Seaweed products for the future: Using current tools to develop a sustainable food industry

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# Abstract

**Background**

Although commonly consumed in Asia, seaweeds are a largely underutilized food source in the Western world. However, interest is rising, and seaweeds have a major potential as both main and functional ingredients in European markets. The current barriers for seaweeds as food products relate to food safety, quality preservation and optimization, and food neophobia.

**Scope and approach**

This commentary provides an overview of current challenges to providing seaweed in the European market and proposed solutions to tackle these obstacles, taking inspiration from other food sectors. Processing and packaging concepts for future manufacturing of seaweeds as food are explored and insight into market research and strategies for overcoming the barrier of consumer skepticism are given.

**Key findings and conclusions**

Tackling safety issues related to human consumption of seaweeds is required for their widespread use in food applications. Sustainable, multi-target mitigation strategies towards microbiological and chemical (excessive iodine, heavy metals, allergens) hazards are driving the improvement of food safety of seaweeds and derived products. Rapid post-harvest deterioration of seaweeds can be avoided through stabilization techniques, for instance through temporary storage solutions before final processing, direct utilization into food items, and packaging. Innovative drying and alternative processing strategies may reduce energy consumption and processing time, while at the same time improving the safety as well as the nutritional and sensory qualities of the product. Despite the rising popularity of Asian cuisine and the Western-consumers’ perception of seaweeds as a “healthy superfood”, understanding consumer behavior in relation to new foods and facilitating information-based decisions could reduce potential consumer skepticism. In conclusion, innovation tools discussed in this work can be exploited for further development of a sustainable seaweed food industry.

# Keywords:

Seaweed, food applications, food safety, food processing, novel technology, consumer

# Background

Seaweeds are one of the world’s largest unexploited, low trophic, renewable global biomass resources. Overall world production of seaweeds reached 32.4 million tons in 2018, where 97 % was from aquaculture, and the seaweed market had an estimated value of 13.3 billion USD as reported by the FAO state of world Fisheries and aquaculture reports of 2016 and 2020. Macroalgae are currently harvested in approximately 50 countries, with roughly 300 species being utilized commercially, where 46 % are characterized as brown and 54 % as red algae. Green algae currently make up less than 1 % of the production (Moreira et al., 2021). Global seaweed cultivation is largely dominated by Asian countries, with China being the largest producer with over 18 million tons, followed by Indonesia, South Korea, the Philippines, North Korea, and Japan (FAO, 2020). The vast majority of macroalgal biomass, 87 % according to FAO is used for direct human consumption in both fresh and dried staple food items (85 %), or further processed into food ingredients (15 %; mainly hydrocolloids, like alginate, agar, and carrageenan (Rioux et al., 2017). FAO has observed seaweed biomass production on global scale to double from 2005 to 2018. The increased interest in seaweed has been attributed to its substantial potential and contribution towards sufficient and healthy global food supply for a population expected to grow by 70 % before 2050. In Europe, seaweed production is in its infancy, with less than 0.1 % of the global production in 2018. However, European seaweed production and utilization has potential for being beneficial for all three Ps of sustainability: People, planet, and profit (Van den Burg et al., 2021). Major public and private large-scale cultivation efforts are directed towards sustainable processing standards, consumer safety, and enhanced product quality.

Although seaweeds’ chemical composition varies across species, harvesting season and eco-habitat, macroalgae contain a large variety of phytochemicals and are naturally rich in valuable nutrients such as minerals, polysaccharides, and dietary fiber (Holdt & Kraan, 2011; Mæhre et al., 2014; Stévant et al., 2017). Moreover, some species, such as the red algae *Palmaria palmata* and *Vertebrata lanosa*, and the green alga *Enteromorpha intestinalis*, have high protein contents (113-123 g/kg dw) and higher quality profiles of essential amino acids and lipids compared to other foods such as rice, corn and wheat (Mæhre et al., 2014). The digestibility of protein from edible algae can also be quite high (at least 60 %) and depend on factors such as species and the degree of processing prior to consumption (Mæhre et al., 2016). Seaweeds may also contribute to the daily intake of vitamin C and the essential mineral selenium, although they are not rich sources (Mæhre et al., 2014; Nielsen et al., 2021). Coupled with variations in sensory attributes, seaweeds’ nutritional content makes them applicable for food use. Although the European market is currently dominated by traditional Asian products, opportunities for more local products are emerging, driven by curiosity and growing consumer demand for local, traceable, and organic food products (Feldmann & Hamm, 2015; Katt & Meixner, 2020). With respect to market and consumer insight, the development of both “niche” products and new processing strategies for inclusion of seaweeds in existing products could lead to value creation on a relatively short time horizon (Stévant et al., 2017), if these foods are created with a holistic perspective of health, nutrition and sensory properties (Figueroa et al., 2021). The latter strategy of inclusion of seaweeds in traditional food items such as snacks, bread and soups has been applied globally during recent years (Nova et al., 2020).

The high water content of seaweeds, commonly ranging between 63-92 % (Mæhre et al., 2014), poses a challenge for product preservation and transport, as seaweeds are characterized by rapid microbial decomposition after harvesting. Additionally, macroalgae are susceptible to contamination by heat-tolerant, spore-forming pathogenic bacteria that may be resistant to prolonged freezing, drying or anaerobic conditions (Blikra et al., 2019; Martelli et al., 2021). Although process technologies such as drying, freezing, fermentation or salting can effectively stabilize seaweed biomass, large investment costs and a potentially undesired impact on quality attributes depending on the operational settings may challenge industrial implementation (Stévant, Indergård et al., 2018). The availability of required equipment may also be limited in the proximity to harvesting sites and investments in equipment may be held back by its anticipated low use during the off season. Integration of hurdle technology to control food pathogens along with the emerging contribution of innovative non-thermal processing shows potential for preservation of nutritional and sensory attributes and extended shelf-life.

