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The Role of Algae in Sustainable Food and Feed Systems

Annex to the Final Report

European Maritime, Aquaculture and Fisheries Fund (EMFAF)

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Abbreviations

AT	Asparagopsis Taxiformis
BW	Body Weight
CAP	Common Agricultural Policy
CFP	Common Fisheries Policy
CO2	Carbon dioxide
DMI	Dry Matter Intake
EG	Euglena Gracilis
EIA	Environmental Impact Assessment
EPA	Eicosapentaenoic Acid
EU ETS	European Union Emission Trading System
GHG	Greenhouse Gasses
GSI	Gridpoint Statistical Interpolation
GWP	Global Warming Potential
IMTA	Integrated Multi-Trophic Aquaculture
LCA	Life Cycle Assessment
NWES	North-Western European Seas (North Sea and the English Channel)
R&D	Research and Development
R&I	Research and Innovation
SAFFHC	Seaweed and Algae Fit For Human Consumption
SWES	South-Western European Seas
THMs	Trihalomethanes
TRL	Technology Readiness Level

Executive summary

This report constitutes the deliverable of Work Package 6 (WP6) of the Study to support Sustainable EU Algae Industry.

The report explores the role of algae in sustainable food and feed systems – for both human consumption and animal and aquaculture feed – as well as the environmental services algae can provide. WP6 aimed to provide evidence to support the increased use of algae and to bridge existing knowledge gaps. Four distinct tasks were implemented.

The first task focused on evaluating and quantifying the benefits of algae. A comparison was carried out between six algae species and other protein sources. The selection of species was based on various criteria, including the availability of Life Cycle Assessment data, the type of algae (micro or macro), their origin, current cultivation within the EU, nutritional value, and end use. It was found that while microalgae are generally sold as dried algae or as specialty products used as food additives, macroalgae are marketed in a more diverse range of forms: dried, fresh, frozen, or processed into products or supplements. Challenges were identified in the comparability of available data, with potential benefits linked to future scaling-up of production and increased technological maturity (e.g., pilot versus industrial stage). Overall, despite interspecies differences, algae were found to have a high greenhouse gas (GHG) reduction potential compared to other protein sources, albeit with higher production costs, as well as a relatively strong consumer acceptance. Some species have a high nutritional content, while others are richer in carbohydrates and minerals. Production levels across the EU vary considerably.

The second task consolidated data on algae consumption, using a combination of bottom-up (consumer data), top-down (producer data on algae content), and EU-Asia comparative approaches. Both micro- and macroalgae have a wide array of applications – from cosmetics to fertilisers, and from feed to phycocolloid extraction. For food applications, which represent the primary market for EU production, algae can be used as an ingredient, a supplement, a main culinary component, or an additive.

Nevertheless, data on European algae consumption remains fragmented, incomplete, and generally of low quality. In terms of production, it was found that the European algae industry remains largely overlooked and limited, with an output of approximately 290,000 tonnes per year – representing about 0.8% of global production. This production is primarily derived from wild harvesting rather than cultivation and is largely driven by Norway (accounting for 61% of European production), followed by France and Ireland. The sector includes a total of 225 macroalgae and microalgae-producing companies, along with more than 200 Spirulina producers. Despite these relatively modest figures, Europe records the highest number of seaweed start-ups and equity investments globally.

The European market has significant growth potential, with demand for seaweed-based products projected to reach between EUR 3.0 and 9.3 billion by 2030. However, the regulatory framework – though still evolving – remains a challenge for the industry's expansion. As of 2022, only around 20% of the more than 150 algae species historically consumed in Europe had been approved for food and food ingredients market use under existing novel food legislation. Other challenges include limited availability, knowledge gaps, production constraints, high costs, environmental concerns, health and safety issues, and consumer perception. Conversely, advances in algae-related technology, the increasing popularity of Asian cuisines, sustainable labelling, and rising public interest represent potential drivers for growth.

The third task analysed the potential of algae to reduce methane emissions. Incorporating algae into livestock feed can significantly lower methane emissions, presenting a promising alternative and nutritional source for cattle. *Asparagopsis* was notably identified as a potentially effective methane mitigant for livestock, with reductions of up to 80%. However, the extent of this reduction depends on several factors, including dosage, diet composition, and animal type. The study also highlighted several implementation challenges, such as supply chain limitations, the need for economic incentives to support adoption, and issues related to large-scale cultivation. Furthermore, the possible high concentrations of bromoforms, heavy metals, and minerals present in some algae species necessitate lower dosages to mitigate associated health risks – while still achieving meaningful methane reductions. The study also identified limitations and research gaps that must be addressed to enable successful future adoption and implementation.

Three business cases for the introduction of EU-native algae species into animal feed were developed. The study provided insights and comparisons with five commonly used animal feed ingredients across several parameters, including environmental impact, economic aspects, logistics, and safety. Overall, it found that existing research on the potential of algae is insufficient. Nonetheless, across many dimensions, algae species show potential to deliver meaningful benefits.

The fourth task presented recommendations for the use of algae in animal feed. The algae sector in Europe is evolving, with significant growth potential in both human food and animal feed markets and has not yet reached maturity. The use of algae in these sectors is gaining momentum, driven by policy support, regulatory progress, and increasing market interest. However, limitations in production scalability (and therefore cost-competitiveness), along with a lack of comparable data, present challenges in accurately assessing environmental performance and overall impact.

Asparagopsis was again identified as a species with significant potential, though key challenges remain. Investment in research and development, as well as biotech innovation, should be increased. This includes standardising research methodologies to ensure the availability of consistent data. Financial support for

algae farmers and start-ups should also be enhanced. Simplifying the regulatory framework is essential, and awareness-raising initiatives should be implemented to stimulate demand.

Conclusions and recommendations of this report are laid down in section 6.

1. Introduction

The objective of WP6 was to provide substantiation for the increased use of algae in human food, animal feed, and aquaculture, as well as to explore the environmental services algae can offer. It also addressed key knowledge gaps concerning the role of algae in sustainable food and feed systems.

WP6 consisted of four main tasks:

- Task 6.1 Evaluate and quantify algae benefits
- Task 6.2 Data on algae consumption
- Task 6.3 Potential to reduce methane emissions
- Task 6.4 Recommendations for using algae as animal feed.

The use of algae in both human food and animal feed is gaining momentum in Europe, driven by regulatory advancements and increasing market interest.

More than 20 new algae species have been added in 2024 to the EU Novel Food Status Catalogue, allowing them to be sold as food or food supplements without requiring pre-market authorisation. This development supports innovation and diversity in the food market, making algae-based products more accessible to consumers.

The European Commission has adopted in November 2022 the EU Algae Initiative to support the algae sector, aiming to unlock its potential and respond to growing demand for algae products.

Algae are currently being explored as a sustainable alternative to traditional animal feed and human food. Various studies have shown that algae can yield higher quantities of dry mass, protein, and lipids compared to conventional crops. However, production costs and the carbon footprint of algae – particularly microalgae – remain relatively high. Efforts are underway to enhance the nutritional value and digestibility of algae for animals, while also addressing concerns such as mineral and heavy metal toxicity.

In conclusion, based on our research, the algae sector in Europe is evolving and holds significant potential for growth across both human food and animal feed markets.

1.1. WP relevance to EU Algae Initiative

This WP is contributing to the following **actions** identified in **EU Algae Initiative**:

6. Starting in 2023 and together with the algae industry, examine the algae market and propose market-stimulating mechanisms to support and promote the transfer of technology from research to market (Task 6.4);

7. Support, through Horizon Europe and other EU programmes, the development of new and improved algae processing systems and novel production methods for high-value compounds traditionally sourced from algae (e.g. biorefineries, precision fermentation, cell-free systems), processing algae to make circular bio-based products for multiple applications (Task 6.4);

20. Starting in 2023, support raising consumer awareness by:

    (a) doing a consumer behaviour and preference analysis of the perceptions of algae-based products (Task 6.2);

    (b) launching a fact-based EU-wide and/or, where relevant, regional or local communication campaign(s) to promote the variety of applications and benefits of algae-based products.

2. Evaluation and quantifying of algae benefits

There are significant differences in the greenhouse gas emissions associated with the production of (animal) proteins. Algae represent a promising and sustainable source of protein for human consumption and have the potential to become a key component of future sustainable diets. The objective of this sub-task is to evaluate the direct benefits and avoided costs of producing and consuming six algae species for human food, in comparison with other protein sources, based on the carbon footprint of algae production. This includes a quantification of benefits and emissions, resulting in a comparison of greenhouse gas (GHG) emissions per kilogram of protein for six European algae species.

This chapter will elaborate on the selection criteria used to identify the six algae species under consideration, present the selected species, and outline the study's limitations. Following this, a comparison of the costs and benefits associated with each of the six algae species will be presented.

2.1. Selection of algae species

Through this initial desk study and discussions with the Client, a set of selection criteria was identified to guide the choice of algae species to be compared later in the task. The most important criteria were the availability of a Life Cycle Assessment (LCA), achieving a balance between micro- and macroalgae, a balance between native and non-native (alien) species, and whether the species are cultivated within the EU. Additional, though less critical, criteria included the species' current uses and their nutritional value.

Table 1 – Selected Algae Species

Species	Micro/ Macro	Native/ Alien	EU Cultivation	Nutritional Value	Common Use
A. platensis (Spirulina)	Micro	Alien	Yes	High in protein	Dietary supplement and food ingredient
Chlorella vulgaris	Micro	Alien	Yes	High in protein	Protein supplement
Tetraselmis chuii	Micro	Native	Yes	High protein content, source of omega 3 and 6 fatty acids, and pigments; rich in vitamins such as A, B1, B2, B6, C, E)	Food, flavour
Saccharina latissima (Sugar Kelp)	Macro	Native	Yes	Contains high amounts of mineral elements including sodium, magnesium, potassium, chlorine, sulphur and phosphorus; and micronutrients (e.g., iodine, zinc, copper, selenium, molybdenum)	Food and feed (products)
Alaria esculenta (Winged Kelp)	Macro	Native	Yes	High in protein, sugar, vitamins and minerals and contains and antioxidant/anti-inflammatory elements	Food products, supplement, ingredients
Ulva (Sea Lettuce)	Macro	Native	Yes	High in vitamins and minerals and contains proteins and antioxidant/anti-inflammatory elements	Food products, supplement, ingredients

Source: CBI. (2023) ([1])

The microalgae included in this study are typically sold as dried algae (e.g., in powder form or as tablets) or as specialty products isolated and extracted from the algae for use as food additives (e.g., astaxanthin, beta-carotene, phycocyanin). The macroalgae in scope are generally sold in various forms – primarily dried, occasionally fresh, frozen (particularly in the case of *Ulva*), or as

([1]) CBI. (2023). The European market potential for chlorella and spirulina for health products

processed products or supplements. In addition, these algae can also be used for industrial applications.

LCA Selection

This subtask aims to compare six algae species in terms of their environmental impact. The primary sources of information are peer-reviewed LCAs or LCAs funded through EU research and innovation programmes.

Limitations

Many of the research limitations are related to the use and comparison of LCAs. As outlined above, the algae species under consideration differ in their forms and intended uses. Moreover, the LCAs available have been conducted in varying contexts. Differences may include the **system boundaries** (i.e., which stages of a product's life cycle are included in the analysis), the **functional units** (i.e., the metric used to quantify the system's output or function), variations in **production scale and maturity** (e.g., more developed or established processes tend to be more efficient than newer ones or those involving species still in pilot or small-scale production), and the influence of **local context** (e.g., energy is often the primary driver of carbon emissions, depending on the local energy mix or conditions at a specific production site). These factors must also be considered when comparing algae-based protein sources with other (animal-derived) proteins.

Over time, the Global Warming Potential of a novel production system can decrease significantly as the system becomes more optimised. For example, GHG emissions reported in the Spirulina LCAs from the EU SPIRALG project declined by approximately 20% between two data collection points (2019 and 2022). This reduction was largely due to decreased use of nutrients and electricity during the cultivation and drying processes ([2]).

The nutritional value of food should also be taken into account – particularly when comparing micro- and macroalgae. This aspect is not incorporated into the comparison of GHG emissions using a mass-based approach. However, the nutritional profiles of different products can vary significantly, which is important to consider when evaluating their overall sustainability and suitability as protein sources.

The forthcoming #EU4Algae report O1.18 - *Verification Of Sustainable Microalgae & Seaweed Products with High Market Potential and Available Criteria & Tools Assessing Their Environmental Performance* highlights several key challenges. These include the lack of clear guidelines for conducting LCAs of seaweed value chains, the complexity and low Technology Readiness Levels

([2]) SPIRALG. (2023). Deliverable D5.2 - Life Cycle Assessment

(TRLs) of many algae production systems, and the seasonal variation in biomass. The report also emphasises the importance of considering the local context – though relevant data is often lacking ([3]).

Finally, while a substantial number of LCAs are publicly available for some well-established species (e.g., Spirulina, *Chlorella* sp.), there are few LCAs available for less-established algae species. This is particularly true for LCAs focused on algae-derived food products.

2.2. Comparison of costs and benefits to use of algae for human food

As mentioned earlier, the comparability of LCAs is essential to ensure the credibility of environmental impact measurements and estimations. Without such comparability, results can be misleading. To calculate GHG emissions per kilogram of protein produced, we mapped out the available LCAs and developed a structured database comprising the following elements:

- Goal
- Functional Unit
- System Boundaries
- Life Cycle Inventory
- Impact Assessment
- Interpretation
- Assumptions and Data Quality
- Geographical Scope
- Temporal Scope
- Life Cycle Stages Covered
- Global Warming Potential

Our analysis focuses on the Global Warming Potential (GWP) impact category – also referred to as climate change. GWP is expressed in kilograms of CO_2-equivalents (kg CO_2-eq) and provides a standardised method for assessing the

([3]) EU4Algae (2025). Verification of sustainable microalgae & seaweed products with high market potential and available criteria & tools assessing their environmental performance. Forthcoming - https://maritime-forum.ec.europa.eu/theme/blue-economy-and-fisheries/blue-economy/eu4algae_en

climate impact of GHG emissions. The different LCAs use various functional units. These methodological differences affect the comparability of the results. The most used functional units are either kilograms of algae in dry weight or kilograms in wet weight.

To standardise the findings, conversion factors were applied to studies that used wet weight as the functional unit, enabling results to be expressed in kg CO_2-equivalents per kg dry weight. Subsequently, in some cases, Global Warming Potentials (GWPs) were further converted to g CO_2-eq per kg of protein. These conversion factors were sourced from peer-reviewed literature. While such assumptions introduce a degree of uncertainty and may limit the comparability of LCAs, every effort was made to harmonise the results. For this study, however, we sought to align the findings as much as possible through by systematically considering each study's objective, functional unit, system boundaries, life cycle inventory data, impact assessment method, interpretation, assumptions and data quality, geographical scope, temporal scope, and the life cycle stages covered. Most of the LCAs used a cradle-to-gate approach, focusing on the production process up to the point at which the product is ready for sale.

Assessment of the 6 algae species

In addition to the six previously introduced algae species, we selected six other (non-algae) protein sources for comparison: beef (beef herd), beef (dairy herd), lamb and mutton, eggs, poultry meat, and peas ([4]). **Table 2** provides an overview of the CO_2eq. kg per kg protein produced for the six algae and six non-algae proteins. **Source**: **SpiralG** ()

Figure 1 provides a visual overview. The findings show that GHG per kilogram of protein produced vary significantly among different algae species. Compared to other protein sources, the cultivation and production of algae generally result in lower greenhouse gas emissions. However, this is not the case for *Tetraselmis chuii ([5])* – the species with the lowest market readiness – meaning its production processes are not yet as efficient as those of more established species.

([4]) Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. Science, 360(6392), 987-992.
([5])**Tetraselmis chuii**, a green microalga, is increasingly used in several high-value markets due to its rich nutritional profile (e.g., proteins, omega-3 fatty acids, antioxidants, and bioactive compounds)

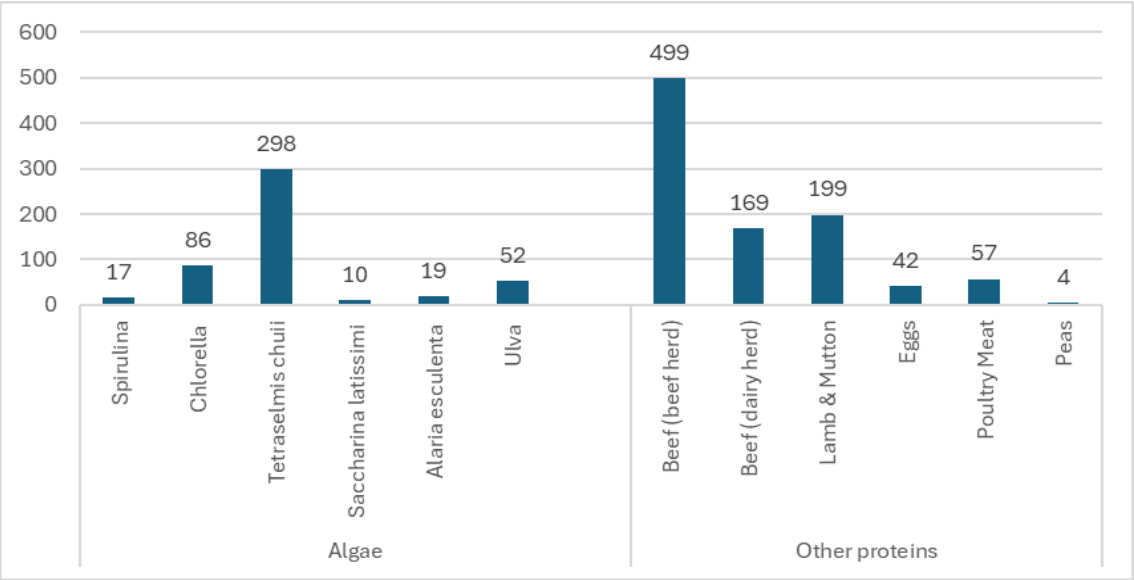
Table 2 – CO2eq. kg per kg protein produced

Protein	CO2eq. kg per kg protein produced
Algae	
A. platensis (Spirulina)	16.5 – 19.6
Chlorella vulgaris	86.0
Tetraselmis chuii	297.7
Saccharina latissima	10.0
Alaria esculenta	19.1
Ulva Rigida	52.0
Other proteins	
Beef (beef herd)	498.9
Beef (dairy herd)	168.7
Lamb & Mutton	198.5
Eggs	42.1
Poultry Meat	57.0
Peas	4.4

Source: SpiralG ([6])

([6]) A. platensis (Spirulina) - SpiralG Deliverable D5.2 Life Cycle Assessment; Chlorella vulgaris and Tetraselmis chuii - ProFuture D7.2-Report on Life Cycle Assessment and Life Cycle Costing and other ProFuture presentations; Saccharina latissima and Ulva Rigida - GENIALG Deliverable 5.5. and 5.6; Alaria esculenta - https://doi.org/10.1016/j.biortech.2021.126637

Figure 1 – Comparison CO2eq. kg per kg protein produced – Algae and other Proteins



Multi-Criteria Decision Matrix on the direct benefits and avoided costs of the production and consumption of six algae species

As previously mentioned in the section on study limitations, the LCAs provide a snapshot of current production processes. The comparison of these LCAs therefore implicitly reflects differences in the scale and maturity of production. As a result, the climate impact of certain algae production processes may appear less favourable – particularly when compared to other protein sources that are already produced on an industrial scale, whereas some algae are still produced at the pilot stage.

