WORKING GROUP 3

ULVA AS FOOD, FEED AND BEYOND

LEADER

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RATIONAL AND OBJECTIVES

With a rapidly growing world population, the agricultural food gap will increase due to climate change-induced constraints on natural resources, i.e., freshwater and farmland. Consequently, ensuring food security has become a global imperative. Thereby, the oceans will play an increasingly important role in providing food, animal feed and other valuable, sustainable biomaterials. However, marine wild stocks cannot meet the increasing demand for fish or other biomass sources, including macroalgae. Therefore, seaweed cultivation may be essential for contributing to food security by provisioning food or feed ingredients (Araújo et al. 2022; Forster and Radulovich 2015; Radulovich et al. 2015). Several distinct characteristics indicate an immense potential for green algae in the genus *Ulva* in playing a central role in the European seaweed aquaculture industry. The most notable characteristics of *Ulva* include world-wide coastal distribution, fast growth rates, relatively simple life cycle, ease of culture, historical use in food and feed, documented bioactivity and efficiency as a biological filter (Mata et al., 2010; Lawton et al., 2013; Sebök & Hanelt, 2023; Al-Hafedh et al., 2014; Stedt et al., 2022; Shahar et al., 2020; Bao et al., 022; Kirst 1990; Steinhagen et al., 2021).
From a food and feed perspective, *Ulva* species contain suitable levels of proteins, vitamins, trace minerals, and dietary fibers for human and animal consumption (Toth et al. 2020; Trigo et al. 2021; Stedt, Trigo, et al. 2022; Stedt, Toth, et al. 2022; Steinhagen, Larsson, et al. 2022; Steinhagen, Enge, et al. 2021; Taboada et al., 2009). With an amino acid composition comparable to soy or egg protein, and including all essential amino acids (except tryptophan), selected strains of *Ulva* bearing high protein contents can partially substitute less sustainable protein sources (Dominguez & Loret 2019). In addition, high contents of essential dietary fibre and other bioactive substances such as phenolics, vitamins, minerals, fatty acids, and pigments render it a beneficial food item providing health and functional advantages (Rajapakse and Kim 2011; Holdt and Kraan 2011; Lopes et al. 2019; Moreira et al. 2022; Qi et al. 2005).
The sustainable exploitation of *Ulva* as food and feed can therefore contribute to the increasing demand for renewable and novel nutritious food sources, emphasized by the UNSDGs (United Nations, 2015; Faber et al. 2021). The currently increasing trends for health-promoting foods and lifestyles and the recommended consumption of plant (and algae)-based foods (Willett et al. 2019) imply important opportunities for the food industry to develop seaweed-based products.

The tasks for this WG3, *Ulva as food, feed and beyond** have been defined as follows:
The collective knowledge on *Ulva* food for human consumption, animal feed, and use of *Ulva* as a source of biomaterials will be consolidated. The nutritional value of *Ulva* and its safety as food will be validated. The existing knowledge of *Ulva* biology and mariculture (WG 1, 2) will be identified concerning the food and feed production industries. This will fulfil challenge **(b**), namely developing commercial applications in food and feed industries. The WG activities include the following tasks:
Task 3.1 The applications and nutritional values of *Ulva* spp. in humans and animal nutrition, including food processing, will be identified; **D 3.1.**
Task 3.2 *Ulva* as a source of new biomaterials will be investigated; **D 3.1**

***The following task adjustments had been made:**

want to appear here.

At the beginning of the Action period, a better distinction between WG3 and WG4 tasks had been defined to avoid overlap of topics. We defined WG3 to deal with *Ulva* only as a raw source for food and feed as well as biomaterials beyond for non-food applications, e.g. as bioplastics, packaging or biostimulants. In contrast, WG4 was clearly focusing on the chemistry of extractable substances from *Ulva* and extracted bioactives of processed *Ulva* as well as *Ulva*-associated microbial metabolites. Extracts would then be applicable for e.g. health supplements, nutraceuticals, food additives.