Marine macroalgae may accumulate potentially toxic elements (PTEs) from the environment in which the seaweeds are grown. This include certain heavy metals (e.g., cadmium, mercury, arsenic), which can be toxic to living organisms (Banach, Hoek‐van den Hil, et al., 2020). The concentration of these must be monitored and controlled. In addition, marine macroalgae may also contain high concentrations of iodine (>2000 mg/kg dw; e.g., Nitschke & Stengel, 2015). Iodine is an essential mineral but required in relatively low doses (150 μg/day for adults recommended by EFSA Panel on Dietetic Products, Nutrition and Allergies). Excessive iodine intake may lead to similar physical disorders as its deficiency, including hypothyroidism and goiter. An intake between 150 and 600 μg/day for adults is recommended by EFSA to avoid both deficiency and excess. White fish and dairy are dietary sources of iodine, but, apart from seaweeds, no good vegan dietary source exists. Therefore, seaweed consumption could potentially help combat iodine deficiency, which is more common in Europe than iodine excess (Lazarus, 2014). However, incorporation of seaweeds into the European diet should be carried out thoughtfully to avoid overconsumption of iodine, which is common in countries where seaweeds are consumed as a staple in the diet, including Japan (Zava & Zava, 2011). Iodine intake from seaweed can be effectively controlled by targeted processing and product formulation, as well as seasonality and location of harvested stocks (Blikra et al., 2021; Nielsen et al., 2020; Rana & Raghuvanshi, 2013). Adoption of seaweeds as staple food items in the daily diet requires multi-target processing schemes ensuring biomass safety, nutritional value, and appealing sensory attributes for human consumption. If the food safety issues are not handled properly during early stages of European market introduction, this may enhance food neophobia and thus negatively affect the European seaweed food industry in both the short and long term.

There are already some excellent reviews discussing key aspects towards commercialization of seaweeds for food, such as nutritional aspects (Brown et al., 2014; Cherry et al., 2019; Holdt & Kraan, 2011), food safety and legislation (Banach, Hoek‐van den Hil, et al., 2020), and culinary applications (Figueroa et al., 2021; Rioux et al., 2017). In the present article, we go a step further to explore the innovation tools and technologies for the development of the sustainable European seaweed food industry of tomorrow.

# Current challenges and solutions

## Culinary innovation and commercial food product applications

In several European regions, previous generations utilized seaweeds for food (Mouritsen et al., 2013). However, most of these traditions have been lost, and presently, the European population has little knowledge about local seaweeds and how to use them as food. For the majority of European consumers, seaweed represents an unfamiliar product category in relation to their own country’s cuisine (Mouritsen et al., 2013). The reintroduction of seaweeds in European cuisines faces possible consumer barriers related to sensory unfamiliarity, such as seaweeds’ color or appearance, elastic/chewy texture and strong flavor and/or smell (Figueroa et al., 2021; Mouritsen et al., 2019; Nova et al., 2020). However, during the past few decades, the popularity of traditional Asian dishes containing seaweeds, such as sushi and ramen, has increased in countries worldwide. This trend has introduced seaweeds to new groups of people.

Several food trends over the past 20 years, in addition to the already mentioned Asian food trend, have allowed European consumers to rediscover seaweeds as a food. The modernist food trend in the early 2000’s, especially represented by avant-garde restaurants, used seaweeds and their hydrocolloids to introduce new dining experiences such as encapsulated liquids and faux caviar (Mouritsen, 2012). The “superfood” trend has introduced followers to algae products such as spirulina and seaweeds. From the beginning of the millennium, the Nordic food trend and New Nordic Cuisine established a focus on locally sourced plants and species, seaweeds among them. In combination with a rediscovery of traditional Nordic preservation techniques, this cuisine resulted in the creation of new food experiences (Mouritsen et al., 2012). The Nordic food trend’s philosophy has been adopted in many parts of the world and can be regarded as an initiating factor in the current sustainable and local food movement.

Seaweeds are increasingly finding their way into new commercial products in the Western world and are already used in numerous, potentially commercial food applications (Table 1). This includes both the use of raw seaweeds and seaweeds processed in numerous ways to extend shelf life or to improve product properties – such as drying, cooking, freezing, pickling, and fermentation. A range of seaweed species may be used in the applications listed in Table 1. Potential strategies for new product development focus on culinary innovation and seaweeds’ positive product features, such as flavor or texture enhancement, nutritional contribution, functional properties or sustainability aspects. An accessible innovation field for European seaweeds is to make new versions of traditional, well established Asian seaweed applications, such as nori sheets, wakame salads, and dried kombu (Mouritsen et al., 2012).

## Food safety challenges

The current section focuses on major food safety issues challenging the widespread use of seaweeds in food applications, which could be controlled or mitigated through appropriate processing and packaging strategies, described in Section 3.

###  Microbial safety

The general belief is that human pathogens may occur on seaweed in the same density as in the surrounding water masses. Hence, the harvesting or cultivation location of the seaweed is an important factor concerning microbiological food safety, but contamination and recontamination during handling and processing may also occur (Banach, Hoek‐van den Hil, et al., 2020). Locations with poor water quality, and coast-near locations periodically affected by heavy rainfall may be predisposed to human pathogens (Ziino et al., 2010).