It is therefore important to consider additional factors relevant to the future production and consumption of the algae species under review. To this end, we developed a Multi-Criteria Decision Matrix, considering GHG reduction potential, current EU production levels, production costs, nutritional value, and consumer acceptance.

The assessment presented in the matrix is based on an extensive desk study of these aspects for the selected algae species. Each species is scored using a three-point scale: high (+++), medium (++), or low (+), with ‘high’ indicating a positive evaluation and ‘low’ indicating a negative one.

Table 3 – Multi-Criteria Decision Matrix

The direct benefits and avoided costs of the production and consumption of six algae species

Algae	GHG reduction potential	EU Production ([7])	Production Costs ([8];[9];[10])	Nutritional value / Relative protein content	Relative carbohydrate and mineral content	Relative consumer acceptance ([11])
A. platensis (Spirulina)	+++	+++	+++	+++	+	+++
Chlorella vulgaris	++	++	+	+++	+	+++
Tetraselmis chuii	+	+	+	+++	+	+
Saccharina latissimi	+++	+++	++	+	+++	++
Alaria esculenta	+++	+++	++	+	+++	++
Ulva Rigida	++	++	++	+	+++	++

Note: +++ refers to high, ++ refers to middle, + refers to low.

([7]) Vazquez Calderon, F. and Sanchez Lopez, J., (2022). An overview of the algae industry in Europe, Guillen Garcia, J. and Avraamides, M. editor(s), Publications Office of the European Union, Luxembourg, https://dx.doi.org/10.2760/813113.
([8]) van Duinen, R., Rivière, C., Strosser, P., Dijkstra, J. W. Rios, S., Luzzi, S., Bruhn, A., Olaf Nielsen, M. Göke, C., Bhagya Samarasinghe, M., Chassé, E., Heide Nielsen, C., Thomsen, M., Algae and Climate, Publication Office of the European Union, Available here.
([9]) According to Ciravegna et al. (2023), there is little consensus on the actual costs of seaweed production and yields, due to different studies reporting on different contexts (e.g., pilot-scale versus industrial-scale operations). Nevertheless, for this MCDA, the relative production costs extracted from different studies are used.
([10]) Ciravegna, E., Koch, S., & van den Burg, S. (2023). The business case for seaweed aquaculture in the North Sea: Learning from international experiences. Wageningen Economic Research. https://doi.org/10.18174/585349
([11]) Mendes, M. C., Navalho, S., Ferreira, A., et al. (2022). Algae as Food in Europe: An Overview of Species Diversity and Their Application. *Foods*, *11*(13), 1871. https://doi.org/10.3390/foods11131871

3. Data on algae consumption

3.1. Introduction

The objective of this sub-task is to gain insight into the intensity of algae consumption in both EU and non-EU countries.

The methodology for this task consisted of three main steps:

1. An extensive literature review.
2. A survey to collect additional data, targeting a broad range of EU stakeholders with knowledge of the algae sector.
3. Expert review and selected interviews.

3.2. Methodology

Due to limited data on algae consumption intensity, we applied three complementary approaches to estimate it: a bottom-up method based on consumer data; a top-down method using producer data on algae content in food products and their consumption levels; and a comparative analysis between Europe and Asia. However, data remain unavailable for many European countries, limiting the completeness of the analysis.

3.3. Literature and interview findings on algae consumption

In many Asian countries, algae consumption has long been an integral part of the culinary tradition. This is not the case in most other regions, including much of Europe. In recent years, the dynamic and fast-growing global seaweed market has attracted increasing attention, driven by rising demand for healthier, eco-friendly foods and the growing popularity of Asian cuisine. Nonetheless, **the European algae industry remains relatively overlooked and limited** ([12]).

The **European algae production represents only 0.8% of global production**, with around 287,390 tons per year ([13]). However, with the global algae market

([12]) Mendes et al. (2022). Algae as Food in Europe: An Overview of Species Diversity and Their Application. Foods, 11(13), 1871 https://www.mdpi.com/2304-8158/11/13/1871
([13]) Kuech, A., Breuer, M., Popescu, I. (2023). The future of the EU algae sector - Research for PECH Committee, European Parliament. Available here.

projected to grow significantly – potentially reaching €9.3 billion by 2030 – Europe's share of this market holds considerable potential for expansion. In the high-ambition scenario, European demand for seaweed-based products is expected to reach between €3.0 and €9.3 billion by 2030. This includes not only food, but also non-food applications such as feed, cosmetics, pharmaceuticals, biofertilisers, and other industrial uses.

Both macroalgae and microalgae offer a wide range of applications. For centuries, algae have been used as food, fertiliser, and animal fodder, as well as for the extraction of bioactive compounds. More recently, they have gained prominence in the production of cosmetics and animal feed. Another widespread, though less well-known, use is the extraction of phycocolloids – valuable compounds employed in the food, pharmaceutical, wine, and textile industries due to their gelling, stabilising, and thickening properties. In addition, algae are attracting interest in the development of innovative biosorbent materials ([14]).

Nevertheless, the focus of this section is on the **consumption of algae as food**, rather than on their non-food industrial applications.

([14]) Fernandez et al. (2023). Fundamentals in applications of algae biomass: A review. Journal of Environmental Management, 338, 117830. https://doi.org/10.1016/j.jenvman.2023.117830

Table 4 – Applications of algae for human consumption

Category	Description	Examples
Food ingredient	Algae are used directly in food products to enhance their nutritional value, texture, and flavour	• Seaweed extract powder • Blue spirulina extract • Microalgae protein powder • Seaweed flavouring
Food supplements	Algae provide essential nutrients a bioactive compound	• Spirulina and *chlorella* as vitamins • Omega-3 fatty acids (EPA & DHA), extracted from microalgae • Astaxanthin (*Haematococcus pluvialis*) • Fucoxanthin (Brown Seaweed)
Whole algae for cooking	Macroalgae used as a culinary ingredient	• Nori (*pyropia*) • Wakame (*Undaria pinnatifida*) • Kombu (*Saccharina japonica*) • Dulse (*palmaria palmata*) • Sea grapes (*caulerpa lentillifera*)
Food additives	Algae-based compounds used in food processing for their functional properties	• Agar-agar (red algae extract) • Carrageean (from red algae) • Alginate (from brown algae)

Source: European Algae Biomass Association (2024) ([15])

Quantitative findings on EU consumption

European algae production is predominantly based on wild harvesting, which accounts for approximately 99% of total output, with only a small share coming from cultivation. The sector is dominated by Norway, producing around 160,000 tonnes per year (61% of all European production), followed by France (50,000 tonnes) and Ireland (30,000 tonnes) ([16]). A 2021 study indicates that **seaweed**

([15]) European Algae Biomass Association (2024). Algae for food. Yum Algae.
([16]) Centre d'Étude et de Valorisation des Algues (2024). Report of the current algae industry in Europe. Zenodo. https://doi.org/10.5281/zenodo.13375431

production in Europe is primarily directed at food (34-36%) and food-related applications (15%), such as supplements ([17]).

Moreover, a report conducted by the European Commission's Knowledge Centre for the Bioeconomy found that the food sector is the main market for macroalgae-supplying enterprises (accounting for nearly 34%) and for microalgae enterprises (23%). The study is based on a dataset containing socio-economic data on the algae industry. However, the report acknowledges that the dataset does not offer a comprehensive view of the European algae sector, and that knowledge gaps remain ([18]).

The European algae sector comprises 225 producing companies, of which 67% focus on macroalgae and 33% on microalgae. In addition, 222 Spirulina producers were identified, 15% of which are also classified as microalgae producers and included in that total. These producers are spread across 23 countries ([19]).

France, Ireland, Norway, and Spain lead in terms of average turnover generated by algae companies in Europe, with annual averages of €76,000, €40,000, €17,000, and €14,000 respectively. The majority of sales stem from macroalgae (68%), followed by microalgae (17%) and Spirulina (11%). While Europe accounts for a relatively small share of global algae production, it hosts the highest number of seaweed start-ups and equity investments ([20]).

Data on European algae consumption is fragmented, incomplete, and generally of low quality, which hinders robust analysis of the sector. This is recognised as a limiting factor in evaluating the full potential of the algae industry in Europe ([21]). Nonetheless, it is estimated that European algae consumption is significantly lower – less than 50% – compared to that in many Asian countries, where average daily seaweed intake among adults ranges from 4 to 8.5 grams ([22]).

([17]) Naylor et al. (2021). A 20-year retrospective review of global aquaculture. Nature 591, 551–563 https://doi.org/10.1038/s41586-021-03308-6
([18]) European Commission: Joint Research Centre, Vazquez, Lopez. (2022). An overview of the algae industry in Europe – Producers, production systems, species, biomass uses, other steps in the value chain and socio-economic data, Publications Office of the European Union. https://data.europa.eu/doi/10.2760/813113
([19]) Araújo et al. (2021). Current Status of the Algae Production Industry in Europe: An Emerging Sector of the Blue Bioeconomy. Front. Mar. Sci. 7:626389. https://doi.org/10.3389/fmars.2020.626389
([20]) Kuech et al. (2023). Research for PECH Committee – The future of the EU algae sector, European Parliament, Policy Department for Structural and Cohesion Policies, Brussels. Available here.
([21]) Vigani et al. (2015). Food and feed products from micro-algae: Market opportunities and challenges for the EU. Trends in Food Science & Technology, 41,1,81-92 https://www.sciencedirect.com/science/article/pii/S092422441400278
([22]) Mendes et al. (2022). Algae as Food in Europe: An Overview of Species Diversity and Their Application. Foods, 11(13), 1871. https://doi.org/10.3390/foods11131871

Recent surveys have been conducted to assess the consumption behaviours of the European population regarding algae-based products. One survey, carried out among the French population, found that average seaweed consumption through food was approximately 293 mg per day. However, the authors noted that the sample used was not representative of the entire population and may have included a higher proportion of regular seaweed consumers than is typical for the general public ([23]).

Another survey, conducted in the Netherlands, revealed that around one-quarter of respondents had consumed algae-based products at least once in the four weeks prior to the survey. The median daily intake was estimated to be approximately 0.5 grams of dried seaweed per person ([24]).

A survey was also conducted during the first EU Algae Awareness Summit, organised by EU4Algae, which took place in Paris in October 2023. The survey included 93 participants, one-third of whom reported that they would be “very likely” to try new algae-based products in the future. The survey covered all types of algae-based products, not just food; however, most respondents indicated that food products were the algae application they were most interested in trying.

It is important to note, however, that the definition of an “algae-based product” can be ambiguous, as it is not always clear what percentage or form of algae a product must contain to qualify as such. For this reason, the results may be skewed, and it is more accurate to refer to “algae-containing products” instead ([25]).

Analysing import and export data can provide useful insights into algae consumption trends in Europe. The volume of imported seaweeds and other algae fit for human consumption (SAFFHC) decreased from 12,400 tonnes in the 2014-2016 triennium to 8,211 tonnes in 2020-2022, indicating a downward trend. Conversely, exports rose from 3,854 tonnes in 2014-2016 to 3,612 tonnes in 2017-2019, and then to 8,088 tonnes in 2020-2022, showing a clear upward trajectory. However, it remains unclear whether these trends reflect a decline in domestic consumption or whether local production is increasingly meeting internal demand ([26]).

It is worth noting that algae consumption has been the subject of research in Europe for several decades. Nevertheless, this research did not translate into commercial uptake until the introduction of Regulation (EC) No. 258/97 of the

([23]) Ficheux et al. (2022) Seaweed consumption in France: Key data for exposure and risk assessment. Food Chem. Toxicol. 159:112757. https://doi.org/10.1016/j.fct.2021.112757
([24]) Dinnisen et al. (2021). Zeewierconsumptie in Nederland (RIVM-rapport 2020-0195). Rijksinstituut voor Volksgezondheid en Milieu (RIVM). https://doi.org/10.21945/RIVM-2020-0195
([25]) EU4Algae. (2025). Verification of sustainable microalgae & seaweed products with high market potential and available criteria & tools assessing their environmental performance. Forthcoming - https://maritime-forum.ec.europa.eu/theme/blue-economy-and-fisheries/blue-economy/eu4algae_en
([26]) Zarbà et al. (2024). The trade of algae consumption: The common market competitiveness and impacts on the European Union legislation. Journal of Agriculture and Food Research, 18, 101407. https://doi.org/10.1016/j.jafr.2024.101407

European Parliament and of the Council of 27 January 1997, concerning novel foods and novel food ingredients. This highlights the regulatory framework as a key barrier to the growth of the European algae industry. In fact, as of 2022, only around 20% of the more than 150 algae species historically consumed in Europe have been approved for market use under the current novel food legislation, creating a significant regulatory bottleneck ([27]).

Additionally, national authorities in Member States – such as the Netherlands Food and Consumer Product Safety Authority (NVWA) – have increasingly focused on monitoring iodine content and the presence of heavy metals in algae products. This has negatively influenced public perception, further deterring the growth of algae consumption in Europe ([28]).

Overall, the **European regulatory landscape concerning algae consumption remains relatively new**. While the production and use of algae often fall under broader agricultural and food regulations, these frameworks are typically sector-specific and do not address algae explicitly. Furthermore, regulation is frequently not harmonised at the EU level and varies considerably between Member States. This lack of alignment creates limitations in the use of algae and results in regulatory "grey zones" that discourage companies from taking risks in the sector. Nonetheless, new regulations are gradually beginning to take algae consumption into account, helping to reduce uncertainty and offering a more supportive environment for industry development ([29]).

Challenges

Despite the long history of algae consumption and their numerous benefits – ranging from health and environmental advantages to culinary versatility – significant challenges remain that prevent the transition of algae from a niche product to a mainstream food source.

One of the main bottlenecks is the EU regulatory framework. Under the Novel Food legislation, only around 20% of algae species known to have been consumed are formally approved for market use ([30]). To support the mainstreaming of algae consumption, the Novel Food regulation should be updated to accommodate a broader range of algae species.

In addition, food safety regulations – such as those limiting iodine and heavy metal content in seaweed – continue to affect consumer trust. Experts and

([27]) Mendes et al. (2022). Algae as Food in Europe: An Overview of Species Diversity and Their Application. Foods, 11(13), 1871. https://doi.org/10.3390/foods11131871
([28]) Dinnisen et al. (2021). Zeewierconsumptie in Nederland (RIVM-rapport 2020-0195). Rijksinstituut voor Volksgezondheid en Milieu (RIVM). https://doi.org/10.21945/RIVM-2020-0195
([29]) Centre d'Étude et de Valorisation des Algues. (2024). Report of the current algae industry in Europe. Zenodo. https://doi.org/10.5281/zenodo.13375431
([30]) Mendes et al. (2022). Algae as Food in Europe: An Overview of Species Diversity and Their Application. Foods, 11(13), 1871 https://doi.org/10.3390/foods11131871

producers interviewed agree that while such rules are essential, many are outdated. These regulations should be transparent and grounded in the latest scientific evidence to build consumer confidence in algae-based products (see also section on trends and drivers).

Table 5 – Applications of algae for human consumption

Challenge	Description
Production constraints	• Scale-up system • Contaminants
High costs	• Capital and operational costs at upstream and downstream production process
Environmental concerns	• Resource demand (energy, water, and fertiliser) • Not yet a priority for consumers
Health safety	• Algae toxicity • Contaminants (nonbiological and biological)
Legality	• Legal approval for consumption and commercialisation
Consumer's perception	• Colour, odour, flavour, and texture

Source: Mendes et al. (2022) ([31]).

In most cases, algae-based products represent less than 5% of the food market, largely due to consumer perceptions. The taste, texture, and appearance of algae can create uncertainty and hesitation, reducing consumers' willingness to try or regularly consume such products ([32]).

A survey conducted during the EU Algae Awareness Summit in October 2023 asked participants why they are deterred from purchasing algae-based products. Most respondents stated that **lack of availability and knowledge** are the main reasons for not purchasing these products ([33]).

Studies conducted on French consumers identified four key barriers to algae consumption: a **general lack of knowledge** about how to use algae-based foods,

([31]) Mendes et al. (2022). Algae as Food in Europe: An Overview of Species Diversity and Their Application. Foods, 11(13), 1871. https://doi.org/10.3390/foods11131871
([32]) Boukid and Castellari (2022) Algae as Nutritional and Functional Food Sources. Foods, 12(1), 122. https://doi.org/10.3390/foods12010122
([33]) EU4Algae (2025). Verification of sustainable microalgae & seaweed products with high market potential and available criteria & tools assessing their environmental performance. Forthcoming - https://maritime-forum.ec.europa.eu/theme/blue-economy-and-fisheries/blue-economy/eu4algae_en

limited availability in physical stores, **unappealing taste and image**, and **overall sense of apprehension**.

Overall, there is clear evidence of a lack of awareness and accessibility regarding algae, and socio-demographic factors appear to influence the level of knowledge and attitudes towards algae-based products. For example, survey results show that Spanish consumers often cite environmental benefits as a key reason for consuming microalgae. In contrast, Belgian consumers do not view the eco-friendly aspect as a strong incentive for algae consumption.