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ACTIVITIES AND KEY FINDINGS

During the 4 years Action period, the number of WG3 members steadily increased to 216 (May/2025, from 39 countries), thereof ~30 actively involved in participating in meetings and publications. On one hand, this group reflected the high interest and engagement in the network to share information and knowledge dissemination which led to the **publication of two reviews** (Hofmann et al., 2024, Vargas et al., 2025, see below). On the other hand, the large number of WG inscriptions, which included ~18 SMEs, also show the lack and demand of knowledge for *Ulva* cultivation, processing as ingredients for food and feed applications and product development. Although algal cultivation technology has improved in the last decade, there is still a need to optimize production for (energy) efficiency, product quality, post-harvest processing, consumer safety, and biomass utilization for the food and feed industry.

Co-initiation of EULVA project
(https://sites.google.com/view/eulva , see in detail under WG1 and WG4)
Ulva Taxonomy: Why Identification Complexity Impacts Nutritional Assessment

Ulva species exhibit simple morphologies (mostly tube or foliose forms) that are challenging to identify, particularly due to phenotypic plasticity —meaning the physical form of one species can vary widely with environmental conditions and its algal microbiome - making traditional morphological identification methods on species-level unreliable. However, most of the existing *Ulva* literature to date is based on morphological identification, rendering species-level identification data questionable. The correct identification of both wild stocks and cultivated *Ulva* spp. biomass is necessary, as the traits vary between the species, and is particularly important due to their prevalent application in commercial projects and industrial product labelling. In order to identify species and strains of particular commercial value, for example using species selection criteria, molecular identification methods such as DNA barcoding must be consistently used in future.
The aim of the EULVA taxonomy initiative of WG1 and WG4, which was co-initiated by WG3 members, was to identify and specify species distribution across Europe and combine the data with biochemical and nutritional characteristics and microbiome data. This was initiated in order to clarify common taxonomy issues with *Ulva* (see below) and to identify and characterise wild and cultivated Ulva strains for a potential future selection for cultivation purposes. EULVA results will be reported by the respective WG1 and WG4. However, the originally intended separate nutritional analysis of cultivated *Ulva* strains remained unsuccessful due to insufficient available sample material, lack of participating producers, and technical issues in the volunteering laboratory.

D 3.1 (a, b). Report on *Ulva* for human consumption, animal feed and use of inedible fractions as a source of biomaterials.

In order to improve awareness of the seaweed *Ulva* in food, feed, and beyond, and to disseminate the latest knowledge, 27 authors from the COST consortium contributed to this comprehensive **review** publication (**Hofmann et al. 2025**; https://doi.org/10.1080/10408398.2024.2370489). The paper provides a critical review of the current status, challenges and opportunities of incorporating this genus into the mainstream so that it may become tomorrow's "wheat of the sea". It includes chapters on *Ulva* in aquaculture, human consumption, aquafeed, terrestrial feed, and applications beyond food and feed.

Of course, consumption of seaweeds in general and *Ulva* in particular also raises safety concerns as it may entail microbiological or chemical risks, in particular by accumulating harmful heavy metals. In a **separate review, Vargas-Murga et al. (2025)** https://doi.org/10.1016/j.foodchem.2025.145941 critically analysed 176 peer-reviewed papers to evaluate metal(oid) accumulation in *Ulva*. This paper revealed substantial variability in the essential and non-essential element content due to environmental conditions, geographic regions, morphological forms, and analytical methods used in both wild and cultivated *Ulva*. Based on these findings, the review identified and outlined key areas requiring attention to ensure the safe and effective use of *Ulva*. Standardised analytical protocols are needed to improve consistency and comparability across studies and to enable accurate detection of toxic element forms.

With these papers, WG3 achieved its MoU deliverable **D 3.1**.

a. Results for Task 3.1: see also:

Hofmann, L. C., Strauss, S., Shpigel, M., Guttman, L., Stengel, D. B., Rebours, C., ... & Meléndez-Martínez, A. J. (2025). The green seaweed Ulva: tomorrow's "wheat of the sea" in foods, feeds, nutrition, and biomaterials. *Critical reviews in food science and nutrition*, *65*(19), 3728-3763.; https://doi.org/10.1080/10408398.2024.2370489 ;

Vargas-Murga, L., Dürrani, Ö., Adams, J., Steinhagen, S., Turan, G., Aruçi, E., ... & Shpigel, M. (2025). Metal(oid)s in Ulva –should we be worried?. *Food Chemistry*, 145941.https://doi.org/10.1016/j.foodchem.2025.145941

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Applications and nutritional values of *Ulva* for human *and animal* food, including food processing.