There are a few studies that specifically assess the prevalence of human pathogens in edible seaweeds (Sánchez-García, Hernández, Palacios, & Roldán, 2021). The Danish food safety authority concluded in 2017 that, as long as pollution sources such as harbors and agricultural and industrial run-off are avoided, it is safe to collect seaweeds in Danish waters. The surface of seaweeds is densely populated by bacteria, including bacterial species with pathogenic potential that may be problematic during processing or improper storage (e.g., Blikra et al., 2019). However, as concluded by a Norwegian study, the risk of foodborne disease associated with macroalga is expected to be in the same range as other non-filtering marine organisms, including fish. Low microbial numbers, between 1 and 3 log cfu/g, were found in raw and heat treated brown macroalgae (*Alaria esculenta* and *Saccharina latissima*) cultivated in Norway, but the human pathogens enterococci, coliforms, pathogenic *Vibrio* spp., or *Listeria monocytogenes* were not detected (Blikra et al., 2019). However, small amounts were detected of the potentially toxin-producing spore-forming bacteria *Bacillus licheniformis* and *B. pumilus*, which have both been suspected as causative agents of food poisoning (Salkinoja-Salonen et al., 1999). Although their concentrations were far lower than what is considered the infective dose, measures need to be taken to control the growth of these species in the food during handling and storage (Blikra et al., 2019). Similarly, concerns have been raised about *Bacillus cereus* in dehydrated, ready-to-eat seaweed products sold in Italy (Martelli et al., 2021), and about *Bacillus subtilis* on brown macroalgae harvested off the coast of Ireland (Gupta et al., 2010). Using sensitive quantitative polymerase chain reaction (qPCR) assays combined with microbial pre-enrichment, Barberi et al. (2020) detected pathogenic bacteria *Salmonella enterica* ser. Typhimurium, *Vibrio parahemolyticus*, and *Escherichia coli* O157:H7 in 83, 78 and 56 % respectively of cultivated seaweed samples from North-East USA. The findings of pathogenic *Vibrio* spp. in edible seaweeds collected along the coast of Japan (Mahmud et al., 2008) and off Sicily, Italy (Ziino et al., 2010) encourage proper processing and hygiene practices, especially in summer when concentrations are normally higher. As non-filter feeders, macroalgae may not be considered a risk for food borne viral transmission. However, a limited number of norovirus outbreaks have been linked to macroalgae in Asia (Park et al., 2015) and in macroalgae food products imported from Asia to Europe.

When seen together, these findings necessitate further studies, risk assessment and updated guidelines concerning food safety of both wild harvested and cultivated macroalgae. The Centre d’Etude et de Valorization des Algues (CEVA) recommended guidelines regarding quantitative limits of aerobic mesophiles, fecal coliforms, anaerobe sulphite reducing bacteria, *Staphylococcus aureus*, *Clostridium perfringens* and *Salmonella* spp. in edible macroalgae. The general principles and requirements of macroalgae food safety in the EU are subject to the EU enforced Regulation (EC) no 2073/2005. In many countries, the food manufacturing process is subject to Hazard Analysis and Critical Control Point (HACCP) assessment, a system adopted by the World Health Organization and the Codex Alimentarius Commission as a recommended international code of practice for general principles of food hygiene.

###  Chemical hazards

Macroalga contain several potentially toxic chemical elements (PTEs) in varying amounts, such as iodine, inorganic arsenic and cadmium. The levels vary according to species, location, season, and other growth conditions (Roleda et al., 2019; Roleda et al., 2018). Some elements, such as arsenic, cadmium and mercury, may bioaccumulate and can only be processed in very small amounts by the human body. Levels of these elements should therefore be kept to an absolute minimum in our diets. Various studies where levels of arsenic, cadmium, lead and mercury in seaweeds have been analyzed indicate that the levels of some of these elements may be a concern in macroalgae (e.g., Duinker et al, 2020). This includes potentially high levels of cadmium in *A. esculenta* (Stévant, Marfaing, et al., 2018) and in *S. latissima* cultivated towards the north of Norway (Duinker et al., 2020), and high levels of inorganic arsenic in *Laminaria digitata* (Maulvault et al., 2015; Duinker et al 2020). CEVA has proposed maximum allowable limits for PTEs in seaweeds, and a limit for cadmium in seaweeds was also put forward by the EU (3 mg/kg ww; Commission Regulation (EC) No 1881/2006).

Contrary to the PTEs discussed above, iodine is a mineral requirement. Several seaweed species, especially the kelps, are very rich in iodine compared to other food sources, and, depending on the consumption pattern, pose a risk of overconsumption (Aakre et al., 2021; Aakre et al., 2020; Blikra et al., 2021). Therefore, Germany has put forward a national limit of 20 mg/kg dw iodine in seaweed, whereas a much higher limit of 2000 mg/kg dw iodine was proposed by CEVA. No such limit has been put forward by the EU or other European countries, although EU acknowledges the risk of dangerously excessive iodine consumption associated with consumption of dry, iodine-rich algal products containing more iodine than 20 mg/kg dw.

To illustrate the relative potential concern of the PTEs in seaweed, a meta-study was performed (Supplementary material). Using data for the mean and maximum content of PTEs found by Duinker et al. (2020) and Roleda et al. (2019), the contents of PTEs in a 5 g portion of dry seaweed was calculated and compared to the tolerable daily intake (TDI; EFSA Panel of Contaminants in the Food Chain) for a 70 kg person (Table S1 and S2; Alexander et al., 2009). For iodine, the recommended maximum limit of 600 μg/day was used by the Scientific Committee on Food & Scientific Panel on Dietetic Products, Nutrition and Allergies. The analysis showed that, in general, there is not a great risk of heavy metal poisoning associated with a maximum dose of 5 g dry seaweeds per day, as long as species with high contents (especially *L. digitata* and *Undaria pinnatifida*) are avoided or minimized. None of the red and green algae analyzed contained mean heavy metal levels above 20 % of the TDI for any of the heavy metals. Considering iodine, the mean iodine content in a 5 g portion of unprocessed seaweed was lower than 600 μg in three species, namely *Himanthalia elongate* (brown), *Codium* spp. (green), and *Porphyra* spp. (red; Table S1). On the other hand, a 5 g dry portion of the brown algae species *S. latissima*, *A. esculenta* or *L. digitata* contained iodine levels above the lowest observed adverse effect level (1800 μg/day). To make matters more complex, intraspecies variations in iodine content can be great. As an example, the concentration of iodine in *S. latissima* cultivated in the sea can range from 670 to 10.000 mg/kg dw (Roleda et al., 2018; Stévant, Marfaing, et al., 2018; Duinker et al., 2020).