Studies have also identified target audiences with a higher propensity to consume algae-based foods, based on psychographic factors. These groups include individuals who participate in sports, as well as vegetarians, vegans, and food enthusiasts ("foodies"), who tend to be more open to innovative and health-conscious dietary choices ([34]).

Another challenge to the growth of the algae market in Europe is the **high production cost,** which is currently estimated at around €5 per kilogram. In a best-case scenario, this cost could decrease to approximately €0.50 per kilogram within the next decade. However, achieving such a reduction is only feasible if research and development efforts are significantly intensified ([35]).

Trends and Drivers

In recent years, commercial interest in algae-based products has grown significantly. As a result, this category of food and drink has gained increasing representation in European retail markets. Notably, in 2018, algae-based meat substitute products – such as algae burgers and grills – accounted for €1.82 million in sales across Europe. This positive trend can be attributed not only to recent advances in algae-related technologies, but also to the growing mainstream popularity of Asian cuisines across Europe and the expansion of seaweed harvesting in countries such as France, Ireland, and others ([36], [37]).

Public interest in algae consumption is increasing, but remains inconsistent, as highlighted in stakeholder interviews. While start-ups have introduced novel algae-based products to the market – often enjoying brief periods of popularity – these products frequently disappear just as quickly. Stakeholders report that major retailers and corporations, such as Unilever, have shown interest but have yet to fully commit. *Nori* remains a notable exception in terms of popularity;

([34]) Mendes et al. (2022). Algae as Food in Europe: An Overview of Species Diversity and Their Application. Foods, 11(13), 1871. https://doi.org/10.3390/foods11131871.
([35]) Boukid, F., & Castellari, M. (2022). Algae as Nutritional and Functional Food Sources. Foods, 12(1), 122. https://doi.org/10.3390/foods12010122
([36])Mendes et al. (2022). Algae as Food in Europe: An Overview of Species Diversity and Their Application. Foods, 11(13), 1871 https://doi.org/10.3390/foods11131871.
([37]) Centre d'Étude et de Valorisation des Algues. (2024). Report of the current algae industry in Europe. Zenodo. https://doi.org/10.5281/zenodo.13375431.

although it is not produced within the EU, its long shelf life and light weight make it easy and cost-effective to import.

In recent years, growing concerns around food safety have shifted public and commercial focus away from sustainability and local sourcing. According to stakeholder consultations, significant barriers to market entry persist, as many algae species have yet to receive approval as novel foods. As a result, many start-ups and companies pivot towards non-food applications instead. Nevertheless, even small-scale weekly consumption of seaweed by European consumers could meaningfully stimulate sector growth.

This encouraging trend is reflected in the latest (2024) Eurobarometer survey on EU consumer habits regarding fishery and aquaculture products. Conducted for the fourth time since 2016, the 2024 edition is the first to include questions on algae consumption. Of the 26,510 respondents, two-thirds reported consuming algae products in the past year – primarily in the form of sushi (41%), followed by salads (20%), dietary supplements (18%), and snacks (18%). However, 22% indicated they had never tried algae products. Taste was the most frequently cited reason for consumption (47%), followed by perceived health benefits (35%). Other motivations included habit (23%), interest in new products (22%), availability (19%), ease of preparation (17%), and environmental benefits (15%) ([38]).

An important driver is the **sustainable label** that is attributed to algae. As a matter of fact, algae can be used as a source of plant-based protein, and their cultivation requires less land and water then terrestrial crops. This has contributed to an increase in funding for algae-related research within the EU. The algae sector is slowly moving towards larger market, largely thanks to its eco-friendly image, and has now the opportunity to generate new jobs, new academic programmes and economic value ([39]).

The increase in research targeted to algae product is evident. Using the Scopus database (Elsevier's abstract and citation database), a search was performed from 1990 to 2022, selecting "algae and foods" as keywords; a total of 17,216 publications were obtained ([40]).

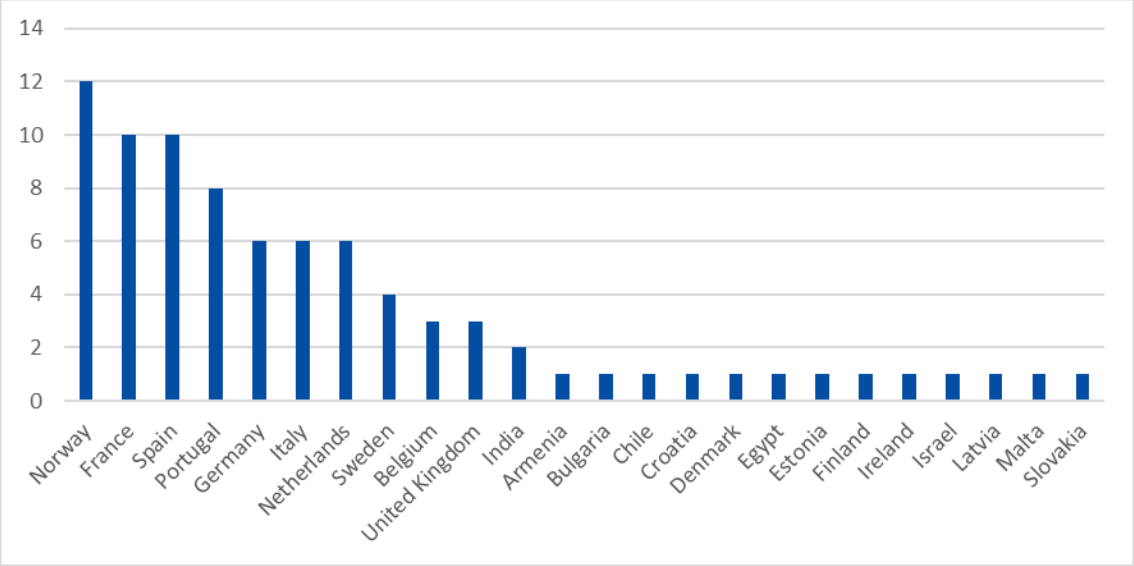
([38]) European Commission: Directorate-General for Maritime Affairs and Fisheries. (2025). EU consumer habits regarding fishery and aquaculture products – Eurobarometer report. https://data.europa.eu/doi/10.2771/5798498
([39]) Mendes et al. (2022). Algae as Food in Europe: An Overview of Species Diversity and Their Application. Foods, 11(13), 1871. https://doi.org/10.3390/foods11131871
([40]) Boukid, F. & Castellari, M. (2022). Algae as Nutritional and Functional Food Sources. Foods, 12(1), 122. https://doi.org/10.3390/foods12010122

3.4. Survey on algae consumption

The responses to the survey were collected over a two-month period, in February and March 2025.

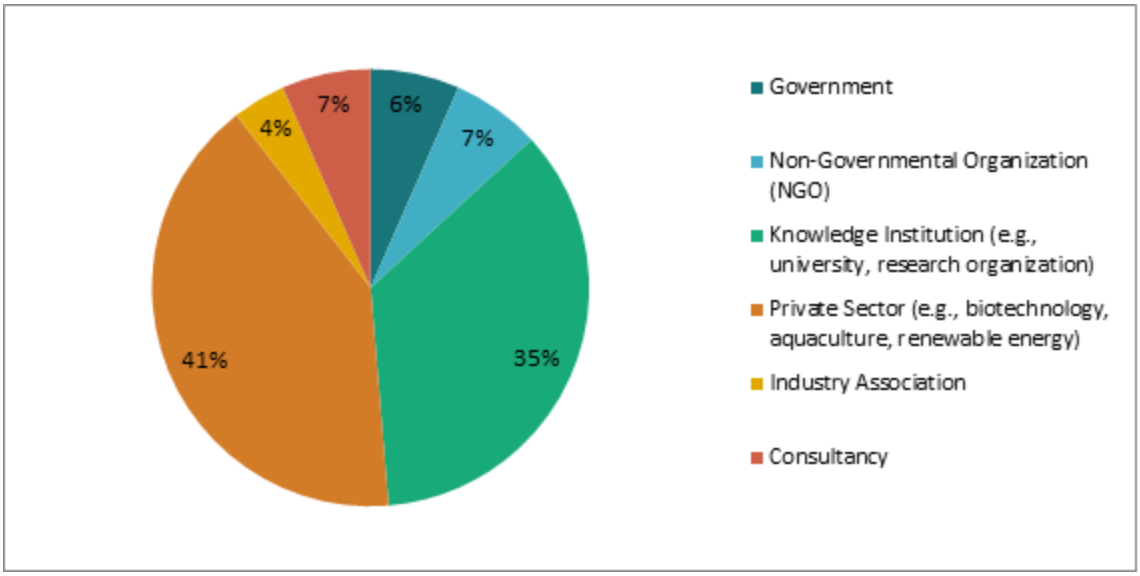
In total, the survey received 92 responses. However, only 56 were complete, resulting in a completion rate of 61%. We decided to include the incomplete responses to gather as much information as possible.

Question 1 – What is your country of residence?



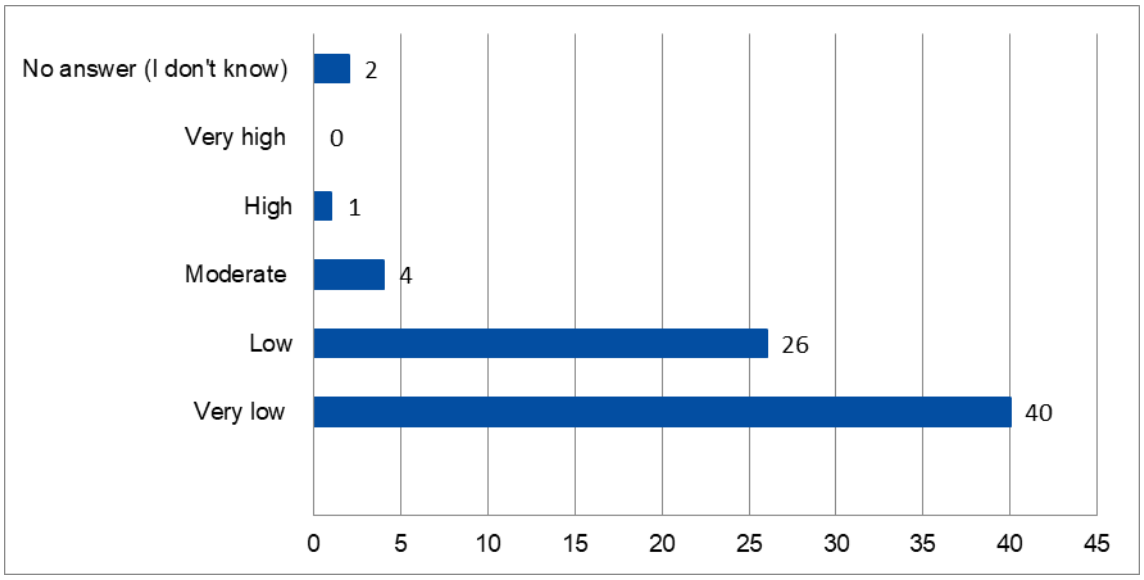
Note: n=83.

Question 2 – Which sector do you currently work in?



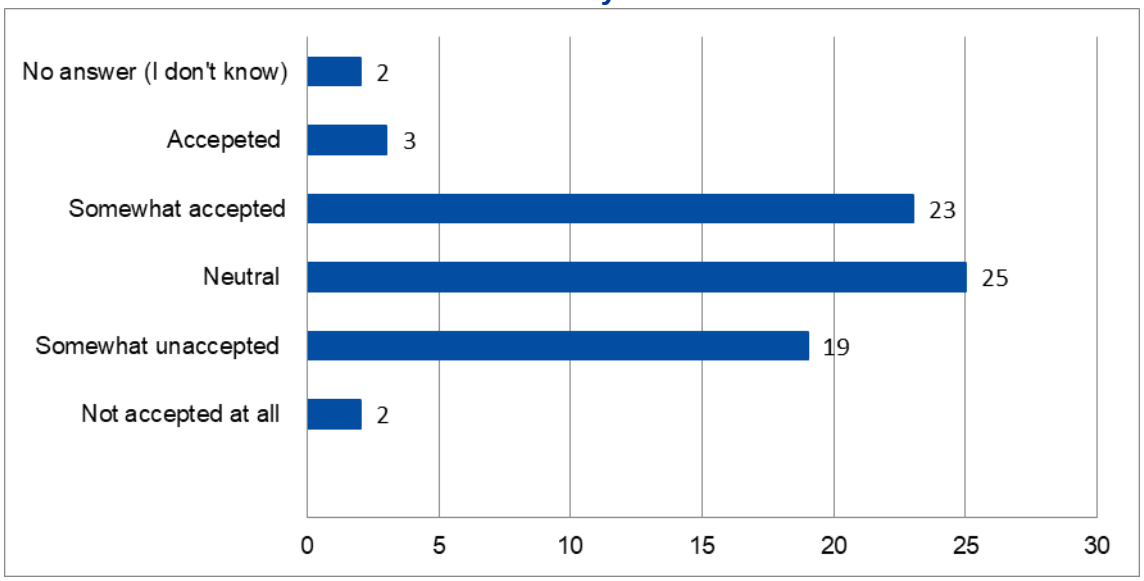
Note: n=76.

Question 3 – How would you describe the current level of algae consumption in your country?



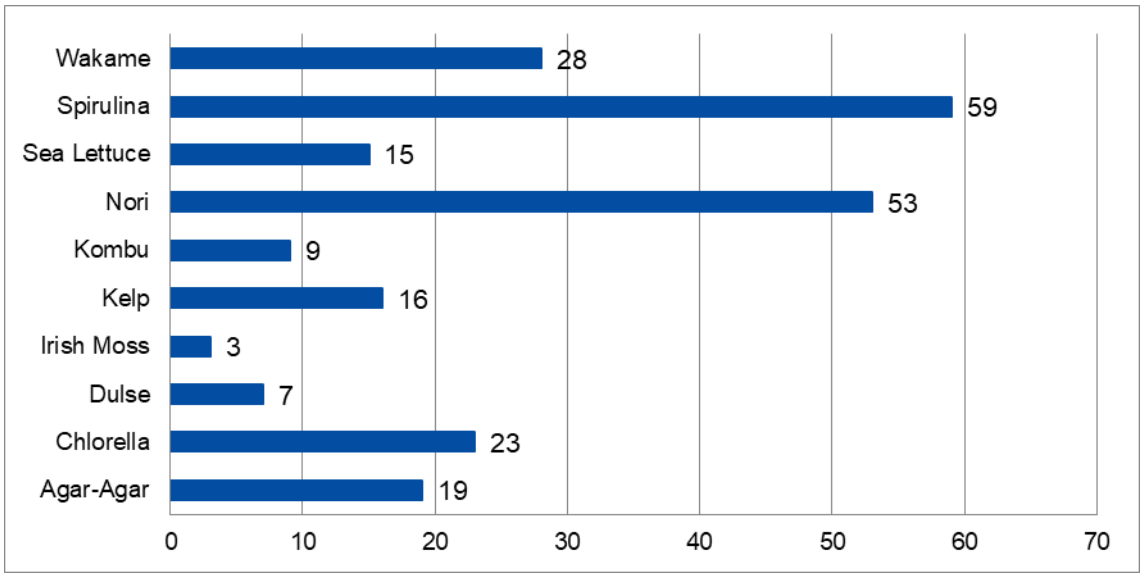
Note: n=73.

Question 4 – How culturally accepted is the consumption of algae in your country?



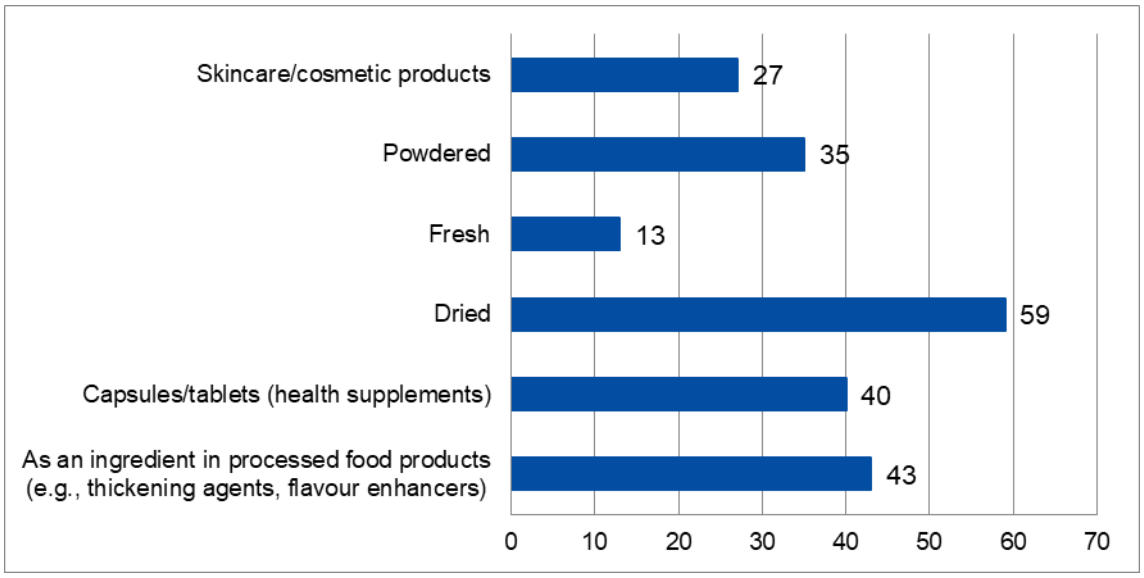
Note: n=74.

Question 5 – What types of algae are most commonly consumed in your country?



Note: n=75, multiple answers possible. Respondents were asked to select all that apply.

Question 6 – In what forms is algae commonly consumed?



Note: n=75, multiple answers possible. Respondents were asked to select all that apply.

