rebours & Stévant, *in prep.*) and the Danish model scenarios on cultivation of *S. latissima* as a marine measure for mitigating eutrophication (Bruhn et al. 2025) be extended to European-scale farming through integrated modelling approaches (Macias et al. 2025) and include species beyond kelps that may be better suited to warmer cultivation conditions.

For the seaweed industry to fully demonstrate its sustainability performance and report under the EU taxonomy as any other bio-based sector, further research is needed to close knowledge gaps and support climate-beneficial innovation, sustainable industry development, and long-term integration of seaweed into the European bioeconomy.

Beyond greenhouse gas emissions and nutrient flows, the sustainability performance of the seaweed sector must be evaluated within a broader framework that also considers biodiversity impacts, economic resilience and social contributions. As discussed in this chapter, these dimensions are increasingly reflected in EU environmental and sustainability assessment frameworks, including ecosystem and biodiversity accounting approaches. Integrating LCA with site-specific biodiversity evaluation, value-chain economics and social impact assessment is therefore essential to provide a comprehensive and credible sustainability profile of seaweed production systems. Such integrated assessment will be critical for informing policy development, guiding responsible sector growth and supporting evidence-based sustainability claims as the European seaweed industry continues to scale.

- **Sustainability performance for seaweed-based foods:** Farmed seaweed generally exhibits a low environmental footprint compared to other seafoods. However, processing steps (e.g., drying, freezing) represent major environmental hotspots and will strongly influence sustainability outcomes as production scales up.
- **Carbon and nutrient dynamics:** Seaweed assimilate carbon and nutrients during growth, but carbon storage in food and feed applications is short-lived. Claims related to long-term climate mitigation must therefore be clearly distinguished from temporary carbon uptake and supported by transparent, evidence-based sustainability assessments and accounting.
- **Nutrient recovery potential:** Cultivated seaweeds can contribute to nitrogen and phosphorus removal at local scales, especially in integrated systems, but effectiveness is highly site- and species-specific and should not be assumed uniformly.
- **Value-chain perspective:** Life cycle assessments show that farm design, energy sources and processing choices are key determinants of environmental performance. Harmonised methods and improved data availability are needed to enable meaningful comparison across systems.
- **Policy alignment:** To credibly position seaweed production within EU sustainability frameworks and taxonomy criteria, measurable, verifiable and context-specific evidence is required, particularly regarding nutrient mitigation and climate impacts.
- **Biodiversity:** Seaweed cultivation may influence marine biodiversity both positively and negatively. Integrating seaweed farming into EU biodiversity frameworks (e.g. Biodiversity Act, MAES, BISE) is essential to ensure site-specific, evidence-based assessment and responsible spatial planning.
- **Economic sustainability:** While seaweed farming has a low environmental footprint at the cultivation stage, processing remains a major cost and impact hotspot. Applying circular economy principles and environmental-economic accounting approaches can support cost-efficient and resilient value-chain design.
- **Social and economic contributions:** Seaweed systems may support coastal employment and regional development, but benefits depend on governance and business models. Using established frameworks such as CICES (v5.2) enables systematic assessment of ecosystem services and social value creation.

8. Conclusions and recommendations for industry

This chapter builds on the scientific evidence and sustainability assessment presented in the preceding chapters to formulate practical conclusions and recommendations for the food industry and related stakeholders. While **Chapters 2–7** addressed nutrients, food safety, processing strategies, sensory quality, consumer acceptance and sustainability performance, this final chapter translates these insights into guidance for responsible product development, supply-chain organisation and market communication. The recommendations focus on enabling safe, high-quality and economically viable seaweed-based food products, while aligning industry practices with emerging EU sustainability, biodiversity and value-chain assessment frameworks.

This report demonstrates that seaweeds have a significant potential as safe, nutritious and savoury **food ingredients**, for the European food industry, if processing, production, regulation and communication strategies are carefully designed. **Tailored processing routes,** designed to meet specific quality objectives such as iodine reduction, product stability, or ingredient functionality, enable the development of a wide range of innovative seaweed-derived food ingredients. Gentle processing approaches support the retention of **natural flavours and nutrients**, while more intensive processing can yield fibre-rich fractions suitable for **functional or textural applications** in food products.

Seaweeds can serve as valuable alternative **sources of fibres, minerals and vitamins**, including iodine. However, **iodine levels in final food products** must be carefully controlled to prevent excessive intake. For kelp species, iodine content can be reduced through targeted processing steps, such as mild seawater blanching, or managed by incorporating unprocessed kelp at low inclusion levels (typically ≤1%), where it can still deliver functional benefits e.g., flavour. Robust **quality management** and processing controls are therefore essential to ensure food safety and regulatory compliance. In parallel, selected seaweed ingredients, owing to their textural properties, offer clear potential as **alternatives to synthetic or ultra-processed food additives,** contributing to cleaner labels, improved nutritional profiles, and greater transparency for consumers.

For large-scale integration into the food industry, seaweed ingredients must be supplied consistently, at high and predictable quality, and at competitive prices. The development of a **harmonised quality framework** for edible seaweeds is recommended to support product consistency, guide processing decisions, and facilitate market positioning across different food applications and market.