Although prone to high levels of iodine and moderate (high in some few species) contents of certain heavy metals, these components (especially the iodine and arsenic content) can to a large extent be controlled by processing technology (e.g., Blikra et al., 2021; Nielsen et al., 2020; Noriega-Fernández et al., 2021; Stévant, Marfaing, et al., 2018). In addition, careful selection of seaweed species, potentially at the genotype level, as well as the location for cultivation should be practiced. Monitoring levels of PTEs in each species, at each location and in every season should be routine to avoid excessive levels in seaweeds used for food. Coupled with optimal processing technology and recipe formulation based on specific contents of PTEs, foods with seaweeds with optimal iodine contents and low contents of other PTEs can be developed. Similarly, when recommending consumption patterns or portion sizes for foods with seaweeds, the content of PTEs in the specific seaweed ingredient must be considered.

### Seaweed allergenicity

Seaweeds are very rarely involved in allergic reactions and thus neither regarded as allergenic foods nor subjected to compulsory allergen labelling by EU (Commission Regulation 1169/2011). To our knowledge, only one case of seaweed food allergy has been reported (Thomas et al., 2019). This case involved red seaweeds only, and no response to green or brown algae was documented in the patient.

The main allergen risk in seaweeds is the unintended presence of shellfish (crustaceans and mollusks) in seaweed food products, which are hosted by seaweeds in their natural habitat and at cultivation sites. Epiphytic biofouling linked to large-scale and high-density seaweed cultivation, typically in the vicinity to fish or integrated multitrophic aquaculture farms, may entail serious allergy risks due to cross-contamination with traces of shellfish proteins (Bannister et al., 2019). Food allergy is a major global public health concern, with shellfish as one of the foremost staple food items that can cause life-threatening outcomes for allergic or sensitized consumers (Davis et al., 2020). Products containing unintended and undeclared shellfish (e.g., seaweeds) can pose severe health issues due to accidental exposure to the offending allergen, as well as significant costs associated with product recalls. On the other hand, the widespread and inconsistent application of precautionary allergen labelling drastically limits food choices and triggers risk-taking consumer behavior, which may eventually lead to nutritional deficiency syndromes (Remington et al., 2015). Food processing has recently gained interest as a preventive strategy towards both attenuation of food allergenicity and manufacturing of hypoallergenic products (Dong et al., 2020).

## Food quality characterization

Within the same species, the biochemical content, size and quality of cultivated seaweeds may vary substantially throughout the season and from location to location (Roleda et al., 2019; Roleda et al., 2018; Sharma et al., 2018; Stengel et al., 2011). However, this variation is not generally considered in European seaweed products and there is a lack of general quality standards the seaweeds must meet in order to reach the market. Thus, the quality of each species or product category may vary between producers and even from batch to batch. This may make it difficult for consumers to anticipate the quality of the product. Furthermore, there are no retail standards for “high quality seaweeds” in terms of sensory attributes, biochemical content, microbial quality and food safety. The lack of consensus regarding which attributes and concentrations of specific compounds are valued is also a potential concern during marketing and labelling of products.

Thus, in order to efficiently characterize product quality and enable product-segmentation, species-specific general quality standards should be developed and homogenized across the European seaweed industry. Chemical characterization should be a part of this quality standard, as the content of chemical hazards in seaweeds vary from acceptable to unacceptable for human consumption. In addition, other factors that improve the value of seaweeds for direct consumption should be considered, such as the presence of biofouling organisms, color, texture, and taste compounds. Analysis of color might be used as an indicator for degradation of bioactive compounds, which have a similar tolerance to light and heat as the various seaweed pigments. Low-tech color measurements such as color-fans can be considered and rapidly developed to allow analysis in an initial industrial phase, but more sophisticated methods such as spectroscopy will give a higher accuracy and can be used to measure the entire harvest instead of only test samples (Liu et al., 2020).

## Novel food regulation

Although there is no harmonized seaweed/algae regulation in Europe, their suitability for human food consumption is governed by the Novel Food Regulation (EU) 2015/2283. This applies to any food not used for human consumption to a significant degree within the Union before 15 May 1997, including «food consisting of, isolated from or produced from algae». If the eligible product does not fall within the Union list of authorized novel foods, food business operators must submit an application for pre-market authorization to the EC, in compliance with the EC implementing rules and the EFSA guidance on safety assessments, before placing the novel food on the market. The Novel Food Catalogue (European Commission) lists products subject to the Novel Food Regulation based on information provided by the EU Member States and serves as orientation on whether a product will need an authorization under the Novel Food Regulation. The eligibility of specific products under the novel food regulation may be uncertain among food business operators, who should address the respective national authorities. Furthermore, the novel food regulation might be a serious obstacle for small enterprises. A list of seaweeds and seaweed ingredients included in the Novel Food catalogue has been compiled by CEVA. Common seaweed species used as food (e.g., *S. latissima*, *A. esculenta*, and *P. palmata*) are regarded as not novel. This regulatory framework may impact the time-to-market and return on investment for those applications subjected to novel food evidence, whilst the applicant-specific (5-year) data protection may promote innovation and, eventually, competitive advantage over market competitors (Holle, 2014).

# Processing and packaging concepts for future European food products

## Value-chain schemes on European market for seaweeds

From a commercial perspective, it is preferable to avoid storage and preservation methods unless they add value to the product, but typically this can not be avoided in a modern society with the sale, transportation, and reselling of food items before reaching the final user. For seasonal products, long-term storage (> 6 months) must often be used. An overview of processing steps in a typical value chain and the final products resulting from these processes is shown in Figure 1. Many different business models that are suitable for a sustainable bioeconomy may result from these value chain options. The food processing steps are further detailed in Figure 2.

The emerging European seaweed industry has not only taken advantage of existing equipment for aquaculture, fisheries and food processing, but also developed new technology. A recent example is that when companies began with aquaculture of seaweeds, they soon discovered the need for new technology, e.g., high capacity drying at low temperatures to preserve quality and limit energy consumption. This was the incentive needed to develop a very low humidity, low temperature drying facility, which later has found a place in the market for drying both seaweeds and other temperature sensitive foods. Development of harvesting vessels is another example. Many new coastline aquaculture methods have been established, but the most challenging part has been to go offshore. Several concepts for offshore cultivation have been developed (Engelseth & Kvadsheim, 2017). There is, however, some concern about the safety with regards to offshore aquaculture of seaweeds, and Banach, van den Burg, et al. (2020) identified knowledge gaps that have to be solved. These include physical hazards, potential anti-fouling agents used to protect the mechanical installations, and intermediates. The seaweed industry has brought innovation to other sectors and a new industry is emerging around the seaweed aquaculture.