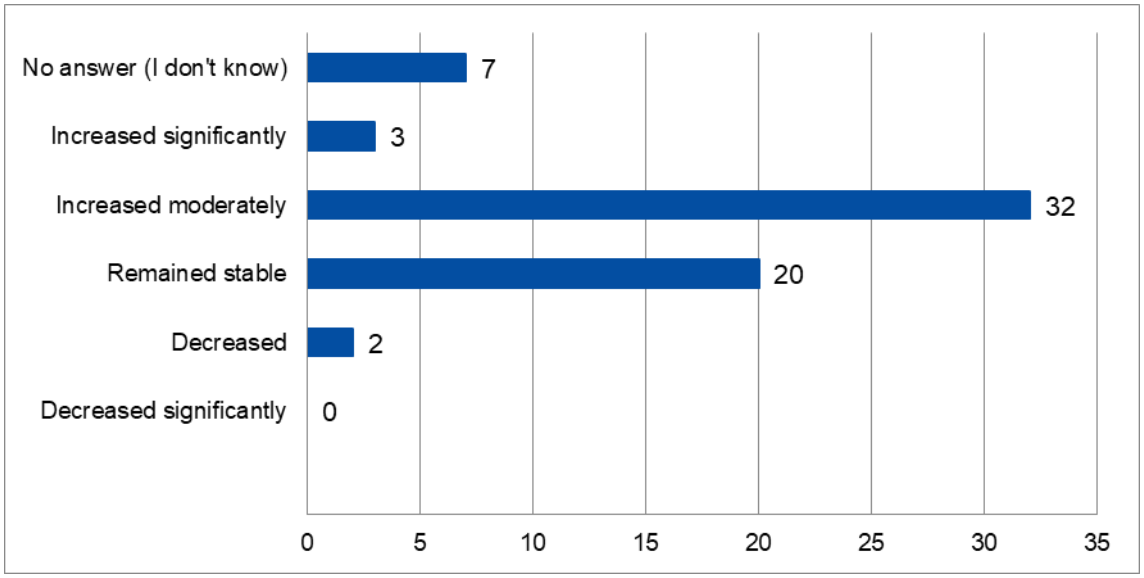
Question 7: Could you give an estimate of the per capita algae consumption in your country?

In total, 36 participants responded to question 7, of whom many (around 15) were unable to provide an estimate.

Most respondents agreed that algae consumption in their country is significantly low. Based on the responses, it appears that algae consumption in the EU generally remains below 1 kg per capita per year. In some countries – particularly

those where algae are not harvested and recent culinary trends are less widespread – consumption stays below 0.5 kg per capita per year.

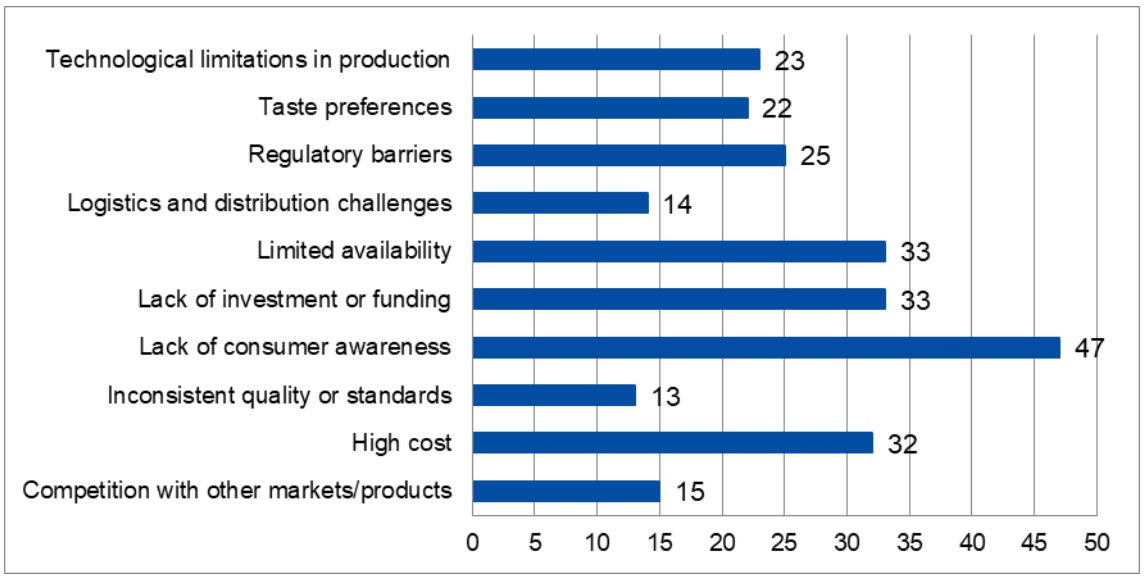
Question 8 – Market Trends: How has the algae market for consumption in your country changed over the past five years?



Note: n=64. Respondents were asked to elaborate in a text box.

18 out of the 64 respondents added a comment. Most participants agreed that algae consumption is on the rise. While some consumers are drawn to sustainable and healthy products, their interest does not always extend to direct consumption of seaweed-based items. The growing popularity of Asian cuisine – where algae is commonly used – also contributes to this trend. However, the strong association of algae with eastern traditions can deter certain consumers who are sceptical of products sourced from Asia.

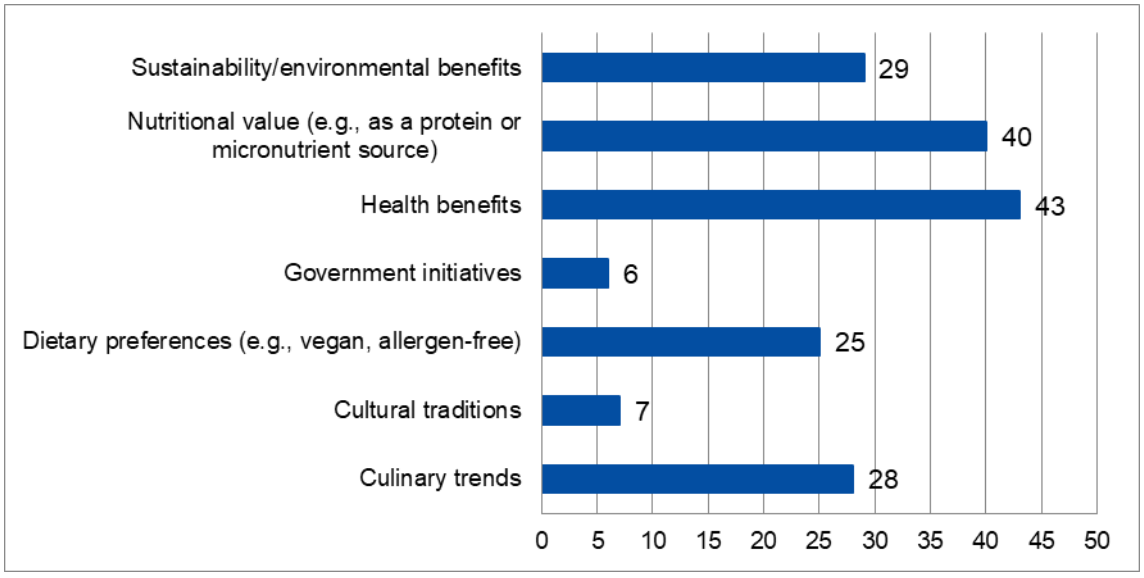
Question 9 – What are the main challenges facing the algae market in your country?



Note: n=68, multiple answers possible. Respondents were asked to select all that apply.

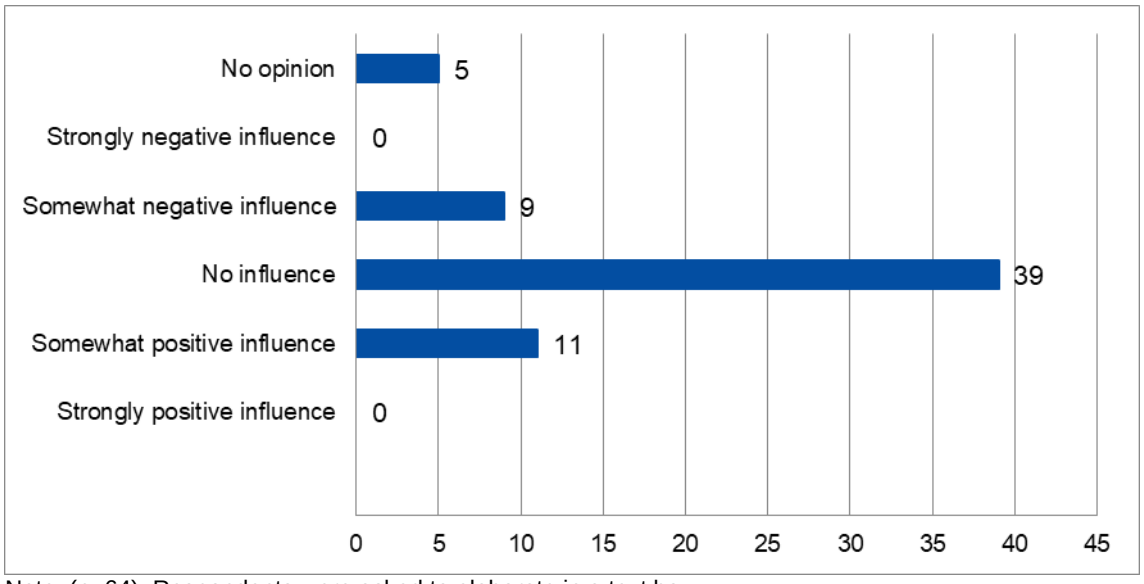
Three respondents selected "other" when answering this question. One cited low overall demand as the main challenge facing the algae market. Another pointed to issues within the value chain as the key barrier. The third respondent emphasized the need for stronger consumer engagement, arguing that progress in the sector cannot rely solely on research and technological investment but must also focus on stimulating consumer interest and demand.

Question 10 – What are the main factors (market drivers) driving algae consumption in your country?



Note: n=68, multiple answers possible. Respondents were asked to select all that apply.

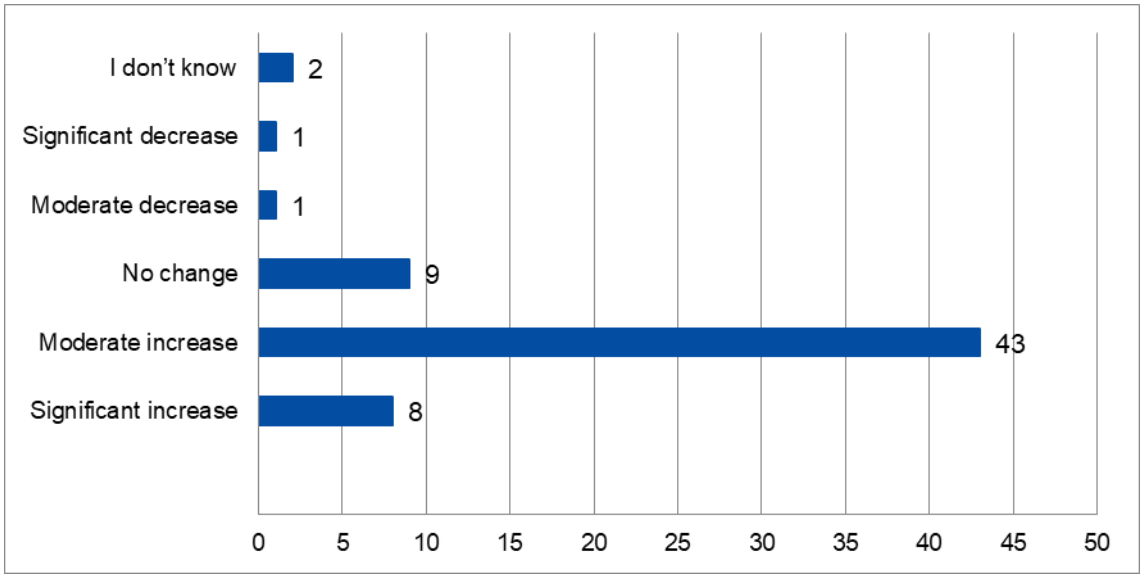
Question 11 – How do current policies influence algae consumption in your country?



Note: (n=64). Respondents were asked to elaborate in a text box.

15 respondents elaborated on the matter, and the responses were quite diverse. Some participants feel that policies act as a deterrent to algae consumption rather than a driver, as they focus more on production and not on encouraging consumers. Moreover, regulatory barriers and the extensive food safety research cause consumers to lose trust in algae products. On the other hand, some believe that policies have positively influenced interest in healthy and sustainable foods, creating a favourable environment for the algae market to flourish.

Question 12 – How do you think algae consumption will change in your country over the next five years? Please elaborate in the text box.



Note: n=64. Respondents were asked to elaborate in a text box.

18 participants shared their views on this topic. Overall, most believe that algae consumption will rise in the near future. They expect consumer interest to grow,

especially due to trends in health foods, sustainable alternatives, and the popularity of eastern cuisine. Some also stressed the need for better technologies to help lower the cost of producing algae-based products.

Question 13 – What (policy/market) opportunities do you see for increasing algae consumption in your country?

With a sample size of 35, the most common response was the need to boost consumer awareness. Respondents suggested advertising campaigns that promote the health and environmental benefits of algae. Many also recommended incorporating algae into existing products and improving the flavour of algae-based foods. Other key points included simplifying regulatory hurdles, expanding the list of approved algae species, investing in local producers, and taxing imports to support the EU internal market.

Question 14: What challenges do you see for increasing algae consumption in your country?

Most respondents (sample size of 36) mentioned high costs, cultural challenges, consumer awareness, consumer acceptance, regulatory barriers, and lack of knowledge as the main challenges. Additionally, they discussed the limited availability of high-quality algae-based products and the absence of effective positive marketing initiatives. Finally, some respondents raised health-related concerns, such as the high levels of iodine and the presence of toxins.

Question 15: What recommendations would you give to stakeholders and/or policymakers looking to promote algae consumption in your country?

Many respondents (sample size of 35) agreed that stakeholders and policymakers should invest in R&D and biotech innovation and provide financial support for algae farmers and start-ups. Moreover, they emphasised that regulation should be simplified, and awareness increased through marketing, education, and influencer engagement. Finally, participants highlighted the importance of cross-sector cooperation within agriculture and the need for incentives to support local production.

3.5. Comparison with other regions of the world

Seaweed and algae-based products have been used for centuries in Asian countries and are a common ingredient in traditional cuisine. **Algae consumption is significant in Korea, Japan, China**, and the northeastern islands, where land for conventional agriculture is difficult to utilise.

While historical evidence suggests that algae have been consumed in Europe for a long time, they are not part of traditional cuisine and are not as culturally

embedded as they are in Asian countries. Interestingly, per capita yearly consumption in Japan is around 2 kg, which is comparable to salad consumption in Europe. Therefore, compared to the Asian market, the European algae market is still relatively niche ([41]).

Consumer preferences regarding Asian versus European seaweed products remain unclear ([42]). Nonetheless, the gap is narrowing as European retailers begin to stock a broader range of seaweed-based products and as culinary traditions increasingly incorporate algae into meals ([43]).

([41]) Mendes et al. (2022). Algae as Food in Europe: An Overview of Species Diversity and Their Application. Foods, 11(13), 1871 https://doi.org/10.3390/foods11131871
([42]) EU4Algae. (2025). Verification of sustainable microalgae & seaweed products with high market potential and available criteria & tools assessing their environmental performance. Forthcoming - https://maritime-forum.ec.europa.eu/theme/blue-economy-and-fisheries/blue-economy/eu4algae_en
([43]) Rioux et al. (2017) Seaweeds: A traditional ingredient for new gastronomic sensation. Food Hydrocolloids, 68, 255–265. https://doi.org/10.1016/j.foodhyd.2017.02.005

Table 6 – Europe vs. top three countries for algae consumption

Based on yearly per capita consumption

Country	Yearly per capita consumption (dry)	History and trends
European countries	< 50% of the average consumption in Asia (below 1 kg per capita, per year)	• Demand for seaweed products is growing at around 7-10% per year. • 44 different genera of algae can be used as food in Europe. • Compared to other countries, European algae production places greater emphasis on eco-friendliness ([44]).
Japan	2 kg	• Around 21% of traditional Japanese dishes include algae. • Around 21 seaweed species are used in everyday cooking. • Consumption is decreasing notably among younger generations, who are shifting towards Western-style diets.
China	1.2 kg	• The Chinese diet includes 74 species of edible algae. • Seaweed is usually consumed cooked.
South Korea	2.1 kg	• Similar algae consumption habits and cultural heritage to those of Japan.

Source: Centre d'Étude et de Valorisation des Algues (2024) ([45]).

([44]) EU4Algae. (2025). Verification of sustainable microalgae & seaweed products with high market potential and available criteria & tools assessing their environmental performance. Forthcoming - https://maritime-forum.ec.europa.eu/theme/blue-economy-and-fisheries/blue-economy/eu4algae_en

([45]) Centre d'Étude et de Valorisation des Algues. (2024). Report of the current algae industry in Europe. Zenodo.

4. Potential of algae to reduce methane emissions

The goal of the section on algae use in livestock for methane emission mitigation is threefold:

1. To understand the **cultivation potential** and suitable areas for *Asparagopsis* in relevant EU maritime regions;
2. To provide an overview of the impacts of incorporating different amounts of *Asparagopsis* **into livestock diets**; and
3. To identify **future research needs** to support the introduction of algae-based ingredients into livestock feed.

Methane (CH_4) is the second most impactful greenhouse gas after CO_2, with a global warming potential 28 times greater than that of CO_2 over a 100-year period. **Livestock farming** – particularly ruminant animals **– is responsible for approximately 24% of global methane emissions**. Cattle and dairy cows alone accounted for 72% of total livestock sector emissions in 2020 ([46]). Furthermore, global demand for animal protein is expected to rise by 68% by 2050, which would further exacerbate emissions. If no action is taken, methane emissions from livestock could increase by 30% by 2050. To align with the Paris Agreement targets and ensure the long-term sustainability of animal by-products (such as red meat, dairy, and wool), methane emissions from animal production must be reduced by 24% to 47% by 2050 compared to 2010 levels ([47];[48]).