From a supply perspective, **seaweed farming** offers clear advantages over wild harvesting by enabling large-scale biomass production without increasing pressure on natural populations. However, current cultivation efforts remain heavily focused on **kelp species (*Saccharina latissima, Alaria esculenta*)**. To support a resilient and diversified seaweed sector, the industry should invest in scaling up the cultivation of additional species with strong potential for application in the food sector, such as ***Palmaria palmata* and *Ulva* spp.**, thereby broadening the raw material base and enabling more diverse product development.

Furthermore, the establishment of **centralised processing infrastructures** represents an opportunity to reduce capital costs, improve resource efficiency, and lower financial barriers for individual actors. Collaborative processing models can enhance competitiveness across the value chain and accelerate the upscaling of seaweed production and processing capacity.

Finally, communication strategies should be adapted to target **consumer segments**. Seaweed ingredients may be explicitly highlighted on product labels and marketing materials when supported by documented nutrition, health, or environmental claims. Such claims should be **evidence-based, proportionate, and transparent, reflecting both the benefits and limitations** of seaweed production and use, in line with emerging EU sustainability and biodiversity assessment frameworks and broader value-chain sustainability considerations, including economic viability and social contributions in coastal regions. Overstated or generic sustainability claims risk undermining **consumer trust and the long-term credibility** of the sector. Food producers should strategically decide how and to what extent the inclusion of seaweed ingredients is communicated, based on the expectations and preferences of different target consumer groups. Regardless of strategy, increasing consumer acceptance will require active engagement through **taste experiences, accessible product formats, and foods** that are easy to adopt within Western dietary habits.

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Appendix

Appendix Table 1: Selected nutrition claims which may be relevant to seaweed-based food products and their associated conditions for application as detailed in the Annex of Regulation (EC) No 1924/2006.

Nutrition claim	Condition
Source of omega-3 fatty acids	The product contains **at least 0.3 g alpha-linolenic acid** per 100 g and per 100 kcal, or **at least 40 mg of the sum of eicosapentaenoic acid and docosahexaenoic acid** per 100 g and per 100 kcal
High omega-3 fatty acids	The product contains **at least 0.6 g alpha-linolenic acid** per 100 g and per 100 kcal, or **at least 80 mg of the sum of eicosapentaenoic acid and docosahexaenoic acid** per 100 g and per 100 kcal
High monounsaturated fat	**At least 45% of the fatty acids** present in the product derive from monounsaturated fat under the condition that **monounsaturated fat provides more than 20% of energy** of the product
High polyunsaturated fat	**At least 45% of the fatty acids** present in the product derive from polyunsaturated fat under the condition that **polyunsaturated fat provides more than 20% of energy** of the product
High unsaturated fat	**At least 70% of the fatty acids** present in the product derive from unsaturated fat under the condition that **unsaturated fat provides more than 20% of energy of the product**
Low sodium/salt	Product contains **no more than 0.12 g of sodium**, or **0.3 g of salt**, per 100 g or per 100 ml
Very low sodium/salt	Product contains no **more than 0.04 g of sodium**, or **0.1 g of salt**, per 100 g or per 100 ml
Source of fibre	Product contains **at least 3 g** of fibre per 100 g or **at least 1.5 g** of fibre per 100 kcal
High in fibre	Product contains **at least 6 g** of fibre per 100 g or **at least 3 g** of fibre per 100 kcal
Source of vitamin and/or minerals	The product contains **at least a significant amount** (i.e. 15% of the reference intake value supplied by 100 g or 100 ml in the case of products other than beverages, or per portion if the package contains only a single portion) of the given vitamin/ mineral as defined in Annex XIII to Regulation EU No 1169/2011 (values are given in Appendix Table 2)
High in vitamin and/or minerals	Where the product contains **at least twice the value of** "Source of vitamin and/or minerals" (values are given in Appendix Table 2)
Naturally/Natural	Where a food **meets the condition(s) laid down in the Annex to Regulation (EC) No 1924/2006**, the term 'naturally/natural' may be used as a prefix to the claim.

Appendix Table 2: Amount of minerals and vitamins (expressed per 100 g, 100 mL or per portion) required in solids and liquid foods (excluding beverages, e.g., oils) to qualify for "Source of" (15% of DRI) and "High in" (30% of DRI) nutritional claims according to Regulation (EC) No 1924/2006 and Annex XIII to Regulation EU No 1169/2011.