## Post-harvest processing

As the natural habitat of the marine seaweeds is salt water, harvesting and storage in air or freshwater results in major quality deterioration (Stévant, Marfaing, et al., 2018). The osmotic pressure increases rapidly in fresh water or even in air, and for some species, e.g., *S. latissima*, this results in an unpleasant, slimy appearance. Furthermore, the seaweeds easily start to dry. Sea urchins, snails and other biofouling organisms that can be attached to the harvest may cause additional damage. Autolysis by enzymes and microbial deterioration may occur after a few days, even at temperatures equal to the sea temperature where the seaweeds originated. The seaweeds therefore need to be preserved or processed immediately post-harvest to avoid degradation.

Typical processing strategies to preserve seaweeds are outlined in Table 2. All these methods result in specific products and are suited for specific market segments. Novel postharvest processing strategies have been reviewed by Zhu et al (2021), who concluded that the utilization of seaweeds has changed from low-cost potash rich fertilizers to functional foods, and further to other high value applications. All steps are dependent on further development in processing technology.

Most European seaweed farms are small businesses operating with low capital for investments. Such a seaweed farm will choose first to use some kind of live storage and then either ferment or freeze most of the harvest. Live-storage can be performed in either refrigerated sea water (RSW) or in on-shore basins with (filtrated) seawater circulation. Both of these methods are effective and maintain quality for weeks (authors’ own observations). Live storage offshore in low nutrient waters may also be a promising option, although the efficiency has not been documented yet.

The availability of low-cost equipment has led many seaweed farms to freeze the seaweeds as block packages in pouches and cartons. This freezing method does not add any value to the product but can extend the durability for up to several years. The drip loss released during thawing may contain dry material in the same magnitude as the seaweed itself (authors’ unpublished results). The contents of the drip loss will vary and can determine whether this should be considered as an economic loss or if the loss could be considered as beneficial. Optimized freezing regimes may lead to better quality of the frozen produce. Choi et al. (2012) found that the optimal freezing regimen for *U. pinnatifida*, with regards to avoiding sensory changes, to be at -30 °C in a 50 % seawater solution, followed by thawing in running tap water for 6h. This treatment resulted in algae with no significant changes in color, tensile strength or bacterial counts compared to fresh controls, even after two subsequent days at 10 °C.

Drying is also a suitable option for many seaweed farms, but even if some of the harvest is dried immediately, there is rarely sufficient capacity to dry the entire harvest directly, as the time window for harvesting is so narrow (typically a few weeks). Additionally, drying is often done on demand using previously frozen or fermented seaweeds as the raw material to limit the costs of drying (labor, energy, space, equipment rental or write-down of interest).

### Drying and preprocessing technologies

The most important reasons for drying seaweeds are: extending shelf life by reducing the water activity, reducing weight and volume, improving quality and product characteristics, and improving sanitation. Conventional air drying involves heat and mass transfer and phase change, and, with high energy demands, it is a costly process (Fernandes & Rodrigues, 2007). Solar drying is cheaper, but it gives a low relative retention of vitamins and phytochemicals (Ho & Redan, 2020) and variable weather conditions may cause a loss of quality and product yield.

Given the costs and the capacities of the drying process, it can be ill suited for processing massive volumes of seaweeds, given their high water content, in the harvesting season. The feasibility would also depend on the commercial value of the products. Production costs may be reduced and capacity increased by introducing microwave heating (Hakim et al., 2020) into the drying process. This combination technology can reduce drying time and improve the energy conversion, thus reducing energy costs (Zhang et al., 2010). The drying process parameters can significantly influence the content of nutrients and antioxidant activity of a dried seaweed product (Ho et al., 2020). Normally, a reduced thermal load is beneficial for nutrient (vitamins and phytochemicals) retention, but the effects and the subsequent quality are species specific (Badmus et al., 2019). Hence, drying technologies and conditions should be optimized for individual species, focusing on the compounds of interest and the potential end-use.

In addition to optimizing the drying technology, preprocessing with technologies that can reduce the water content of seaweed prior to drying may be incorporated in future processing strategies. Such preprocessing steps, like freezing/thawing, pulsed electric field processing (PEF) or ultrasound (US) can lead to cell wall breakage or perforation and, after a subsequent a mechanical dewatering step, reduce the energy and time demand of the drying process. The expelled liquid will contain both valuable and unwanted components (Prabhu et al., 2019), which are easier to separate in the liquid phase.

Freezing is a relatively cheap and readily available technology that can preserve large volumes, and it is currently used within seaweed harvesting and processing (Nordtvedt et al., 2019). Depending on factors like freezing rate and frozen storage temperature and time, freezing will inherently lead to the formation of ice crystals, which often cause cell membrane damage and liquid loss (James et al., 2015). Hence, freezing could serve both as an intermediate preservation step, as well as preprocessing to induce liquid loss.

Pulsed electric field is a technology that is currently used commercially to "perforate" cells in order to achieve increased efficiency in subsequent extraction (e.g., olive oil or fruit juice; Salehi, 2020). Combined with mechanical pressure, the technology has also shown promising results for the processing of macroalgae. When used on the species *Ulva ohnoi*, PEF can improve de-watering (Prabhu et al., 2020) and produce ash reduction (Prabhu et al., 2019; Robin et al., 2018). PEF treatment has also been shown to lead to reduced drying time for both fruit and vegetables, as well as reduced drying time and energy consumption during freeze-drying (Wu & Zhang, 2014). For wakame (*U. pinnatifida*), Yamada et al. (2020) found that PEF increased the drying rate. Pulsed electric field processing is well suited for high throughput processing, with existing continuous lines (e.g., for potatoes) that can process 3-70 t/h. Investment costs (in the range of 300 - 600 k€ for the previously mentioned lines) have to be considered, therefore more studies are required in order to strengthen the basis for the economic aspects. Other preprocessing technologies may also be applicable for seaweed. For instance, the use of US as a pre-treatment reduced the drying time and energy costs during drying of the brown seaweed *Ascophyllum nodosum* (Kadam et al., 2015).