The challenge is clear – and so is the opportunity to innovate and implement sustainable solutions. To mitigate ruminant methanogenesis, a key microbial process, several strategies have emerged. These include improved farming practices, dietary modifications, feed additives, probiotics, immunisation against the rumen microbiome, and selective breeding. Among these strategies, the use of feed additives – particularly those that directly or indirectly inhibit methanogens – plays a significant role ([49]). Seaweeds are one such additive and have traditionally been included in livestock diets since the earliest records of agricultural practices. Research indicates that **algae, when used as a feedstuff**

([46]) FAO. FAOSTAT Database Collections. http://faostat.fao.org/
([47]) IPCC, & Masson-Delmotte et al. (2019) Global Warming of 1.5°C. An IPCC Special Report on the 1.5°C. Ans of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.
([48]) Arndt et al., (2022). Full adoption of the most effective strategies to mitigate methane emissions by ruminants can help meet the 1.5 °C target by 2030 but not 2050. *Proceedings of the National Academy of Sciences of the United States of America,* 119(20), e2111294119. https://doi.org/10.1073/pnas.2111294119
([49]) Rojas-Downing et al. (2017). Climate Change Impact on Livestock: Adaptation and Mitigation. *Climate Risk Management, 16*. https://doi.org/10.1016/j.crm.2017.02.001

or additive, can substantially reduce methane emissions, positioning them as a promising and sustainable nutritional alternative for cattle.

In an early-on fermentation experiment ***Asparagopsis*** ([50]) **emerged as the algae that most effectively suppressed methane production** when compared to nineteen other macroalgae ([51]). Moreover, an experiment in which *Asparagopsis* was added to steers' feed found a reduction in methane emissions of up to 98% and weight gain improvements of up to 53% ([52]). No negative effects were observed on daily feed intake, feed conversion efficiency, or rumen function, and no traces of bromoform ([53]) were detected in the tissue samples studied ([54]). These findings were reinforced by another study, which also found no bromoform residues in animal tissues, although bromoform was detected in excreted milk and urine. Further nuance was provided by research showing that bromoform is only detected when excessive amounts of *Asparagopsis* are administered to the animals ([55];[56]). Overall, over the past ten years, **researchers have examined the effects of *Asparagopsis* on methane production** in both in vitro and in vivo ruminant experiments, concluding that it is **highly effective as a methane mitigant for livestock** ([57];[58]).

([50]) *Asparagopsis taxiformis*, a red macroalgae species is often simply referred to as *Asparagopsis*. Macroalgae (seaweed) are aquatic plants harvested for commercial purposes (such for containing bioactive compounds).
([51]) Machado et al. (2014). Effects of marine and freshwater macroalgae on in vitro total gas and methane production. Initial studies by Paul et al. (2006) identified a unique cellular structure in *Asparagopsis* capable of retaining bioactive compounds like bromoform.
([52]) Recent studies have shown that the inclusion of microalgae can improve the growth performance of animals for both meat and milk production. The nutritional profiles of microalgae species are quite variable but are mainly characterized by protein (25–40%), fat (10–30%), and carbohydrate (5–30%) contents that are comparable, if not superior, to traditional feed ingredients like soybean meal, corn, and wheat.
([53]) Bromoform ($CHBr_3$) has been proven to be highly effective at inhibiting methanogenesis and is found within many seaweed species but in higher levels in the red seaweed *Asparagopsis taxiformis* (Machado et al., 2016a).
([54]) Kinley, R.D. et al. (2020). Mitigating the carbon footprint and improving productivity of ruminant livestock agriculture using a red seaweed. https://doi.org/10.1016/j.jclepro.2020.120836
([55]) Króliczewska et al., (2023). Strategies Used to Reduce Methane Emissions from Ruminants: Controversies and Issues. *Agriculture*. 13(3). https://doi.org/10.3390/agriculture13030602
([56]) E. Wasson et al., (2022). Enteric methane mitigation through *Asparagopsis* taxiformis supplementation and potential algal alternatives. *Front. Animal Sci.,* 3. https://doi.org/10.3389/fanim.2022.999338
([57]) Studies found that inclusion of *Asparagopsis* at certain levels resulted in a 99% reduction in methane without negatively affecting fermentation (Kinley et al., 2016).
([58]) In vivo studies with sheep began confirming these results in Li et al. (2018). Further validation in both in vitro and in vivo studies with lactating dairy cattle showed a 67% reduction in methane production (Roque et al., 2019). A study in Sweden (Chagas et al., 2019) identified *Asparagopsis* as the most effective methane inhibitor with minimal impact on rumen fermentation.

4.1. The cultivation potential and areas of *Asparagopsis* in relevant EU maritime regions

This growing interest has led to a rising global demand for seaweed. As a result, research is advancing rapidly to scale up *Asparagopsis* cultivation ([59]) and to develop aquaculture systems that ensure a high-quality and reliable supply chain. Alongside efforts to establish production strategies, it is also crucial to assess the potential benefits and risks of using *Asparagopsis* as a feed ingredient for ruminant livestock.

The potential of large-scale seaweed cultivation and its contribution to achieving ambitious sustainability objectives is widely recognised. However, the lack of information on the suitability of EU marine regions for the installation of macroalgae cultivation infrastructures hampers progress. One of the biggest challenges lies in gathering and harmonising data, as well as refining models to better reflect the ecological factors relevant to the species – such as water temperature, nutrient availability, ocean currents, and ecosystem compatibility – which requires considerable effort. Although only a few modelling assessments currently exist, they aim to identify the potential for cultivating various seaweed species across EU marine regions to determine the most suitable areas for growth. The EU Atlantic region appears to be particularly well-suited to farming cold- and intermediate-water species such as *Asparagopsis* ([60]). It possesses a diverse range of maritime regions that offer potential sites for cultivating *Asparagopsis* or other type of algae (see **APPENDIX A**, **APPENDIX B** and **APPENDIX C**).

The potentially suitable area for seaweed cultivation at sea is vast – **totalling over 1.5 million km² for intermediate species and over 1 million km² for cold water species mostly in the North-Western and South-Western European Seas (NWES and SWES)** ([61]). In contrast, the Mediterranean and Black Seas appear unsuitable for large-scale seaweed cultivation at sea. **The available cultivation area exceeds 1 million km²**, and even a conservative **estimate**

([59]) *Asparagopsis taxiformis* is native to tropical and subtropical regions and is considered invasive in European waters. In Europe, seaweed aquaculture is still in its early stages, with production remaining relatively low compared to Asia. This is largely due to challenges such as complex regulatory frameworks and concerns about the introduction of non-native species, which could disrupt local ecosystems.

([60]) Macias et al. (2025). Assessing the potential for seaweed cultivation in EU seas through an integrated modelling approach. *Aquaculture.* 594, https://doi.org/10.1016/j.aquaculture.2024.741353. This study employs the World Offshore Macro Algae Production Potential (WOMAPP) model, alongside advanced hydrodynamic–biogeochemical models, to assess the potential for seaweed cultivation across EU marine regions. Realising this potential requires careful consideration of several uncertainties, including the need for species-specific growth data, concerns about environmental impacts (such as competition with native species and broader ecological risks), and limitations in current biophysical modelling approaches.

([61]) NWES**:** North-Western European Seas, such as the North Sea and the English Channel. SWES**:** South-Western European Seas, including the Iberian Peninsula and the waters around Spain, Portugal, and parts of France.

suggests it could yield over 30 million tonnes annually. However, logistical constraints such as water depth and distance from the coast could limit production to 5 million tonnes per year.

The benefits of Integrated Multi-Trophic Aquaculture (IMTA) – a system where species from different trophic levels are farmed together in mutually beneficial ways – could help expand the areas suitable for cultivation ([62]). Nevertheless, significant challenges remain at the technological, legislative, and ecological levels. Further research on both IMTA and seaweed cultivation at sea should prioritise improving model resolution, forecasting climate change impacts, and addressing sustainability concerns ([63]).

In this context, understanding the potential economic incentives for livestock farmers to adopt *Asparagopsis* is key as these drivers will play a key role in determining the feasibility and uptake of algae-based feed additives within the European livestock sector.

Table 7 – Economic incentive of *Asparagopsis* for farmers

Incentive Type	Description	Source
Carbon credits & subsidies	Financial rewards or reduced taxes for reducing methane emissions	EU Green Deal
Grants and funding	Access to EU grants and co-funding for adoption of sustainable algae-based feed solutions	EU Algae Initiative
Market premiums	Ability to market “low-carbon” or “climate-friendly” products at higher prices	EU Farm to Fork Strategy
Regulatory compliance	Early adoption helps avoid future penalties and ensures continued market access under stricter EU regulations	EU Methane Strategy
Productivity improvements	Potential for improved feed efficiency and animal health, leading to economic gains	Research studies

To successfully integrate *Asparagopsis* – or other types of algae – into the European livestock industry, a **reliable supply chain is essential**. However,

([62]) For example, when fish, shellfish, and seaweed are combined in a system, the seaweed helps to absorb excess nutrients from fish farming, improves water quality, and provides an additional product.
([63]) Helping to simulate local oceanographic conditions more accurately (including currents, nutrient flows, and temperature) for optimising IMTA site selection and performance.

large-scale algae cultivation presents several **challenges**, including **political, economic, social, environmental, and legal** considerations (see **APPENDIX D**).

Expanding production through offshore farming or large-scale aquaculture is critical – particularly for *Asparagopsis*, which is not native to Europe and can only be cultivated on land, not in open sea environments.

Equally important is the ability to store and transport the algae efficiently while maintaining manageable costs and preserving its active compounds. Although some strategic policy initiatives (e.g., the European Green Deal and EU4Algae offer support, regulatory complexity and financial constraints remain major barriers, slowing progress in this area. Obtaining EU-wide regulatory approval for the use of *Asparagopsis* in livestock feed – and ensuring economic feasibility by keeping production costs competitive with other methane mitigation strategies – is a key step toward realising its full potential.

On the other hand, high cultivation costs, limited market awareness, and the lack of adapted infrastructures constrain scalability. Consumer resistance to marine-based feed additives highlights the need for public education campaigns to build trust. Additionally, the limited knowledge and scaling technologies for algae farming require further research and development.

From an environmental perspective, concerns about the ecological impact of algae production – particularly by-products such as bromoform – must be addressed through comprehensive environmental assessments. To overcome these barriers, solutions such as cost-reducing technologies, infrastructure improvements, and harmonised regulations are essential. Exploring alternatives to algae, such as land-based feed sources and other methane-reducing additives, could also provide viable options.

In addition to reducing carbon emissions, **large-scale seaweed farming could offer economic benefits** such as job creation and ocean-positive economic growth. However, **further research is needed** to ensure that seaweed farming is conducted **sustainably, balancing environmental protection with its economic advantages.** At the same time, the potential impact on local ecosystems and the disruption of natural cycles caused by seaweed farming must also be carefully analysed.

4.2. An overview of the impacts of adding different amounts of *Asparagopsis* into livestock diets

The literature review of the available data (see **APPENDIX E**, **APPENDIX F,** and **APPENDIX G**) demonstrated the effectiveness of using algae, specifically *Asparagopsis*, as a feed ingredient or additive for significantly reducing enteric methane emissions in ruminant livestock. Specifically, the review highlights

Asparagopsis' ability to reduce enteric emissions – particularly methane – as well as its potential impacts on animal health, welfare, and food safety, with particular attention to the risks associated with bromoform in *Asparagopsis* biomass**. *Asparagopsis* can reduce methane emissions by up to 50% at an inclusion rate of 0.2-0.5% of Dry Matter Intake (DMI)** ([64];[65];[66]). Feeding *Asparagopsis* to ruminants has proven highly effective in reducing methane emissions, with the added potential to improve feed efficiency and animal performance ([67]).

Table 8 – Methane reduction potential of *Asparagopsis*

Inclusion rate	DMI	Methane reduction potential
Low inclusion rates	0.2-0.5% of DMI	30-50%
Higher inclusion rates	around 1% DMI	80% or more

The reported benefits are substantial, but certain risks and uncertainties must be considered – such as reductions in feed intake and potential health effects on both animals and humans (e.g., bromoform emissions and accumulation). ***Asparagopsis* has high concentrations of bromoform,** heavy metals, and minerals ([68];[69]), **such as iodine**, which can be excreted in milk. This may lead to elevated levels of these substances in animal products, posing potential health risks for humans. Proposed solutions to these issues include dietary adaptation protocol, land-based cultivation to better control heavy metal and mineral content, and strict monitoring of supplementation – particularly for lactating animals – to prevent residues in milk. However, while lowering doses can mitigate these risks, it also reduces the methane reduction potential.

([64]) Kinley et al. (2020). Mitigating the carbon footprint and improving productivity of ruminant livestock agriculture using a red seaweed, Journal of Cleaner Production. 259. https://doi.org/10.1016/j.jclepro.2020.120836
([65]) Roque et al. (2021). Red seaweed (Asparagopsis taxiformis) supplementation reduces enteric methane by over 80 percent in beef steers. PLoS ONE 16(3): e0247820. https://doi.org/10.1371/journal.pone.0247820
([66]) DMI refers to the amount of solid feed excluding water content that an animal consumes. It directly influences the energy and nutrient intake of ruminants and is typically measured in kg/day.
([67]) Due to the specific conditions of each experiment, it is not feasible to convert different measuring units (Organic Matter (OM) versus Dry Matter (DM) or animal Body Weight (BW)) into a single unit. OM refers to the part of the dry matter that consists of plant and animal substances, excluding inorganic minerals, while BW is the total mass of an animal, including both water and dry matter. Extrapolating a specific amount from these variables is not possible. Discussing findings in general terms based on the scientific consensus is more suitable.
([68]) Minerals or ashes need to be limited in ruminant diets to avoid negative effects on animal health and productivity.
([69]) National Academies of Sciences, Engineering, and Medicine (2021). Nutrient Requirements of Dairy Cattle: Eighth Revised Edition. Washington, DC: The National Academies Press. https://doi.org/10.17226/25806.

Table 9 – Risks associated with *Asparagopsis*

Risk type	Concern
Bromoform accumulation	Potential transfer into milk and meat raising food safety
Iodine excess	High iodine content may exceed tolerable intake levels, posing a risk of thyroid dysfunction in livestock ([70])
Animal health	Long-term effects of bromoform exposure on livestock
Palatability	Some animals may reject feed containing seaweed, affecting adoption rates

Asparagopsis reduces methane emissions in ruminants by disrupting microbial pathways in the rumen, specifically inhibiting the process of methanogenesis ([71]). Nearly **9,000 papers on rumen methanogenesis** were published between 1960 and 2018 ([72]). The use of *Asparagopsis* has proven effective in reducing methane emissions. However, its inclusion in livestock diets must be carefully managed, as **several environmental and health risks** need to be considered.

Bromoform, a volatile compound present in *Asparagopsis*, can easily evaporate into the atmosphere and **contribute to ozone depletion** ([73]). Regarding health precautions, the scientific community remains uncertain about the extent to which bromoform – a bioactive compound found in algae ([74]) – may enter the food chain through cow milk and meat. Research from Wageningen University & Research ([75]) found that bromoform can be detected in cows' milk and urine, raising concerns about food safety. Signs of inflammation were also observed in the rumen walls of some cows, and the long-term effects remain unknown, highlighting the need for further research to ensure the safety of both animals and consumers.

Prolonged or high-level exposure to bromoform in other contexts has been associated with health risks, ranging from irritation of the skin, eyes, and respiratory system to more serious long-term effects ([76]). Long-term exposure to trihalomethanes (THMs), such as bromoform, may carry cumulative health risks. Research on bromoform exposure since 1982 suggests a potential cancer risk. Current evidence points to a possible link with bladder cancer at higher exposure

([70]) Machado et al., (2014). Effects of marine and freshwater macroalgae on in vitro total gas and methane production. PLoS ONE 9(1). https://doi.org/10.1371/journal.pone.0085289
([71]) A process where specific microbes known as methanogens break down food in environments without oxygen, such as the rumen, which is the stomach compartment of ruminants.
([72]) Beauchemin et al. (2020). Review: Fifty years of research on rumen methanogenesis: Lessons learned and future challenges for mitigation. *Animal,* 14(1). https://doi.org/10.1017/S1751731119003100
([73]) Nature (2023). Vaunted treaty to protect the ozone layer has a hole. Available here.
([74]) Bromoform is a bioactive compound found in certain red algae which affects biological functions such as reducing methane production in cattle.
([75]) Muizelaar et al. (2021). Safety and Transfer Study: Transfer of Bromoform Present in *Asparagopsis taxiformis* to Milk and Urine of Lactating Dairy Cows. *Foods,,* 10(3). https://doi.org/10.3390/foods10030584
([76]) Bromoform is a chlorination by-product formed when chlorine disinfects drinking water.

levels ([77]), but there is insufficient evidence on the exact threshold or duration of exposure to cause harm ([78]). While bromoform and other chlorination by-products are considered possibly carcinogenic, the actual risk from typical drinking water concentrations remains uncertain.

Asparagopsis contains high levels of iodine. While it is an essential nutrient for ruminants, excessive iodine intake can lead to thyroid dysfunction. Research suggests that adding about 0.5% to 1% *Asparagopsis* (DMI) to cattle diets is a safe range to avoid iodine toxicity ([79];[80];[81]). The National Academies of Sciences, Engineering, and Medicine recommend a daily iodine intake for growing beef cattle of 0.5 mg/g DMI and a maximum tolerable limit of 50 mg/g DMI ([82]). In one study ([83]), *Asparagosis* containing 2.27 mg iodine/g was fed at levels resulting in a maximum daily intake of 106–127 mg/day (low inclusion) and 173–225 mg/day (high inclusion) for cattle. These levels did not exceed the maximum tolerable limits, though they were above daily recommendations. The iodine residues in meat remained far below human upper intake limits, suggesting a wide margin of safety at these inclusion rates.

The required amount of *Asparagopsis* supplementation to be efficient is significant, raising concerns about practicality. Lactating dairy cows weighing an average of 545 kg will consume approximately 3% of their body weight in DMI daily ([84]). Thus, the demand is approximately 16.4 kg ([85]) of dry matter per day for that class of animal. Beef cattle, particularly those in feedlot or high-performance systems, generally consume 8–14 kg of DMI per day. The recommended inclusion rate of *Asparagopsis* at 0.2–0.5% of DMI, aligning with existing studies, equates to 58 g/day for dairy cows and 39 g/day for beef cattle.