Nutritional profile of *Ulva*
Depending on the species, season, and environmental conditions, *Ulva* strains contain various amounts of **protein** (9–29% DW, dry weight). Therefore, an optimization of cultivation conditions and strain selection is crucial for a high protein yield. Ulva proteins are rich in essential amino acids and are comparable to soy/egg in quality.

Carbohydrates range from 40–60% DW and are mainly structural polysaccharides (ulvans, cellulose, xylans). Ulvans (sulfated polysaccharides) are indigestible to humans but act as prebiotic soluble dietary fibre promoting beneficial gut microbiota and showing immunomodulatory potential. Small amounts of digestible sugars include glucose, rhamnose, and xylose.

A very low **lipid** content, typically <2% DW, contributes little to energy intake but adds nutritionally beneficial fatty acids, such as valuable PUFAs (EPA, ALA).

Ulva contains generally high amounts of **minerals** (ash, 15–30% DW) with rich profiles in K, Mg, Ca, Fe, Zn, Mn, and Se. A favourable K/Na ratio (>2) is for beneficial cardiovascular health (after desalting) and a high iron content can contribute to anaemia prevention.

Vitamins, thereof Vitamin C (ascorbic acid), are present though heat-sensitive and reduced by drying/blanching, as well as Vitamin A precursors (β-carotene, lutein, zeaxanthin), and B-group vitamins (folates, niacin, riboflavin) and vitamin E (α-tocopherol) in moderate levels.

Bioactive phytochemicals like polyphenols and flavonoids as well as the pigments chlorophylls and carotenoids (β-carotene, lutein) show antioxidant and anti-inflammatory activities.

Safety Considerations

The ability of *Ulva* to accumulate potentially toxic trace elements (such as As, Cd, Pb, Hg) is raising health safety concerns and is also proving useful for biomonitoring studies. In response to this concern, our review (Vargas et al. 2025) emphasises on the importance of harmonization of analytical methods as well as standardised cultivation parameters that are crucial to control elemental composition in farmed *Ulva* and to ensure its suitability for human consumption and commercial applications. Furthermore, standards and guidelines related to seaweed products can vary nationally, and should be unified at the European level. In addition, it is crucial to increase knowledge on how the processing methods may affect the content of hazards, including the possible and unintentional presence of products or substances with adverse health effects.

Relevance of post-harvest processing

The impacts of post-harvest processing on biomass quality not only involve food safety, but also sensory quality, and nutrient retention. Processing methods such as washing, blanching, drying, freezing, salting, brining, or fermentation can be performed to ensure food quality and safety but also taste. Drying is the most applied method for seaweed preservation ensuring a long shelf life and enabling the most economical solution for storage and transport. However, depending on the application or final product, the choice of another of above mentioned preservation methods can even be more relevant to modify taste, texture, colour or digestibility of the biomass. For a successful product, processing must balance safety/stability with sensory appeal to encourage consumer acceptance.

Ulva in Human Food Applications

The use of *Ulva* in food profits from its broad versatility. It can simply be the main ingredient in e.g. a salad or replace green-leaved vegetables in traditional home cooking. Further, it can be used as sprinkle-on seasoning, leveraging the natural umami and salty flavour profile of *Ulva* to reduce added salt. However, *Ulva*'s most promising applications on a large scale are as an enriching ingredient to increase its sustainable impact and to profit from its health benefits.

The enrichment of cereal-based products such as bread, pasta, or crackers with 1–4% *Ulva* powder or dried flakes can improve the products' nutritional profiles with higher fibre and mineral content without impairing the taste. Furthermore, *Ulva* can serve as gluten-free ingredient in pasta or bread.

Ulva can also be included in processed meats such as burgers and sausages, producing juicier meat with less cooking loss, whereas the *Ulva* proteins and fibres contribute to texture and water-binding capacity. As already seen with other seaweed species, the substitution of up to 40% (ww) of meat or fish content with *Ulva* in burgers or sausages can result in a tastier and healthier product with less fat, increased fibres, and reduced CO_2 footprint. Additionally, the increasing demand for meat-free and seafood analogues opens further opportunities.