For food purposes, potential effects on the sensory profile of algae following various pre-treatments are also of importance. The color of *A. nodosum* after US treatments was found to be lighter than control samples (Kadam et al., 2015), and minor softening of the texture was found after US treatments of *Durvillaea antarctica* (Mateluna et al., 2020). The changes in color and texture during treatment of other macroalgae, or during other pre-treatments (microwave or PEF treatments) are, to the best of our knowledge, not documented. Neither is the effect on taste for any of the mentioned pretreatments. During further application and testing of new preprocessing treatments, sensory evaluation should also be considered to ensure that the sensory quality is not compromised.

### Taking advantage of innovative processing of seaweeds towards improved food safety and quality

Thermal treatments are extensively used in macroalgae stabilization and processing, despite their environmental footprint and undesirable impact on nutritional and sensory attributes. Alternatively, non-thermal processing technologies (e.g., high pressure, US, UV-light, cold plasma, pulse electric field), alone or in the frame of hurdle technology, have gained attention in the last decade in response to the increasing consumer demand for safe, minimally processed and value-added products, due to their timely and substantial contribution to product safety and quality, production efficiency and green shifting (Al Khawli et al., 2019). Overall, non-thermal processing is acknowledged to better preserve nutritional value, bioactivity, and sensory attributes, which results in healthier products with a longer shelf-life, as recently reported for edible seaweeds treated with high pressure processing (del Olmo et al., 2019; 2020). However, the implementation of these technologies in the seaweed sector has been scarcely documented. In addition, their multi-targeted integration within predictive microbiology modelling could be an effective strategy to anticipate the synergistic impact of technological and food intrinsic and extrinsic factors on safety and spoilage of algal products, with further applications in HACCP, risk assessment and product innovation. Furthermore, predictive microbiology modelling can pave the way for user-friendly decision-support interfaces in relation to microbial risk management by seaweed business operators.

Innovative technologies, such as microwaves and US, have successfully been applied for the removal of organic and inorganic iodine from edible seaweeds (Muñiz-Naviero et al., 2004). With regards to organic iodine (mainly bound to proteins), such technologies, either as an individual or combined step, have been integrated prior to enzymatic proteolysis (e.g., pancreatin) towards protein breakdown and enhanced removal of iodinated amino acids (Romarís-Hortas et al., 2013). Simultaneous removal of organic and inorganic iodine species has been reported when microwave and US are combined with diluted alkaline/acid reagents, surfactants and ionic liquids (Peng et al., 2018; Wang et al., 2017). Moreover, microwave- and ultrasound-assisted processing, typically combined with mild temperatures, green solvents or chelating agents (e.g., ethylenediaminetetraacetic acid, EDTA), has succeeded in the removal of heavy metals from edible seaweeds (Henriques et al., 2019; Noriega-Fernández et al., 2021). In a recent study, the combination of US and EDTA at 50 °C for 5 min led to a significant reduction in the arsenic (32 %), cadmium (52 %) and iodine (31 %) content in *Laminaria hyperborea* (Noriega-Fernández et al., 2021). Thus far, these technologies have mainly been tested in research applications, but not been optimized for commercial food processing. However, the efficiency of the methods for removal of PTEs from seaweeds can be envisaged, although further adaptation and optimization is required prior to use in the food industry.

Besides well-established processing strategies towards hypoallergenic foods (e.g., heating, enzymatic hydrolysis, fermentation), non-thermal processing technologies can contribute to allergen mitigation by altering conformational or linear epitopes through protein aggregation, crosslinking or alteration of amino acid sequences, and thus antibody binding ability, while retaining the original characteristics of the foodstuff (Dong et al., 2020). This is particularly relevant for the unintended presence of shellfish allergens, namely tropomyosins, in seaweeds, which exhibit a remarkable resistance to typical mitigation strategies such as thermal processing and enzymatic digestion (Davis et al., 2020). Although complete removal of food allergenicity through processing may not be feasible today, attenuation of sensitization and elicitation thresholds could be achieved through optimal operating conditions. Implementation of innovative processing in the frame of hurdle technology (e.g., US assisted enzymatic hydrolysis at mild temperatures) could be a successful approach towards improved hypoallergenic potency.

## Potential packaging concepts for future seaweed products

There are not many papers published on the actual packaging of seaweeds or products made from seaweeds. The current research has been focused on how seaweeds can be used to make biomaterials. This is beyond the scope of this paper, although many recent reviews on the topic can be found, e.g., Carina, Sharma, Jaiswal, and Jaiswal (2021) and Abdullah, et al. (2021).

### Packaging of live fresh seaweeds

Being a respiring product, much of the same approach as for other respiring produce can be used when developing packaging for live seaweeds. This involves determination of the respiration rate to make a controlled atmosphere package with an optimum O2 and CO2 content. Controlled atmospheric packaging could also be achieved using microperforated packages with low enough O2 barriers to avoid anaerobic conditions and thus anaerobic respiration with its subsequent loss of quality. The only paper we found covering this topic reported a shelf-life of one week in polystyrene containers without seawater for green algae (Terada et al., 2018), but the principles of packaging of respiring produce in general are reviewed by Fonseca et al. (2002). Another approach to keep live seaweed fresh within a package could be immersion in a brine with a salinity close to the pre-harvest environment of the given seaweed. The storage period of such a product would probably be limited by the available amount of O2 dissolved in the brine at the time of packaging. Chilled conditions would be beneficial to keep respiration rates as low as possible. These concepts of packaging of live seaweeds would require further experimentation to pinpoint the optimum conditions, as well as establishing the shelf-life of such packaged products.

### Packaging of processed seaweeds

Packaging of non-respiring seaweed, i.e., after processing such as thermal, drying or freezing would have many of the same requirements as for packaging of other foods that have undergone the same type of processing. As for live seaweeds, few papers are published on this topic, however a study of Hyun, et al. (2018) showed the effect of relative humidity and temperature during storage of dried kelp and showed the importance of using a closed or airtight package instead of an open one.