([77]) As per the International Agency for Research on Cancer (IARC), no epidemiological data relevant to the carcinogenicity of bromoform is available. There is limited evidence in experimental animals for the carcinogenicity of bromoform. Bromoform is not classifiable as to its carcinogenicity to humans (Group 3).
([78]) Helte et al. (2017). Chlorination by-products in drinking water and risk of bladder cancer – A population-based cohort. *Water Res.* https://doi.org/10.1016/j.watres.2022.118202
([79]) Machado et al., (2014). Effects of marine and freshwater macroalgae on in vitro total gas and methane production. PLoS ONE 9(1). https://doi.org/10.1371/journal.pone.0085289
([80]) Kinley et al. (2020). Mitigating the carbon footprint and improving productivity of ruminant livestock agriculture using a red seaweed, Journal of Cleaner Production. 259. https://doi.org/10.1016/j.jclepro.2020.120836
([81]) Stefenoni et al. (2021). Effects of the macroalga Asparagopsis taxiformis and oregano leaves on methane emission, rumen fermentation, and lactational performance of dairy cows. Journal of dairy science, 104(4), 4157–4173. https://doi.org/10.3168/jds.2020-19686
([82]) National Academies of Sciences, Engineering, and Medicine (2016). *Nutrient Requirements of Beef Cattle: Eighth Revised Edition*. Washington, DC: The National Academies Press. https://doi.org/10.17226/19014.
([83]) Stefenoni et al. (2021). Effects of the macroalga Asparagopsis taxiformis and oregano leaves on methane emission, rumen fermentation, and lactational performance of dairy cows. Journal of dairy science, 104(4), 4157–4173. https://doi.org/10.3168/jds.2020-19686
([84]) US Department of Agriculture (2024). National Organic Program (NOP) regulations. Available here.
([85]) Dry Matter Demand (kg) = 545 × (3.0/100) = 16.4 kg

Table 10 – Required amount of *Asparagopsis* supplementation

Animal	DMI (kg/day)	0.2% Inclusion (g/day)	0.5% Inclusion (g/day)	Average Inclusion (g/day)
Dairy Cow	16.4	33	82	58
Beef Cattle (average)	11	22	55	39
Average	13.7	27	69	48

At those inclusion rates, the estimated iodine intake from *Asparagopsis* supplementation in cattle is as follows:

Table 11 – Estimated iodine intake from *Asparagopsis*

Animal	Average inclusion (g/day)	Estimated iodine intake (mg/day)	Comments
Dairy Cow	58	132	Slightly above recommended intake, below tolerable limit
Beef Cattle (average)	39	89	Within low inclusion range, safe iodine residue levels
Average	48	109	Represents mid-range inclusion, safe margins maintained

Note: The iodine content of *Asparagopsis* is approximately 2.27 mg/g dry weight. This figure has been cited in several peer-reviewed studies evaluating the mineral composition of *Aparagopsis* species used as feed additives for ruminants aiming to reduce methane emissions. Machado et al. (2016) ([86]), Kinley et al. (2020) ([87]) and other follow-up studies also report iodine concentrations in *Asparagopsis* species within the range of 1.5 to 3 mg/g dry matter.

Studies indicate methane emissions could be reduced by up to 80%, though the **extent of reduction depends on factors such as dosage, diet composition, and animal type**. Some recent research also suggests that **lower doses (0.1-0.2% of DMI) can still lead to significant methane reductions ([88])**. Additionally, research warns of diminishing returns at higher doses and highlights the need for further studies on the long-term effects on animal health and productivity. Consequently, studies are investigating mixtures that incorporate *Asparagopsis* without adversely affecting ruminal fermentation ([89]).

([86]) Machado et al., (2014). Effects of marine and freshwater macroalgae on in vitro total gas and methane production. PLoS ONE 9(1). https://doi.org/10.1371/journal.pone.0085289
([87]) Kinley et al. (2020). Mitigating the carbon footprint and improving productivity of ruminant livestock agriculture using a red seaweed, Journal of Cleaner Production. 259. https://doi.org/10.1016/j.jclepro.2020.120836
([88]) The emissions from *Asparagopis* production, such as energy use for cultivation and transportation, are also important to consider. The net effect depends on factors like production scale and distance; hence, a full Life Cycle Assessment (LCA) would provide a clearer picture of the overall greenhouse gas impact.
([89]) Eslam et al. (2023). Micro- and Macro-Algae Combination as a Novel Alternative Ruminant Feed with Methane-Mitigation Potential. *Animals*, 13(5). https://doi.org/10.3390/ani13050796.

For example, combining *Asparagopsis* with other additives like phloroglucinol ([90]) could further reduce methane emissions while potentially boosting animal productivity ([91]). However, this combination remains in the early stages of research.

In terms of practicalities, **feedlot systems are considered better suited for the application of additives like *Asparagopsis*** due to their fully formulated rations. In a recent trial conducted at a Queensland feedlot in Australia ([92]), cattle were fed *Asparagopsis* for 200 days, marking one of the longest trials of its kind ([93]). The results, published in the *Journal of Translational Animal Science* ([94]), showed a significant reduction in methane emissions with more than half (a 51.7% reduction in production and a 50.5% reduction in yield) ([95]) over the course of the trial. The peak reduction in methane emissions reached 91% on day 29. Importantly, the meat's taste and quality remained unaffected, and cattle fed the supplement gained 20 kg more than those in the control group. However, experts caution that it is not yet ready for widespread farm use. The study was conducted in a feedlot, which represents less than 1% of industry emissions, and reducing methane from grazing cattle will be much more challenging, as feedlots provide the best conditions for methane reduction whereas grazing systems are far more complex ([96]).

Algae-based additives like *Asparagopsis* are one of the most promising natural solutions, but **some challenges are still to be addressed**. Until safety concerns are fully addressed, its use should be restricted. Research is looking into other options like livestock diets, selective breeding, microbiome adjustments, plant-based compounds, and methane inhibitors (see **APPENDIX H**). The goal is to find the best ways to cut emissions and make livestock farming more sustainable. Methane reduction strategies need to be efficient, affordable, and meet animal welfare and regulatory standards. Researchers are also looking at **ways to mix**

([90]) An organic compound commonly found in various plants, especially in higher quantities in seaweeds (i.e. brown algae).
([91]) Romero et al. (2022). Exploring the combination of Asparagopsis taxiformis and phloroglucinol to decrease rumen methanogenesis and redirect hydrogen production in goats. *Animal Feed Science and Technology, 316.* https://doi.org/10.1016/j.anifeedsci.2024.116060.
([92]) Brown, A. (2024). Feeding seaweed supplement to cattle halved methane emissions in Australian feedlot, study finds. Available here.
([93]) The trial involved 160 Angus steers, each initially weighing 474.4 kg, including a control group. They were fed a commercial *Asparagopsis* supplement, Seafeed, in the form of canola oil infused with 25 mg of bromoform per kg of DMI. Seafeed is produced by CH4 Global, headquartered in the USA, with a presence in New Zealand and Australia
([94]) George et al. (2024). Effect of SeaFeed, a canola oil infused with Asparagopsis armata, on methane emissions, animal health, performance, and carcass characteristics of Angus feedlot cattle. *Transl Anim Sci.* https://doi.org/10.1093/tas/txae116
([95]) Cows produced less methane for every unit of feed they consumed, demonstrating that the algae helped reduce methane emissions without affecting their diet.
([96]) Feedlot systems represent a smaller fraction of global methane emissions, as grazing systems are responsible for most emissions from livestock. Reducing methane emissions from grazing cattle will likely require different strategies and innovations compared to feedlots, where dietary supplements can be more easily managed and controlled.

different solutions, so they fit into real farming practices, and across different farms and conditions.

More **gradual strategies offer long-term benefits**, such as the selection of breeding animals that naturally produce less methane. However, genetic selection requires substantial investment in research and poses risks such as reduced genetic diversity, unintended health issues, environmental impacts like ecosystem disruption, and resistance development, requiring careful regulation and ethical oversight. This approach seems complementary to other strategies. Microbiome manipulation, another innovative approach, focuses on altering the digestive microbiome of ruminants. While it holds great promise, the complexity of microbiome interactions and the difficulty of consistently achieving the desired balance in different environments is challenging.

All types of solutions come with their own set of benefits and challenges. Additives like saponins can greatly reduce emissions, but high doses may lead to toxicity, which varies depending on the source and diet. Lipids can reduce emissions by a smaller proportion but may lower digestibility and affect milk fat synthesis. Plant essential oils show significant reductions *in vitro* but have inconsistent effects *in vivo* and can alter feed intake or fermentation at high doses. Probiotics offer some reduction potential, but their practical application still requires further study.

Other methods, like rumen defaunation ([97]), can reduce emissions to some extent, though they may reduce feed intake and organic matter digestibility. Other approaches like vaccination and chemical interventions (such as 3-NOP ([98])) show promise in reducing methane emissions, but the effectiveness may be inconsistent. The latter may also have metabolic effects or toxicity risks. Additionally, improving forage quality through management practices can boost digestibility and productivity, but adjustments need to be farm-specific and may come with added costs. Each of these methods requires careful consideration and often combining them offers the best results.

The industry's ability to reduce emissions while maintaining animal health, safety, addressing scalability, and obtaining the necessary approvals is one major aspect. Across the globe, **there are already commercialised products based on some of these solutions**. Bovaer, developed by DSM-Firmenich, claims a reduction of methane emissions by about 30% in dairy cows and up to 90% in beef cows with just a small daily dose. It has been approved for use in Brazil and Chile for sheep, cows, and goats. Mootral, made from garlic and citrus extracts, works by altering the rumen microbial populations to reduce methane production. It has been reported to reduce methane emissions by 20–30%, though some

([97]) Rumen defaunation is not the same as rumen alteration or modification. It specifically refers to the removal or reduction of protozoa in the rumen, which can help reduce methane production.
([98]) 3-NOP (3-nitrooxypropanol) is a chemical feed additive used to reduce methane emissions from livestock (particularly ruminants). It works by targeting and inhibiting the activity of a specific enzyme (methyl coenzyme M reductase).

studies mention potential changes in milk flavour, scalability issues for larger herds, and variability depending on diet. Agolin, a plant-based essential oil additive, improves feed efficiency and claims to reduce methane emissions by 10–20%. It is commercially available and has been claimed to be effective in several regions, though its impact can vary based on diet and farm management practices. Finding the right balance between these strategies – or even combining them – is a daunting task. These solutions must be supported and refined through additional research to ensure they can be applied safely and effectively on a large scale and ultimately be accepted by the market.

4.3. Limitations of the research and future study and research needs

As previously discussed, *Asparagopsis* has shown great promise. However, there are several key areas where **additional research is needed to ensure efficient and sustainable use.** The long-term health implications of bromoform exposure must be thoroughly investigated and should take priority as a non-negotiable consideration before any other decisions are made. A lack of a **comprehensive set of long-term data** on the methane-reduction efficiency and the impact of *Asparagopsis* on animal health and welfare, human health, and productivity somehow limits its applicability. Most studies and experiments are of short duration and still show, to some extent, variable results based on factors such as livestock type, diet composition, and inclusion rates. These inconsistencies suggest the need for **more reproducible trials as well as clinical trials**. Some studies show no detectable residues, but there are still concerns about its potential accumulation in livestock products such as milk and meat. Therefore, **long-term and larger-scale studies are essential to evaluate the full range of effects.**

Another major hurdle comes from the **economic and scalability aspects** that are associated with large algae cultivation. The high costs of production, logistical constraints, and the underdeveloped infrastructure for mass production would limit the adoption of *Asparagopsis* as a livestock feed additive. Combined with the lack of data and understanding of the **environmental impact of large-scale seaweed farming**, there would be a need to conduct environmental assessments such as Environmental Impact Assessment (EIA) ([99]) and Environmental Life Cycle Assessment (LCA) before production in any kind ([100]). Research into **cost-effective cultivation techniques** (focusing on land-based farming) would be needed to better understand how to reduce the production costs. Ensuring a safe and efficient large-scale commercialisation of algae-based feed additives come with optimized production methods and mitigation of the risks. Research is also

([99]) European Commission (2023). Guidance Document on Environmental Performance. Available here.
([100]) There are currently no reliable LCA methodologies available to accurately measure the performance of seaweed farming value chains.

needed to **map out optimal cultivation zones using GIS tools and models** and higher resolution models should be developed to assess the suitability of cultivation sites at a more local and detailed scale and considering seasonal and climatic variations and species resilience ([101]).

Integrated **approaches combining *Asparagopsis* with other alternatives** could be explored. Alternatives such as plant-based methane inhibitors like tannins, saponins, and flavonoids have shown potential, though with mixed results; microbiome manipulation or selective breeding could also be explored for more sustainable solutions and within the right established caveats and limitations. *Asparagopsis* offers potential for methane reduction in livestock, but **addressing research gaps in its efficacy, safety, economic viability, and environmental impact** is important for its successful implementation and adoption.

Table 12 – Limitations and gaps of current research

Limited long-term data: most existing studies focus on short-term experiments; need to study prolonged exposure to bromoform and clinical trials or other compounds found in *Asparagopsis*.
Variability in results: research outcomes which depend on factors like animal type, diet composition, and dosage of *Asparagopsis* highlight the need for more controlled and reproducible trials and the definition of optimized inclusion levels.
Economic and scalability: production and scaling up *Asparagopsis* into livestock diets pose challenges (expensive cultivation and infrastructure for mass production, distribution and storage is underdeveloped); need to diversify studies (extend livestock breeds and farming systems).
Improved cultivation methods: further research into optimising *Asparagopsis* cultivation techniques is needed including strategies for reducing production costs, enhancing yield and improving algae quality (with focus on land-based cultivation).
Environmental and ecological impact: large-scale seaweed farming and its potential environmental risks (on local marine ecosystems, biodiversity and nutrient cycles) remain unstudied and need to be thoroughly assessed.
Integrated approaches: methane reduction in livestock being a complex issue integrating *Asparagopsis* with other strategies and the use of other feed additives could be explored; research on the synergistic effects may yield sustainable solutions.

([101]) Maya Miltell et al., (2025). Data integrations in marin water landscaping maps foe defining the bioremediation potential of seaweed in Europe. EU4Algae O1.17 report.

5. Three algae species (native to the EU) that could be used as feed or feed ingredient in animal feed

5.1. Introduction

This sub-chapter provides insights into three algae species (native to the EU) that could be used as feed or feed ingredients in animal feed. More specifically, the goal is to provide a business case for three algae species native to the EU, in comparison to five most commonly used animal feed ingredients in the EU against a selection of parameters.

5.2. Methodology

The first step was the literature review, which covered the microalgae *Nannochloropsis* and *Chlorella* species, and the macroalgae *Ulva* and *Asparagopsis* species. While *Asparagopsis taxiformis* has not yet seen widespread commercial application, it has been tested in dairy cattle feed with promising results, particularly for methane emission reduction ([102]). In addition, we also included broader research on seaweed in general (including both macro- and microalgae). We focused our review on the following parameters:

- Carbon and environmental footprint of using algae in animal feed;
- Social impact of using algae in animal feed;
- Information about the production costs and selling price of using algae in animal feed;
- Economic feasibility of using algae in animal feed;
- Availability of sufficient amount of biomass required to introduce algae in animal feed;
- Feeding logistics related to the use of algae in animal feed;
- Feed safety aspects and impact to animal health;
- Welfare, ethical, and other relevant considerations of using algae in animal feed.

([102]) Roque, B.M., Brooke, C.G., Ladau, J. et al. (2019). Effect of the macroalgae Asparagopsis taxiformis on methane production and rumen microbiome assemblage. *Animal Microbiome,* 1(3). https://doi.org/10.1186/s42523-019-0004-4

The following step was to identify the research gaps identified during the literature review, which at the same time indicates the future study and research needs to introduce seaweed ingredients into cows' diets.

We have also conducted a comparative analysis of the 3 selected algae species against the five commonly used animal feed ingredients in the EU. **Table 13** summarises the results of this comparative analysis.

Table 13 – Direct comparisons between commonly used animal feed ingredients and algae

Animal feed ingredients	Comparison with the selected algae species
Soybean meal	• The carbon footprint of replacing a certain percentage of soybean meal with defatted algae was found to be higher in the study, even before considering the upstream carbon footprint, assuming a high oil content in algae, and applying highly efficient drying techniques; • The cost price of replacing a certain percentage of soybean meal with defatted algae in compound feed (in this case, replacing 12% of soybean meal with 2.8% of defatted algae) was found to be higher in one of the studies.
Maize	Comparison is not possible due to data limitations.
Barley	Comparison is not possible due to data limitations.
Fish Meal	• Microalgae are capable of high-level protein expression and are easy to culture under various growth conditions using minimal energy; • Studies referenced that microalgae are economically and biologically viable as a fish meal replacement in aquaculture feeds; • Microalgae-fed fish showed improvements in growth, feed efficiency, and body composition compared to fish meal diets; • Studies showed that replacing fish meal with microalgae (up to 56.25%) in fish diets had no negative effects on growth and immunity.
Rapeseed Meal	Comparison is not possible due to data limitations.

5.3. Limitations of the research

The main challenge lies in finding specific information for parameters such as social impact, production costs and selling price, feeding logistics, and feed safety aspects.

The primary limitation of the combined studies we reviewed is the absence of a comprehensive comparison of the three selected algae species against five commonly used animal feed ingredients in the EU. Specifically, there is a lack of

analysis regarding the impact of these ingredients on key factors such as environmental effects, animal health and welfare, and economic feasibility.

It is difficult to make a direct comparison between the environmental impact, social impact, and animal welfare aspects of the different animal feed ingredients, as there are many factors at play. For example, the environmental impact of the different animal feeds depends on where they are produced, transportation to the place of consumption, how they are produced, and the balance between different animal feed ingredients in a compound feed. Effects such as the impact of crop rotation on soil nutrients and pest levels are also not considered.

As each study is limited to a given scope, other interconnected factors are rendered invisible, making it difficult to make direct comparisons between animal feeds, and between animal feeds and algae.

A further limitation is the diversity of measurements across the thematic areas, and in some cases the lack of measurement across them. For example, there is no comprehensive economic feasibility comparison for the different feed ingredient types, and production costs and profitability margins are largely missing. Furthermore, measures of “environmental impact” are understandably vast, and given that the studies focus on different measures, it is difficult to make cross-comparisons.

Another limitation is that the effects of climate change on the availability and yield of each animal feed biomass were not explored in depth, and the effect of global trade policies and geopolitics was also not considered. This is particularly important given that the US is the largest producer of maize and largely controls the price of maize. Finally, data on storage, handling and transport logistics, as well as analysis on animal welfare, were largely missing.