Furthermore, *Ulva* can play a positive role in convenience products, snacks, chips and enriches dairy products such as probiotic milk, cheese, seasoned butter, sauces, spreads, and mayonnaise. Additionally, a promising field for the food industry is to investigate the properties of *Ulva* as a functional ingredient, modifying the products' gelling and water-binding properties. However, more research is still required to develop products that meet customer acceptance.

***Ulva* in Animal Feed Applications**

1. Aquaculture

Opportunities for *Ulva* in aquaculture feed (finfish, crustaceans, molluscs) are manifold. First, strains with elevated protein content can serve as sustainable protein source and an alternative with lower ecological footprint compared to soymeal and fishmeal in feed formulations. Numerous studies with different feed formulations showed that suitable inclusion rates did not affect fish growth, feed conversion ratio (FCR), or protein intake. Inclusion rates depend on the trophic level of fed fish and can range from 5% for carnivorous fish and up to 30 % for herbivores. For commercially valuable invertebrates, including shrimp, abalone, sea urchins, and sea cucumbers, studies confirmed the potential to increase *Ulva* content in aquafeeds by over 20%. Second, *Ulva* can be even included in aquafeed at lower percentage as functional feed additive as its bioactives (ulvans, carotenoids, phenolics) show beneficial antioxidant, antimicrobial, and immunomodulatory effects. Some studies also report improved disease resistance (e.g., in shrimp and tilapia). Furthermore, *Ulva* pigments can improve product quality by enhancing the coloration of farmed fish flesh or shells in shrimp/crustaceans. Finally, by integration into IMTA (Integrated Multi-Trophic Aquaculture), *Ulva* closes nutrient loops using fish waste nutrients for its growth which then re-enter the circle as feed.

However, the presence of anti-nutritional factors (ANFs) can also present a challenge to applying *Ulva* in aquafeeds. Observed growth deficits were due to the presence of ANFs, high ash/mineral content and indigestible fiber like ulvan in the dietary *Ulva.* ANFs in *Ulva* include alkaloids, tannins, saponins, lectins, polyphenolics, phytic acid, and other inhibitors that reduce the bioavailability and digestibility of algal nutrients. In addition, potential accumulation of heavy metals (As, Cd, Hg) in *Ulva* poses food safety risks downstream, calling for tight monitoring measures of the *Ulva* biomass and cultivation conditions. Monogastric aquaculture species (e.g., carnivorous fish) may not efficiently utilize *Ulva* proteins without pre-treatment. Finally, the economic feasibility in using *Ulva* in (aqua)feeds is still challenging as large-scale production and processing (to improve digestibility and reduce minerals) is still costly compared to soymeal or fishmeal.

2. Terrestrial Livestock

The use of raw and unprocessed *Ulva* in land animals is still restricted due to mineral overload and digestibility limits in many species. Although ruminants (cattle, sheep, goats) tolerate relatively high *Ulva* inclusion rates because their rumen microbes can partially degrade structural polysaccharides, the use of raw *Ulva* in monogastrics (poultry, pigs) is more constrained by *Ulva*'s undigestible cell walls and structural carbohydrates. Thus, only low inclusion levels (typically < 5–10 %) of whole *Ulva* are showing neutral to modest benefits in gut health or product traits. To overcome these limitations, processing approaches—such as enzymatic hydrolysis, fermentation, mechanical disruption, extraction of protein fractions, or co-feeding carbohydrase enzymes—are necessary to improve nutrient release and reduce anti-nutritional components. Such treatments allow the use of enriched *Ulva* protein fractions rather than whole biomass in monogastric diets but also come at an economic cost.
Furthermore, nutritional and anti-nutritional composition of *Ulva* is highly variable across species, strains, seasons, and cultivation conditions, necessitating systematic quality control in

any feed program. Finally, techno-economic viability for terrestrial feed hinges on integrating *Ulva* into biorefinery cascades, ensuring safe contaminant levels, refining pretreatment protocols tailored to the digestive physiology of the target species, and life-cycle cost assessments. Overall, *Ulva* is currently more readily deployable in polygastric systems (at moderate to higher inclusion) in whole or minimally processed form, whereas monogastric use is likely to depend on processed or extracted fractions and enzyme supplementation. However, economic concerns about increased production costs could be weakened by savings on disease management in healthier animal husbandry. Commercially successful pig feed formulations including fermented seaweed have shown high potential in stimulating overall animal performance, such as improving nutrient absorption and enhancing gut health. Future investigations could explore their role in modulating the microbiome and even influencing animal behaviour through improved health.