Micronutrient	Unit	DRI	Threshold for "Source of" claim	Threshold for "High in" claim
Minerals				
Potassium	mg	2,000	300	600
Chloride	mg	800	120	240
Calcium	mg	800	120	240
Phosphorus	mg	700	105	210
Magnesium	mg	375	56.2	112.5
Iron	mg	14	2.1	4.2
Zinc	mg	10	1.5	3
Copper	mg	1	0.15	0.30
Manganese	mg	2	0.30	0.60
Fluoride	mg	3.5	0.53	1.05
Selenium	µg	55	8.2	16.5
Chromium	µg	40	6	12
Molybdenum	µg	50	7.5	15
Iodine	µg	150	22.5	45
Vitamins				
Vitamin A	µg	800	120	240
Vitamin D	µg	5	0.75	1.5
Vitamin E	mg	12	1.8	3.6
Vitamin K	µg	75	11.2	22.5
Vitamin C	mg	80	12	24
Thiamine (B_1)	mg	1.1	0.17	0.33
Riboflavin (B_2)	mg	1.4	0.21	0.42
Niacin (B_3)	mg	16	2.4	4.8
Pyridoxine (B_6)	mg	1.4	0.21	0.42
Folic acid (B_9)	µg	200	30	60
Vitamin B_{12}	µg	2.5	0.38	0.75
Biotin (B_7)	µg	50	7.5	15
Pantothenic acid (B_5)	mg	6	0.9	1.8

Appendix Table 3: Median concentrations on dry weight of selected mineral elements and vitamins in *Alaria esculenta*, *Saccharina latissima*, *Ulva* spp. and *Palmaria palmata*. Data from the SusKelpFood project and Nordic SeaFarm.

Micronutrient	Unit	*A. esculenta*	*S. latissima*	*Ulva* spp.	*P. palmata*
Iodine	mg kg^{-1}	1,400	4,900	89	200
Na	mg kg^{-1}	56,000	53,000	33,000	24,000
K	mg kg^{-1}	56,000	97,000	31,000	110,000
Mg	mg kg^{-1}	11,000	9,100	26,000	4,200
Ca	mg kg^{-1}	16,000	13,000	5,800	3,500
P	mg kg^{-1}	2,600	1,600	2,300	4,000
Cu	mg kg^{-1}	2.1	1.3	7.2	4.5
Fe	mg kg^{-1}	76	44	140	120
Mn	mg kg^{-1}	4.8	4	12	9.1
Zn	mg kg^{-1}	42	25	13	32
Cr	mg kg^{-1}	0.69	0.39	0	0
Se	mg kg^{-1}	0.23	0.11	0.11	0.16
Thiamine (Vit. B1)	mg kg^{-1}	2.7	2.6		
Vitamin C	µg kg^{-1}	7.7	8.9	360	
Folic acid (Vit. B9)	mg kg^{-1}	7,400	2,300		

Appendix Table 4: Mineral and vitamin contributions of portions sizes of *Alaria esculenta*, *Saccharina latissima*, *Ulva lactuca* and *Palmaria palmata* (in gram, based on median concentrations, **Appendix Table 3**) resulting in a) iodine exposure at adequate intake (AI: 150 µg day^{-1}) and b) tolerable upper intake level (UL: 600 µg day^{-1}) for adults, compared with daily reference intakes (DRI).

a) Consumption resulting in iodine exposure at AI

		A. esculenta	*S. latissima*	*Ulva sp.*	*P. palmata*
	g to AI	0.1	0.03	1.7	0.7
Micronutrient	**DRI**	**% of DRI**			
Iodine	0.15 mg	100	100	100	100
Na	600 mg	1	0.27	9.4	3
K	2,000 mg	0.3	0.15	2.6	4.2
Mg	375 mg	0.33	0.07	12	0.83
Ca	800 mg	0.22	0.05	1.2	0.32
P	700 mg	0.04	0.01	0.56	0.42
Cu	1 mg	0.02	0.004	1.2	0.33
Fe	14 mg	0.06	0.01	1.6	0.64
Mn	2 mg	0.03	0.01	0.99	0.34
Zn	10 mg	0.05	0.01	0.22	0.24
Cr	0.04 mg	0.18	0.03	0	0
Se	0.055 mg	0.04	0.01	0.33	0.21
Thiamine (vit. B1)	1.1 mg	0.03	0.01		
Vitamin C	200 µg	0.00	0.00	0.31	
Folic acid (vit. B9)	80 mg	0.002			

b) Consumption resulting in iodine exposure at UL

		A. esculenta	*S. latissima*	*Ulva sp.*	*P. palmata*
	g to UL	0.4	0.1	6.8	2.9
Micronutrient	**DRI**	**% of DRI**			
Iodine	0.15 mg	400	400	400	400
Na	600 mg	4.2	1.1	38	12
K	2,000 mg	1.2	0.59	10	17
Mg	375 mg	1.3	0.29	48	3.3
Ca	800 mg	0.87	0.19	4.9	1.3
P	700 mg	0.16	0.03	2.2	1.7
Cu	1 mg	0.09	0.02	4.9	1.3
Fe	14 mg	0.23	0.04	6.6	2.6
Mn	2 mg	0.1	0.02	4	1.3
Zn	10 mg	0.18	0.03	0.87	0.95
Cr	0.04 mg	0.73	0.12	0	0
Se	0.055 mg	0.18	0.02	1.3	0.85
Thiamine (vit. B1)	1.1 mg	0.1	0.028		
Vitamin C	200 µg	0.002	0.001	1.2	
Folic acid (vit. B9)	80 mg	0.008	0.013		

About this publication

Seaweeds for food: from production to consumer

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