Oxidative changes and bacterial growth can be slowed down using vacuum or modified atmosphere. Choice of packaging technology and material would depend on the expected shelf-life of the products and the factors limiting the shelf-life. Factors to consider when selecting materials is oxygen and light/UV sensitivity of the products, the need to control bacterial activity, sensitivity to humidity, and aroma transfer barriers. Using a high barrier packaging material, metalized polyester, Senthil et al. (2011) reported a shelf life of 120 days for dried seaweed at ambient temperatures.

For dried seaweeds with an extended shelf-life, the barrier properties of the packaging material could be an important parameter, not only to keep humidity or oxygen out of the package, but also to control the iodine content of the seaweed product. Dechow & Schneider (1973) showed iodine to be able to permeate packaging materials within hours or days at 40 °C depending on material type, fastest in the polyolefins (3-5 hours), and longer for polycarbonate (8 days) or polyester (11 days). The ability of iodine to permeate through the packaging material over time could contribute to the large variances in reported versus measured iodine content in commercial seaweed products (Aakre, et al., 2021).

# Consumer reactions to novel seaweed products

Seaweed products are traditionally consumed in Southeast Asia, but the demand in new markets is growing (Birch et al., 2019a). Depending on how adventurous and educated new consumers are, it is expected that new seaweed products will be faced with consumer skepticism in new markets (Birch et al., 2019b). Italian consumer segments were willing to consume seaweed but would be even more positive to this new food if they would receive more information about its taste and health related characteristics (Palmieri & Forleo, 2020). Similar requirements for higher familiarity have also been reported in France (Perry et al., 2019). Increased consumer acceptance is expected to be driven by perceived benefits of seaweed consumption. In a German study investigating perceptions and acceptability of new food sources and new methods of food production, the major perceived benefits identified were educational effects including re-connection of consumers to their food sources, improved economy in cities, and improved use of resources such as protein (Specht et al., 2019). Additional perceived benefits could be related to the healthiness many associate with seaweed consumption, such as is apparent from the “superfood” trend (Graeff-Hönninger & Khajehei, 2019).

Many uses of seaweed have been explored in terms of food products (Roohinejad et al., 2017). Besides single products, there is evidence of potential market success when specific seaweed species are carefully combined with other food categories, such as fish in products like fish cakes (Chapman et al., 2015). There is also evidence that consumer acceptance of seaweed products would increase once the consumers’ beliefs about the effect of consuming the product is understood and this understanding is exploited for designing and marketing new products (Ing et al., 2010). This suggestion is in line with previous explanations of how a traditional food like sushi from Japan could succeed as a new and adapted product in a new market, like Norway (Altintzoglou et al., 2016).

As previously discussed (Section 3.2), emerging processing technologies could play an essential role in the development of safe and tasty seaweed food products that are suitable for the European market. At the same time, consumers are expected to be skeptical towards such new processing technologies (Nielsen et al., 2009). One way of overcoming consumer skepticism is to focus on clear and transparent communication, describing which method is used and why (Frewer, 2017). Thorough attempts must be done towards empowering consumers to make informed decisions about seaweed foods in the future (Siegrist & Hartmann 2020; Frewer, 2017).

# Conclusions

Seaweeds are an underutilized food source with major potential as main and functional ingredient in European markets. The current market barriers for seaweeds to foods are related to unfamiliarity for European consumers, food safety concerns, quality preservation and optimization, and food neophobia.

Seaweeds have many traits suitable for culinary applications, however, the unfamiliar taste and texture of seaweeds can pose a barrier to market introduction. New trends, including the “New Nordic cuisine” and the “superfood trend” and are promising gateways for introducing seaweeds to European consumers.

Food safety issues related to seaweed consumption should be addressed parallel to commercialization efforts. Main food safety concerns include the presence of pathogenic bacteria, PTEs such as iodine, cadmium and inorganic arsenic, as well as unintended allergen presence attributed to cross-contamination with biofouling organisms. These obstacles can be tackled using general food hygiene practices, careful selection of seaweeds for consumption and targeted processing and packaging technology. Failure to mitigate food safety hazards may fuel food neophobia and will damage the European seaweed food industry in both the short and long term.

In addition, general quality standards for seaweeds are lacking, making it difficult to characterize the seaweeds effectively. The high variation in quality and biochemical content suggests a need for harmonized practices for sorting of seaweeds for food utilization to allow for product differentiation and predictable quality.

Inspired by other food sectors, processing and packaging methods novel to the seaweed industry have been introduced in the present work towards potential future applications in the sector. As seaweeds deteriorate quickly post-harvest, strategies such as temporary storage (e.g., live storage in optimized conditions, drying, freezing, and fermentation) before final processing, creation of food items and packaging must be in place for maintaining or improving product quality. Development of novel and mobile harvesting and preprocessing vessels might be the solution to the seaweed sector’s short-term high-capacity demand per harvesting location. Thermal processing has been researched and applied for seaweed preservation and is an effective tool for reduction of PTEs, especially iodine and arsenic. However, more sustainable and effective non-thermal processing technologies can also be applied for both preservation and removal of PTEs. For instance, drying can be improved by combination with microwaves. The addition of preprocessing technologies to traditional or new drying technology can make the drying more effective in terms of time, energy and cost. Processing with PEF, US, or targeted freezing, combined with mechanical dewatering, all have promising applications for improving drying efficiency, and further research using seaweeds as raw materials is warranted. Thus, application of processing technologies innovative to the seaweed sector may lead to improved quality, nutritional value, and reduced environmental impact, while preserving product safety.