b. Results for Task 3.2; see also:
Hofmann et al., 2025; https://doi.org/10.1080/10408398.2024.2370489 ;

A list of inedible fractions of *Ulva* as a source of biomaterials

Ulva contains a suite of structural and functional components that are not typically considered edible or directly usable in feed but have strong potential as sources of biomaterials. Among these, ulvan, cellulose, and ulvan-free residual biomass stand out as versatile fractions that can be valorised in the fields of sustainable packaging, agricultural biostimulants, and integrated biorefinery concepts.

Packaging materials. *Ulva*'s inedible carbohydrate fractions are increasingly explored as renewable substitutes for petroleum-derived plastics in packaging. The key component here is ulvan, a water-soluble, sulfated polysaccharide with film-forming capacity. When isolated through hot water or acidified extractions, ulvan can be cast into biodegradable films with antioxidant and antimicrobial properties, making it attractive for active packaging and food preservation. However, pure ulvan films often suffer from poor mechanical stability and high water sensitivity. To overcome this, ulvan is blended with cellulose (another inedible *Ulva* fraction), starch, chitosan, or synthetic polymers like polyvinyl alcohol (PVA), yielding composites with improved tensile strength, barrier performance, and UV-blocking ability. Plasticizers such as glycerol or citric acid can also be incorporated to enhance flexibility. *Ulva*-derived cellulose contributes additional rigidity and acts as a reinforcing agent in multilayer films. Beyond standalone films, ulvan has also been applied as an edible coating for perishable foods, where its antimicrobial traits slow spoilage. Collectively, Ulva's polysaccharidic fractions offer a sustainable route to packaging solutions that are biodegradable, functional, and aligned with circular economy goals.

Biostimulants for agriculture. Another application of Ulva's inedible fractions is in biostimulant products, where aqueous or enzymatic extracts are used to enhance plant growth and resilience. Ulvan is again central: its unique sulfated rhamnose-rich structure can elicit defence responses in crops, acting as a plant immune stimulant and promoting tolerance to pathogens or abiotic stress. Studies demonstrate that ulvan extracts can modulate phytohormone signalling and activate systemic resistance pathways, reducing the need for synthetic agrochemicals. In addition to ulvan, crude *Ulva* extracts — containing polysaccharides, phenolic compounds, and trace minerals — can function as foliar sprays or soil conditioners, enhancing root development, nutrient uptake, and yield. Importantly, these uses target the "inedible" biomass fractions that are unsuitable for animal feed, thereby valorising residual or surplus seaweed harvests. *Ulva*-based biostimulants align with sustainable agriculture agendas by lowering fertilizer dependence while maintaining productivity.

Biorefinery approaches. The most integrative strategy for exploiting *Ulva*'s inedible fractions lies in biorefinery concepts, where sequential extraction and processing pathways maximize value from the whole biomass. In such cascades, ulvan is often the first target, extracted for high-value applications (pharmaceuticals, biomaterials), followed by recovery of proteins for feed or nutraceutical uses, leaving behind a cellulose-rich residue. This residue can be converted into bio-based chemicals, nanocellulose, or further used as substrate for microbial fermentation to produce bioethanol, volatile fatty acids, or polyhydroxyalkanoates (PHAs), which are biodegradable plastics. Anaerobic digestion of residual fractions can additionally yield biogas, closing the energy loop. The biorefinery perspective treats inedible *Ulva* fractions not as waste but as feedstocks for a cascade of bioproducts, enhancing economic feasibility and sustainability. By integrating packaging material development, biostimulant production, and bioenergy or biopolymer generation, *Ulva* biorefineries embody circular bioeconomy principles, leveraging rapid algal growth and coastal abundance to deliver multifunctional outputs.