5.4. Presentation of Business case 1 (*Asparagopsis*)

Asparagopsis is a genus belonging to the order Bonnemaisoniales of the phylum Rhodophyta (red algae) and consists of three taxonomically accepted species: the *Asparagopsis taxiformis, the Asparagopsis armata,* and the *Asparagopsis svedelii*. This business case will explore the potential of *Asparagopsis* sp. and compare them to commonly used animal feed ingredients across the following parameters: carbon and environmental footprint, feed safety aspects, animal health welfare aspects and socio-economic benefits.

Carbon and environmental footprint

The species *A. taxiformis* and *A. armata* contain high concentrations of bromoform, which is a substance that has been demonstrated to counteract the formation of methane in the cow’s rumen without negative impacts on the rumen’s

function. As cows exhale this potent greenhouse gas, a possible way to limit methane emissions from cows could be by feeding them the *Asparagopsis* seaweed. Moreover, multiple studies have shown that adding *Asparagopsis* sp. to feed for dairy cattle, beef steers and sheep lowers methane emissions.

Animal health welfare aspects

Bromoform is toxic in its pure form and is harmful to health. According to research done by Wageningen University (WUR) ([103]), cows that consistently consumed 67 g/day of *Asparagopsis taxiformis* (containing 1.26 mg/kg DM bromoform) over 22 days showed abnormalities and signs of inflammation in the rumen wall. The study suggests that inclusion rates around 0.2–0.5% of feed organic matter may be more balanced in terms of maintaining feed intake while delivering bromoform for methane reduction. Another study identified granulomatous and keratotic ruminal-mucosa changes in sheep supplemented with the seaweed ([104]).

Food safety aspects

Research done by the WUR showed that some of the bromoform consumed by the cows in the study ended up in milk produced by these cows ([105]). Whereas there is a limit for the maximum amount of bromoform in drinking water, there is no such limit for food. As food safety must always be beyond any form of doubt, further research should be conducted to rule out negative effects for both cows and consumers. However, other *Asparagopsis* species contain less bromoform and could therefore be a promising alternative. Moreover, macroalgae studies have reported elevated milk iodine concentrations, which may pose public health risks.

Socio-economic benefits

Due to demonstrated decreased methane emissions, as well as weight gain improvements of livestock due to intake of *Asparagopsis*, this could create new economic opportunities. With low inclusion rates of this seaweed in ruminant diets, the industry has the potential to revolutionise the management of greenhouse gas emissions across the ruminant livestock sector, with complementary benefits to the environment and the economy of the wider agriculture sector. Beyond environmental impact, farmers may also benefit from

([103]) Muizelaar, W., Groot, M., van Duinkerken, G., Peters, R., & Dijkstra, J. (2021). Safety and Transfer Study: Transfer of Bromoform Present in Asparagopsis taxiformis to Milk and Urine of Lactating Dairy Cows. Foods, 10(3), 584. https://doi.org/10.3390/foods10030584
([104]) Li, X., Hayley, N., Kinley, R.D., et al. (2016). Asparagopsis taxiformis decreases enteric methane production from sheep. *Anim. Prod. Sci.*, 58, 681–688. https://doi.org/10.1071/AN15883
([105]) 1.26 mg/kg DM bromoform.

improved feed conversion, potential increases in daily weight gain, and eligibility for sustainability-linked premiums or subsidies under EU schemes.

Farm-level benefits

The inclusion of *Asparagopsis* in ruminant diets may improve production outcomes at the farm level. As previously outlined in the report, experimental studies have reported up to 20 kg additional weight gain over 200 days and a 53% improvement in weight gain, alongside significant reductions in methane emissions (up to 91%) (see Section 4.2 and **APPENDIX E)**. While further studies are needed under European conditions, these results indicate that *Asparagopsis* has the potential to enhance both productivity and sustainability at the farm level. Additionally, farmers may become eligible for carbon credits, subsidies, or market premiums, particularly in the context of the EU Methane Strategy and Farm to Fork incentives (see **Table 7**).

Sector-level benefits

At the sectoral level, even modest uptake of *Asparagopsis* could generate measurable economic and climate value. According to Eurostat, the EU had approximately 20 million dairy cows as of 2024 ([106]). Based on a 10% adoption scenario, in which 2 million cows are fed *Asparagopsis*, it could result in a significant reduction in agricultural greenhouse gas emissions.

Dairy cows emit an average of 100 kg of methane per year ([107]), which, using a GWP100 of 27, corresponds to 2.7 tonnes of CO_2e emissions. Supplementation with *Asparagopsis* has demonstrated methane reductions ranging from 30% to over 90% in various studies under EU conditions ([108]). Applying a conservative reduction rate of 40%, this would result in approximately 1 tonne of CO_2e avoided per cow per year. For 2 million cows, this equates to 2 million tonnes of CO_2e annually. At an average carbon price of €65–€85 per tonne of CO_2e (EU ETS, 2024), this represents a potential €130–€170 million ([109];[110]) in avoided emissions costs each year.

([106]) Eurostat (2025). Number of dairy cows. Tag00014. https://doi.org/10.2908/TAG00014
([107]) Average figure based on: IPCC from 90-150 kg/CH_4/year: Hiraishi, T., Krug, T., Tanabe, K., et al. (2019). Chapter 10: Emissions from livestock and manure management. In E. Calvo Buendia, K. Tanabe, A. et al. (Eds.), 2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories: Volume 4—Agriculture, forestry and other land use (pp. 10.1–10.94). Intergovernmental Panel on Climate Change. Available here; and EEA from 90-150 kg/CH_4/year: European Environment Agency. (2023). Methane emissions in the EU: Latest trends and modelling projections. Available here.
([108]) Muizelaar et al. (2021) (refer to note 102), Roque et al. (2021), and Kinley et al. (2020) included in **APPENDIX E.**
([109]) European Securities and Markets Authority (2024). EU carbon markets 2024 (ESMA50-43599798-10379). Available here.
([110]) European Commission. (n.d.). EU ETS.

These benefits reinforce the business case for integrating *Asparagopsis* into sustainable feed strategies, particularly as the EU's Methane Strategy and Green Deal frameworks increasingly incentivise low-carbon farming inputs.

Industry-level benefits

According to estimates presented in Section 3.3, the EU seaweed sector is projected to grow to €2.7 billion in market value and support 85,000 jobs by 2030. While *Asparagopsis* remains a niche species within this landscape, its methane-reducing potential has gained global recognition and attracted early-stage investment. Seaweed farming is known to be labour-intensive compared to traditional agriculture. Studies from the North Sea region suggest that macroalgae cultivation can generate 2 to 4 full-time equivalent jobs per hectare, particularly in coastal and rural areas where alternative employment opportunities may be limited ([111]). If supported by public investment and regulatory clarity, a European *Asparagopsis* value chain could contribute meaningfully to both climate targets and the blue economy, especially in regions with underused marine resources.

Market analysis

The *Asparagopsis* industry is rapidly developing due to its potential to address methane emissions, which has received global recognition and investment. The benefits extend beyond the livestock and dairy industries, creating new industries and employment opportunities ([112]).

The use of *Asparagopsis*, particularly as a feed additive, is subject to several regulations in Europe:

- Feed Additives Regulation (EC) No 1831/200385:
    - This regulation establishes a community procedure for authorising the placing on the market and use of feed additives. It includes rules for the supervision and labelling of feed additives to ensure a high level of protection for human and animal health.
- Novel Food Regulation (EU) 2015/228386:
    - *Asparagopsis* may also fall under the Novel Food Regulation if it is considered a new food ingredient. This regulation requires a safety

([111]) Ciravegna, E., Koch, S., & van den Burg, S. (2023). The business case for seaweed aquaculture in the North Sea: Learning from international experiences. Wageningen Economic Research. https://doi.org/10.18174/585349
([112]) Future Feed (2024). New report tracks *Asparagopsis* industry's rise. Available here.

assessment and authorisation before novel foods may be marketed in the EU.

There are ongoing discussions regarding the iodine and bromine content in *Asparagopsis*, which could affect its approval and use as a feed material. These concerns must be addressed to ensure the safety and efficacy of *Asparagopsis* as a feed additive. An inclusion rate of *Asparagopsis* at 0.2%–0.5% of the daily diet for cattle weighing approximately 470 kg and consuming 15 kg of dry matter (DM) per day equates to 30–75 g/day of *Asparagopsis*, delivering 180–450 mg/day of bromoform (at 6 mg of bromoform per gram of seaweed) per animal. This corresponds to approximately 0.4–1.0 mg/kg/day of bromoform, which is considered a low dose in comparison to those assessed in animal toxicity studies ([113]).

Efforts are currently underway to streamline the regulatory approval process to facilitate the use of *Asparagopsis*, given its potential environmental benefits. As elaborated in detail in **APPENDIX D,** high cultivation and processing costs remain a significant barrier to the scalability and profitability of algae farming – particularly for *Asparagopsis*. Limited awareness among farmers and consumers further impedes market development. Potential solutions include the adoption of cost-reducing technologies, government subsidies, and awareness-raising campaigns and incentives. However, substantial financial challenges persist in the EU context, including high capital requirements, limited land availability, and the absence of economies of scale. Moreover, regulatory hurdles, market uncertainty, and a lack of standardisation continue to delay industry growth and inflate operational costs.

5.5. Presentation of Business case 2 (*Chlorella*)

Chlorella is a genus of unicellular green microalgae belonging to the division *Chlorophyta*. It is characterised by rapid growth, a high protein content, and a rich profile of vitamins, minerals, and bioactive compounds. Several species – most notably *Chlorella vulgaris* and *Chlorella pyrenoidosa* – have been investigated for their potential as alternative protein sources and functional feed ingredients. This business case evaluates the use of *Chlorella* in animal feed, assessing its performance across key parameters including carbon and environmental footprint, animal health and welfare impacts, and socio-economic benefits.

([113]) Eason, C. T., & Fennessy, P. F. (2023). Methane reduction, health and regulatory considerations regarding Asparagopsis and bromoform for ruminants. New Zealand Journal of Agricultural Research, 68(1), 1–30. https://doi.org/10.1080/00288233.2023.2248948

Carbon and environmental footprint

Compared to conventional feed crops such as soya and maize, *Chlorella* can be cultivated with significantly lower land and freshwater requirements. It can be grown in controlled environments such as photobioreactors or open ponds, enabling year-round production on non-arable land. Several LCAs indicate that microalgae like *Chlorella* can reduce greenhouse gas emissions when substituting land-intensive protein sources. Furthermore, its ability to fix CO_2 through photosynthesis positions it as a promising contributor to carbon mitigation strategies in feed production. However, the energy demands associated with controlled cultivation systems – such as artificial lighting and aeration – must be carefully managed to optimise the overall environmental benefits.

Animal health welfare aspects

Evidence from different animal studies shows that *Chlorella vulgaris* improves growth performance, feed conversion ratios, and immune response ([114];[115];[116]). For instance, in ducks and poultry, supplementation improved feed efficiency and reduced stress markers. In aquaculture, *Chlorella* serves as a source of essential fatty acids and carotenoids, supporting larval development and health. Some studies also report enhanced antioxidant activity and improved intestinal morphology, contributing to better nutrient absorption. *Chlorella*'s cell wall, though indigestible, may act as a prebiotic – its processing (e.g., cell wall disruption) enhances digestibility. No significant negative effects have been identified, and the species is generally recognised as safe. In Latvia, the integration of *Chlorella vulgaris* into fish aquaculture ponds has been explored to enhance water quality and increase fish production yields.

A notable initiative by Riga Technical University (RTU) involved developing a pilot-scale facility for cultivating *Chlorella vulgaris*, aiming to utilize its properties for water purification and oxygen enrichment in aquaculture settings. This approach is considered innovative in the Baltic region, as it allows for higher fish stocking densities and improved water quality, thereby potentially boosting productivity in fish farming operations ([117]).

([114]) Oh S.T, Zheng L., Kwon H.J., et al. (2015). Effects of Dietary Fermented Chlorella vulgaris (CBT(®)) on Growth Performance, Relative Organ Weights, Cecal Microflora, Tibia Bone Characteristics, and Meat Qualities in Pekin Ducks. *Asian-Australas J Anim Sci.*, 28(1): 95-101. https://doi.org/10.5713/ajas.14.0473

([115]) Kotrbáček, V., Doubek, J. & Doucha, J. (2015). The chlorococcalean alga Chlorella in animal nutrition: a review. *J Appl Phycol,* 27, 2173–2180. https://doi.org/10.1007/s10811-014-0516-y

([116]) Lemahieu, C., Bruneel, C., Termote-Verhalle, et al. (2013). Impact of feed supplementation with different omega-3 rich microalgae species on enrichment of eggs of laying hens. *Food Chemistry*, 141(4), 4051–4059. https://doi.org/10.1016/j.foodchem.2013.06.078

([117]) To develop the use of the microalgae *Chlorella vulgaris* for water purification and oxygen enrichment, increasing the productivity of fisheries, a new microalgae cultivation facility has been developed at Riga Technical University (RTU) with the support of the Latvian Investment and Development Agency's «PROTOTECH» programme.

Socio-economic benefits

The production of *Chlorella* has the potential to contribute to the circular economy by utilising waste streams (e.g., CO_2 from industrial emissions or nutrient-rich wastewater) as inputs. It also offers opportunities for domestic feed protein production, thereby reducing reliance on imported soymeal. As demand for sustainable and functional feed ingredients increases, *Chlorella* could help meet consumer expectations for environmentally responsible animal products. However, scalability and cost competitiveness remain key challenges. Ongoing innovation in cultivation and processing technologies is expected to reduce production costs and support market integration.

Farm-level benefits

At the production level, *Chlorella* has demonstrated measurable benefits for animal performance and health across different species. In poultry, specifically broiler chickens, a systematic review ([118]) analysing multiple studies found that cumulative intake levels of *C. vulgaris* ranging from 0.8 to 718 g per bird influenced growth rates and feed efficiency. Specifically, an intake of approximately 20 g per bird maximised final body weight, cumulative body weight gain, and daily weight gain. The feed conversion ratio also improved with increasing *C. vulgaris* intake up to this level, although this was not statistically significant.

In aquaculture, a study ([119]) involving Pacific white shrimp found that the dietary inclusion of *C. vulgaris* at concentrations of 15 to 30 g/kg feed over 56 days resulted in significant improvements in growth performance, feed utilisation, and body composition. Additionally, the shrimp exhibited enhanced antioxidant activity and improved survival rates against *Vibrio parahaemolyticus* infection.

Finally, research on weaned piglets ([120]) suggests that *Chlorella vulgaris* supplementation can improve both health status and meat quality. In fact, a 5% incorporation in the diet resulted in improvements in meat protein content, beneficial fatty acid profiles, and immune response indicators, such as increased immunoglobulin levels. *Chlorella* could contribute to better overall performance and product value in pig production, especially when used in combination with feed enzymes to enhance digestibility.

([118]) Mendes, A. R., Spínola, M. P., Lordelo, M., & Prates, J. A. M. (2024). Impact of Chlorella vulgaris Intake Levels on Performance Parameters and Blood Health Markers in Broiler Chickens. Veterinary Sciences, 11(7), 290. https://doi.org/10.3390/vetsci11070290
([119]) Eissa, ES.H., Aljarari, R.M., Elfeky, A. et al. (2024). Protective effects of Chlorella vulgaris as a feed additive on growth performance, immunity, histopathology, and disease resistance against Vibrio parahaemolyticus in the Pacific white shrimp. Aquacult Int 32, 2821–2840. https://doi.org/10.1007/s10499-023-01298-y
([120]) Martins, C. F., Pestana, J. M., Alfaia, C. M., et al. (2021). Effects of Chlorella vulgaris as a Feed Ingredient on the Quality and Nutritional Value of Weaned Piglets' Meat. Foods, 10(6), 1155. https://doi.org/10.3390/foods10061155

Sector-level benefits

At the sector level, *Chlorella* production supports the EU's goals for circularity, feed protein autonomy, and decarbonisation. It can be cultivated using industrial CO_2 emissions and nutrient-rich waste streams, such as those from aquaculture, agriculture, or food processing, enabling nutrient recovery while reducing the need for synthetic fertilisers. A recent study ([121]) demonstrated that integrating CO_2 supply into *Chlorella* cultivation can significantly enhance both productivity and cost-efficiency. Under optimised conditions using a two-day cultivation cycle, monthly biomass yield reached 1,380 kg per 100,000 L reactor, with a peak profitability of 871% when CO_2 supplementation was applied.

Production costs were also reduced to $5.7-6.8 per kilogram of dry biomass (approximately €5.3–6.4/kg), making *Chlorella* more competitive as a feed ingredient ([122]). These results support its integration into high-value livestock systems (e.g. aquaculture, poultry, piglets), where functional benefits may justify a moderate feed cost premium. Moreover, such circular models – recycling emissions and wastewater into feed – are aligned with the EU Green Deal, the Farm to Fork Strategy, and bioeconomy targets for waste valorisation and local protein production.

Industry-level benefits

As part of the broader EU algae sector – projected to grow to €2.7 billion and support 85,000 jobs by 2030 (see Section 3.3) – *Chlorella* has the potential to support rural development, technological innovation, and job creation. While currently more prominent in the food and nutraceutical markets, its use in animal feed is expanding, particularly as consumers and retailers seek functional and low-footprint ingredients. Cultivation systems such as photobioreactors or open raceways can be co-located with wastewater treatment or industrial CO_2 capture facilities, enabling synergies across sectors ([123]). Macroalgae production is reported to generate 2-4 full-time equivalent jobs per hectare ([124]); similar levels may apply to microalgae, depending on the degree of process automation. With continued innovation in strain optimisation, harvesting, and processing, *Chlorella* could play an increasingly important role in the EU's sustainable feed and bioeconomy strategies.