For future applications, more research is needed on several important issues. Firstly, studies on processing technology, including innovative technologies for the sector, for preservation and reduction of PTEs in seaweeds must continue to find and document strategies for increased removal of the unwanted constituents while retaining the wanted components. This will enable using higher amounts of seaweeds in foods and broader utilization in terms of food groups. In addition, more research on the mitigation of unintended allergens is needed to avoid misleading allergen labelling, which can limit the intended uses (food categories) and use levels of seaweeds when applied as food ingredients. Since the allergens associated with seaweeds are mainly introduced by biofouling on the surface of seaweeds, it will be important to develop effective rinsing technologies. Furthermore, packaging strategies implemented in other food sectors should be optimized and validated for fresh and processed seaweed food products based on the shelf-life limiting factors, both at chilled and ambient storage conditions. Alongside new processing and packaging applications, sensory analysis needs to be conducted, as retaining or improving palpability is essential for food product application. In conclusion, defining which processing technologies are more suitable for seaweeds, both in terms of improving safety and sensory attributes, is part of the continuing effort towards the new generations of seaweed products. Consumer acceptance is also an important factor to be taken into consideration. One major reason for consumer skepticism towards seaweed food products is the lack of knowledge regarding their nutritional value and health benefits. In order to promote knowledge-based consumer decision-making, an open and transparent approach must be followed, especially if innovative technologies are used for future processing of seaweeds.

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# Declarations of interests

None.

# Disclaimer

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# Figure captions

Figure 1. Overview of value schemes for seaweed production for common applications, with emphasis on food applications.

Figure 2. Processing and preservation methods used for applications of seaweeds for food.

# Figures



Figure 1. Overview of value schemes for seaweed production for common applications, with emphasis on food applications.



Figure 2. Processing and preservation methods used for applications of seaweeds for food.

# Tables

Table 1. Current and future applications of seaweeds in food, according to the purpose or property they contribute with.

|  |  |  |
| --- | --- | --- |
| Purpose/Property | Description | Product examples |
| Main ingredient | Raw, cooked, dried, pickled or otherwise processed seaweeds used as a main ingredient or as a vegetable in food | Seaweed salads (e.g., wakame salads) or seaweeds as a vegetable or garnish  |
| Flavor agent | Seaweeds used to reduce added salt (salt replacement/reduction), increase marine or umami flavor or to increase sweetness. Seaweeds may also contribute with specific flavors, such as *Polysiphonia lanosa* (truffle flavor) and dulse/*Palmaria palmata* (floral, violet-like flavors in dairy products) | Dried seaweed flakes, for example in spice mixes such as furikake, seaweed powders (dashi/seaweed broth) used to flavor a wide range of products, dishes and beverages (for example tea)  |
| Bulking agent | Seaweed products used to bulk out products/ration other ingredients. A limiting factor in product categories such as baked goods is the need for declaration of possible shellfish traces | Seaweed flours/powders in baked goods or processed seafood products.  |
| Nutritional contribution | Seaweed products consumed for their suggested health properties, due to presence of fibers, minerals or bioactive compounds | “Superfoods”, dietary supplements and sports nutrition products |
| Edible wrapping | Seaweeds used as edible wrapping or to replace cutlery | E.g., the use of nori sheets in sushi and seaweed rolls  |
| Food color / Appearance | Seaweeds or their powders used in food as a source of green, brown or red colors or used to improve the appearance of products | In restaurants, seaweed powders are used to create surface effects on pieces of fish or meats |
| Texture improvement | Seaweeds or seaweed powders used to adjust food texture | Flour-based, dairy, seafood, meat products or beverages |

Table 2. The advantages and disadvantages of traditional and emerging processing methods for seaweeds to be used as food or ingredients in food.

|  |  |  |  |
| --- | --- | --- | --- |
| Methods | Advantages | Disadvantages | Future perspective |
| Live storage (RSW or FSC)   | Preserves seaweed well (for weeks) if light, oxygen and nutrient supply is sufficient. | Requires large volumes of water-to-seaweed which must be recycled and refrigerated | Limited to use on harvesting vessels |
| Solar drying | The least expensive of drying methods; Preserves seaweed well for long periods of time (> 1 year) provided aw<0.9 | Product loss and quality changes, e.g., due to weather;Food safety challenges;Time consuming | Requires technical solutions in accordance with food safety regulations |
| High temperature Air-drying (> 50 °C) | Preserves seaweed well for long periods of time (> 1 year) provided aw<0.9;Subsequent sensory quality dependent on drying parameters [1];Iodine content may be slightly reduced [1, 2] | Requires costly infrastructure;Energy demanding and costly (can be reduced by pre-processing steps (Section 3.2.1));Limited capacity – may require intermediate storage | Expected to be continued with heat recovery systems and fluidized bed solutions |
| Low temperature air drying (< 50 °C) | Preserves seaweed well for long periods of time (> 1 year) provided aw<0.9;Better nutrient retention than high temperature drying | Time consuming;Limited capacity – may require intermediate storage | Expected widely used |
| Freeze-drying | High nutrient retention | Energy demanding/ and the most expensive drying method;Requires costly infrastructure;Low capacity – may require intermediate storage | Limited to very high price end products |
| Freezing | Preserves seaweed for long periods of time (> 1 year);Infrastructure is often developed or available at low cost;May preserve sensory quality of seaweeds well if freezing and thawing conditions are optimized [3];Potential for reduction in PTEs | Energy demanding;Loss of mass as drip loss may be substantial, depending on parameters of the freezing;May result in quality deterioration (especially block freezing);Capacity of quick freezing is limited by investment cost in equipment | Market development for frozen products unclear |
| Fermentation | Preserves seaweed well for long periods of time if sufficient pH reduction is achieved;Can be upscaled to large volumes;Sensory profile may be enhanced [4]; | Strict hygiene requirements;Requires optimization of process and stringent pH control to avoid issues with unwanted microbiology | Highly depending on further development |
| Dry salting/ brining | Preserves seaweed well for long periods of time [5];Low capital investment required;Can easily be upscaled;Fresh like product [5] | Increases sodium content and associated health risks;May require de-salting before consumption | In use for seasoning salt in limited scale |

RSW: refrigerated seawater; FSC: Filtrated seawater circulation.

[1]: Stévant, Indergård et al. (2018); [2]: Duinker et al. (2020); [3]: Choi et al. (2012); [4]: Bruhn et al. (2019); [5]: Perry et al. (2019).