In summary, the inedible fractions of *Ulva* — especially ulvan, cellulose, and residual biomass — represent a versatile resource for innovation in sustainable biomaterials. As packaging substrates, they offer biodegradable, functional films; as agricultural biostimulants, they activate plant defences and growth responses; and within biorefineries, they enable cascaded valorisation into polymers, fuels, and chemicals. Remaining challenges include scaling extraction methods, standardizing composition across variable *Ulva* harvests, and improving mechanical properties of ulvan-based films. Nonetheless, the convergence of these three fields underscores the pivotal role of Ulva's inedible components in advancing bio-based industries beyond food and feed.

FUTURE DIRECTIONS & RECOMMENDATIONS

Below listed are key areas where further work is needed and recommendations for advancing the science and applications of *Ulva* in food, feed and biomaterials.

1. Species identification, genetic diversity and strain selection

One of the foremost gaps is still in reliable species identification and characterisation of *Ulva* strains. Many cultivated *Ulva* may not have definitive taxonomic identity, which complicates comparisons between studies, reproducibility, and optimisation (e.g. in strain-specific performance, nutritional profiles, growth rates). Consistent and standardized molecular identification is needed to characterise and share suitable *Ulva* strains for particular end-uses (food, feed, biomaterials).

2. Nutritional composition and safety

While *Ulva* has favourable nutritional potential (notably in protein, vitamins, antioxidants, fibres), there remains incomplete understanding of how composition varies with species, growth conditions (light, nutrients, temperature), cultivation system, harvest time, and post-harvest processing. Therefore, there is a need to prioritize a systematic nutritional profiling under standardised conditions, including assessment of how processing (e.g. washing, blanching, drying, fermentation) can affect nutritional value and safety.

3. Processing, value-added products and ingredient development

There is a gap in understanding and employing suitable processing methods for *Ulva* to create value-added, sensory attractive ingredients for food and feed. Furthermore, scalable, costefficient processing pipelines that preserve *Ulva*'s functional compounds (proteins, ulvan polysaccharides, pigments, bioactives) are still lacking. More research could ensure that the resulting ingredients meet regulatory, sensory, and functional standards. In addition, durable biomaterials (films, gels, coatings) need better characterization of mechanical, chemical, and biodegradability properties, and how these are influenced by *Ulva* species and treatment.

4. Safety, regulatory and consumer acceptance

Ulva-based foods, feeds, and biomaterials must undergo rigorous safety assessment including contaminants (pathogens, heavy metals, environmental pollutants), allergenicity, and long-term exposure. Regulatory frameworks at national and European levels are in many cases not yet fully adapted to *Ulva*-derived ingredients, which creates uncertainty for producers and consumers. Moreover, consumer perception and acceptance of *Ulva* in food products needs to be better addressed by specific marketing strategies and improved communication. Social science research should further be involved for acceptance, labelling, taste, texture, and cultural compatibility.

5. Economic feasibility, scaling up and life cycle assessment

Many promising studies are small-scale. However, translating yields and value-added product development into economically viable large-scale production remains a challenge. Cost of cultivation (especially in offshore or land-based systems), harvesting, transport, drying, processing, and downstream product formulation need better cost modelling. Moreover, life cycle assessment (LCA) and environmental impact (energy, carbon, water, nutrient budgets) are under-represented. More economic and environmental analyses should be integrated alongside technical development to ensure that *Ulva* applications are sustainable at scale.

6. Functional performance in end-use applications

For future-proof *Ulva*-derived products, more testing in real end-use settings is recommended. For feed that means trials with different classes of livestock, aquaculture species, with attention to performance metrics, gut health, immune responses, microbiome. For human food, above all more sensory trials and competent product development considering the special requirements of algal ingredients. For biomaterials, tests on durability, stability, and regulatory compliance in intended applications.

In summary, while *Ulva* offers great promise as a sustainable marine SeaWheat resource for food, feed and beyond, realizing its full potential demands interdisciplinary coordinated research to fill critical gaps in taxonomy, nutrition and safety, processing and material science, scaling and economics, and consumer acceptance.