([121]) Lukyanov, A., et al. (2024). Biotechnological and economic assessment of the productivity of Chlorella vulgaris IBSS-19 microalgae under different cultivation regimes. Bioresource Technology Reports, 101907. https://doi.org/10.1016/j.biteb.2024.101907
([122]) Martins, C. F., Pestana, J. M., Alfaia, C. M., et al. (2021). Effects of Chlorella vulgaris as a Feed Ingredient on the Quality and Nutritional Value of Weaned Piglets' Meat. Foods, 10(6), 1155. https://doi.org/10.3390/foods10061155
([123]) Lukyanov, A., et al. (2024). Biotechnological and economic assessment of the productivity of Chlorella vulgaris IBSS-19 microalgae under different cultivation regimes. Bioresource Technology Reports, 101907. https://doi.org/10.1016/j.biteb.2024.101907
([124]) Ciravegna, E., Koch, S., & van den Burg, S. (2023). The business case for seaweed aquaculture in the North Sea: Learning from international experiences. Wageningen Economic Research. https://doi.org/10.18174/585349

Market analysis

The *Chlorella* market is experiencing significant growth, driven by increasing consumer awareness of its health benefits and nutritional value. *Chlorella* is rich in proteins, vitamins, minerals, and antioxidants, making it popular among health-conscious individuals. It is widely used in nutraceuticals, food and beverages, animal feed, cosmetics, and pharmaceuticals.

There is a growing preference for natural, organic, and additive-free products, which is contributing to the rising demand for *Chlorella*. It is known for its detoxifying properties, immune system support, and potential anti-inflammatory effects. Increasing awareness of *Chlorella*'s health benefits – including its high protein content and essential nutrients – is a key driver of market expansion.

Overall, the C*hlorella* market is expected to continue its upward trajectory, with significant growth anticipated in the coming years.

5.6. Presentation of Business case 3 (*Nannochloropsis*)

Nannochloropsis is a genus of marine microalgae explored for its potential in animal feed. The literature reviewed focuses primarily on its application in aquaculture species (e.g., European sea bass) and laying hens. Studies highlight potential nutritional benefits and performance improvements. This business case presents evidence on the use of *Nannochloropsis* as a feed or feed ingredient, structured around its carbon and environmental footprint, animal health and welfare aspects, and socio-economic benefits.

Carbon and environmental footprint

Nannochloropsis is highlighted as contributing positively to the sustainability of feed formulations. Its use in place of conventional marine-derived ingredients, such as fish oil or defatted biomass, is considered a potential strategy to improve the environmental profile of feed. While no quantitative footprint data are included, *Nannochloropsis* is described as a renewable input with environmental advantages. Overall, *Nannochloropsis* is described as a renewable resource with potential environmental benefits, especially in comparison to fish-based inputs.

Animal health welfare aspects

Health effects of *Nannochloropsis* were studied in European sea bass ([125]), where diets supplemented with the microalgae had a positive impact on fish health. In poultry ([126]), its inclusion in laying hen diets was linked to health benefits. While specific welfare outcomes were not detailed, the same study on European sea bass ([127]) mentions ethical considerations and states that animal welfare was considered. No adverse health effects were reported across the studies reviewed.

Socio-economic benefits

Nannochloropsis is described as a commercially available microalga with a rapid growth rate. Its potential to replace fish oil is identified as a factor contributing to economic feasibility, although exact production costs are not specified. The literature suggests that its economic viability depends on the scale and method of production. However, no conclusive evidence or consistent data are currently available to estimate its cost-effectiveness as a feed ingredient. Social impacts are also not explicitly addressed; therefore, it was not possible to conduct further analysis or draw relevant conclusions.

Market analysis

Nannochloropsis is used in aquaculture, animal feed, nutraceuticals, dietary supplements, cosmetics, biofuels, and bioremediation. More specifically, studies have demonstrated that *Nannochloropsis oculata* co-products can fully replace fishmeal in feeds for rainbow trout, resulting in comparable growth performance and reduced feed costs ([128]). Species of *Nannochloropsis,* particularly *N. oculata,* are rich in eicosapentaenoic acid (EPA), a valuable omega-3 fatty acid, making them suitable for inclusion in human dietary supplements ([129]). In addition, non-living cells of *Nannochloropsis oceanica* have been shown to effectively adsorb

([125]) Valente, L.M.P., Custódio, M., Batista, S. et al. (2019). Defatted microalgae (Nannochloropsis sp.) from biorefinery as a potential feed protein source to replace fishmeal in European sea bass diets. Fish Physiol Biochem 45, 1067–1081. https://doi.org/10.1007/s10695-019-00621-w
([126]) Lemahieu, C., Bruneel, C., Termote-Verhalle, R., et al. (2013). Impact of feed supplementation with different omega-3 rich microalgae species on enrichment of eggs of laying hens. Food Chemistry, 141(4), 4051–4059. https://doi.org/10.1016/j.foodchem.2013.06.078
([127]) Valente, L.M.P., Custódio, M., Batista, S. et al. (2019). Defatted microalgae (Nannochloropsis sp.) from biorefinery as a potential feed protein source to replace fishmeal in European sea bass diets. Fish Physiol Biochem 45, 1067–1081. https://doi.org/10.1007/s10695-019-00621-w
([128]) Sarker, Pallab K., Benjamin V. et al. (2025). "Towards Sustainable Aquafeeds: Microalgal (Nannochloropsis sp. QH25) Co-Product Biomass Can Fully Replace Fishmeal in the Feeds for Rainbow Trout (Oncorhynchus mykiss)" Foods, 14(5). https://doi.org/10.3390/foods14050781
([129]) Liu M, Yu L, Zheng J, Shao S., et al. (2024). Turning the industrially relevant marine alga Nannochloropsis red: one move for multifaceted benefits. New Phytol. 244(4):1467-1481. https://doi.org/10.1111/nph.20114

textile wastewater containing azo dyes, demonstrating potential in environmental clean-up applications ([130]).

The *Nannochloropsis* market in Europe is growing steadily, driven by its diverse applications and the increasing demand for sustainable products. *Nannochloropsis* is a type of microalga known for its high lipid content and nutritional value, making it valuable across various industries. There is a growing preference for eco-friendly and sustainable products, which is driving the demand for *Nannochloropsis*. The rising demand for seafood, including finfish and shellfish, has led to increased aquaculture production, boosting the demand for *Nannochloropsis* as a feed ingredient. The nutraceutical and functional food industries are incorporating omega-3 fatty acids into their products, increasing the demand for *Nannochloropsis* as a sustainable source.

In addition, *Nannochloropsis* is considered a valuable feedstock for biofuel production due to its high lipid content and rapid growth rate. A 2023 study investigated the use of *Nannochloropsis oceanica* cultivated in yeast wastewater for biodiesel production. The research found that this cultivation method significantly enhanced the algal lipid content and fatty acid composition, making it a promising approach for sustainable biodiesel production ([131]). Overall, the *Nannochloropsis* market is expected to continue its growth trajectory, with significant advancements in microalgae cultivation and biotechnology.

([130]) Ye, Y., Liu, M., Yu, L., et al. (2024). "Nannochloropsis as an Emerging Algal Chassis for Light-Driven Synthesis of Lipids and High-Value Products" Marine Drugs 22, no. 2: 54. https://doi.org/10.3390/md22020054

([131]) Senousy, H. H., El-Sheekh, M. M., Khairy, H. M., et al. (2023). Biodiesel Production from the Marine Alga Nannochloropsis oceanica Grown on Yeast Wastewater and the Effect on Its Biochemical Composition and Gene Expression. Plants, 12(16), 2898. https://doi.org/10.3390/plants12162898

6. Conclusions and recommendations

6.1. Conclusions

The findings of the study have led to the following conclusions:

1. Cultivation and production of algae generate lower greenhouse gas emissions compared to other conventional proteins.

Typically, the cultivation and production of algae generate lower greenhouse gas emissions compared to other proteins (with the exception of *Tetraselmis chuii,* the species with the lowest market readiness; in this case, the production is not yet performed in the most efficient manner, unlike other studied species, namely *A. platensis (Spirulina), Chlorella vulgaris, Saccharina latissima, Alaria esculenta, and Ulva rigida)*. Thus, the greenhouse gas emissions per kg of protein produced can also differ substantially among different algae species.

2. There is a need for establishing harmonised LCA frameworks to improve understanding of algae's environmental benefits and to integrate algae-based proteins into sustainable food systems.

Certain algae species – particularly *Spirulina*, *Saccharina latissima*, and *Alaria esculenta* – offer promising potential for reducing GHG emissions when used as food or feed alternatives to animal proteins. However, variability in LCA methodologies, the complexity of production processes, low technological readiness levels (TRLs), and seasonal variation of biomass currently hinder accurate and comparable assessments.

3. Despite the global growth of the algae industry, the European algae industry remains limited.

The European algae industry is still very limited and mostly focused on wild harvesting (99%) rather than on cultivation. Current seaweed production in Europe is primarily directed at food and related applications (such as supplements). The production is dominated by Norway (160,000 tonnes per year, 61% of all European production), followed by France (50,000 tonnes) and Ireland (30,000 tonnes).

4. Algae consumption remains low in Europe (<1 kg per capita annually), especially compared to Asia (2+ kg).

Cultural unfamiliarity, regulatory bottlenecks, and limited availability hinder market growth. While algae consumption is not yet mainstream in most European diets, consumer interest is rising. Half of respondents said they enjoy the taste of algae products, and a third believe algae offer health benefits. Other key market

drivers include sustainability awareness and the rise of plant-based diets. European consumers are beginning to recognise the benefits of algae consumption, and early adopters report positive experiences, but broader education, normalisation, and marketing towards health and environmental benefits will be key to increasing regular consumption.

Drivers to increase algae consumption include their nutritional benefits, making algae attractive for consumers and food companies focused on health benefits and plant-based diets. Environmentally, algae are sustainable as they require no arable land or freshwater and absorb carbon and excess nutrients.

5. The algae industry has considerable potential to boost employment in respective areas/regions of cultivation.

Studies done in the North Sea region suggest that macroalgae cultivation can generate 2 to 4 full-time equivalent jobs per hectare, particularly in coastal and rural zones where alternative employment may be limited. Thus, if supported by public investment and regulatory clarity, a European algae industry has the potential to contribute to both climate goals and the blue economy.

6. The regulatory framework for algae in food remains a significant barrier in the EU.

Under the current EU novel food rules, many promisining algae species fall outside the approved list, despite being part of traditional diets. In addition, food safety rules limiting heavy metals and iodine in algae decrease consumer trust. Experts argue that these regulations should be updated to current scientific standards.

7. The lack of information about suitable conditions hampers the advancement of the algae industry.

The potential of large-scale seaweed cultivation and its contribution to achieving ambitious objectives is widely recognised. However, the lack of information on the suitability of EU marine regions for the installation of macroalgae cultivation infrastructures hampers progress. One of the biggest challenges lies in gathering and harmonising data, as well as refining models to better reflect the species' ecological factors, which requires considerable effort (e.g., water temperature, nutrient availability, ocean currents, and ecosystem compatibility).

8. Scalability and cost-competitiveness of European-produced algae remain key challenges to date, limiting the growth of the sector.

Business case analysis shows that reduced production costs would enhance the competitiveness of European algae products, as well as promote circular business models. In the case of *Chlorella*, it was found that reduced production costs would enhance its competitiveness as a feed ingredient, particularly in high-value livestock systems. Its use could support circular models aligned with EU

sustainability goals, contributing to waste valorisation, local protein production, and the broader objectives of the Green Deal and Farm to Fork Strategy.

9. While *Asparagopsis* appears as a promising tool for mitigating greenhouse gas emissions in agriculture and delivering economic benefits to farmers, there are serious concerns about its possible health impacts on animals and humans.

Study results show that *Asparagopsis* can reduce methane emissions from ruminants by over 50% at low inclusion rates (0.2–0.5% of dry matter intake) and by more than 80% at around 1% inclusion, while potentially improving feed efficiency and animal performance. This positions *Asparagopsis* as a promising tool for mitigating greenhouse gas emissions in agriculture and delivering economic benefits to farmers. However, concerns over the presence of **bromoform** and **iodine**, and their possible health impacts on animals and humans, highlight the need for **long-term studies and regulatory oversight.** Observed effects such as rumen inflammation and bromoform excretion in some cases underscore the importance of cautious and science-based integration. Combining *Asparagopsis* with complementary approaches, such as genetic selection for low-methane livestock, could further enhance its impact.

6.2. Recommendations

1. The potential environmental and ecological risks of large-scale seaweed farming (e.g. effects on local marine ecosystems, biodiversity, and nutrient cycles) must be thoroughly assessed.
2. Policymakers and other stakeholders should invest in R&D and biotech innovation, while also providing financial support to algae farmers and start-ups.
3. The regulatory framework for the algae sector should be simplified, with increased awareness through marketing, education, and engagement with influencers.
4. The approved species list for algae under EU Novel Food legislation should be expanded. Streamline authorisation for safe algae species with a tradition of consumption to broaden the permitted range of algae ingredients in food.
5. Update food safety regulations in line with current scientific understanding. Set clear EU benchmarks for the safety of algae products (e.g. maximum permissible levels of iodine and heavy metals) to ensure consumer protection and build trust in algae-based foods.
6. Enhance labelling and consumer information. Ensure that algae-based products feature clear, transparent labelling regarding content, origin, and nutritional benefits. Clear labelling will aid consumer recognition and help

normalise algae in everyday diets. Consumers should be able to easily identify algae ingredients in products to overcome perceptions of unfamiliarity.

7. Promote algae within food education and culture. Encourage Member States to include algae in dietary guidelines and educational programmes, emphasising its nutritional and sustainability benefits.

8. Provide financial incentives and business support to algae-based food SMEs and start-ups seeking to enter mainstream commercial markets. This will facilitate market entry, introduce algae to a wider audience, and build market confidence for larger food companies to invest in algae-based products.

9. Cooperation and integration with agricultural and fisheries policies are essential for the development of the European algae industry. This includes ensuring that frameworks such as the Common Agricultural Policy (CAP) and Common Fisheries Policy (CFP) explicitly support algae sector development.

10. Asparagopsis shows promising potential for reducing greenhouse gas emissions in livestock production. However, due to outstanding safety concerns and high production costs - particularly in land-based cultivation - widespread adoption is not yet recommended. Further research is needed to address these challenges and to explore how integrating Asparagopsis with other mitigation strategies may enhance overall sustainability and effectiveness.

11. Further research should identify optimal cultivation zones for different algae species using GIS tools and models. Higher-resolution models are needed to assess site suitability at more localised scales, accounting for seasonal and climatic variations and species-specific resilience.

12. Consumer awareness campaigns could help overcome concerns about taste and accessibility by promoting the integration of algae into familiar foods and eating habits, thereby enhancing market acceptance.

13. Supportive policies and streamlined regulations can help strengthen the algae market in Europe. These should complement strategies that encourage collaboration among stakeholders in agriculture, aquaculture, and biotechnology. This includes updating regulatory frameworks to support the use of algae as a feed ingredient while addressing safety and sustainability concerns.

14. Transitioning to controlled cultivation systems and promoting stakeholder collaboration would help fortify the European algae industry.

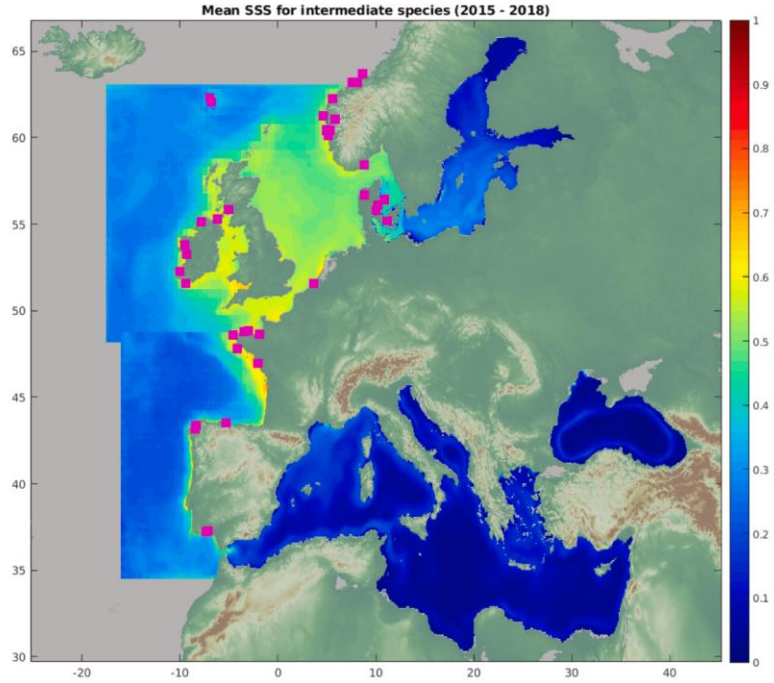
15. To fully realise the potential of algae species and the broader industry, it is essential to standardise research on animal and human health, environmental benefits, and nutritional value. This will ensure consistent

data on the feasibility of algae as a feed ingredient. Further studies are also needed to assess long-term impacts and optimise feeding logistics.

16. Support targeted research and risk-benefit assessments of *Asparagopsis* as a methane-reducing feed additive, while advancing regulatory and safety frameworks to enable its safe and effective integration into ruminant diets.

17. Promote the development of clear, standardised life cycle assessment (LCA) guidelines for algae value chains to better quantify and compare their GHG reduction potential as sustainable alternatives to conventional animal-based proteins.

APPENDIX A – Potentiality of EU Maritime Regions



Source: Macias et al. (2025) ([132]).

Note: To determine which types of seaweed have the highest potential for cultivation in EU marine regions, we assessed the total area where the mean sea surface salinity (SSS) exceeds 0.5, following the criteria established by van Oort et al. (2023). The integrated results clearly indicate that both intermediate and cold-water species are more suitable for cultivation, with mean suitable areas of 1.45 and 1.1 million km², respectively. In contrast, warm-water species appear to have limited potential, with a mean suitable area of just 2,160 km². The analysis covers suitable areas for the cultivation of intermediate seaweed species (SSS > 0.5) across the five EU marine regions.

([132]) Macias et al. (2025). Assessing the potential for seaweed cultivation in EU seas through an integrated modelling approach. *Aquaculture*, 594. https://doi.org/10.1016/j.aquaculture.2024.741353

APPENDIX B – Favourable and unfavourable factors in EU maritime regions for seaweed and *Asparagopsis* cultivation

Maritime region	Favourable and limited factors for seaweed cultivation (salinity, water temperature, etc.)	Favourable and limited factors for *Asparagopsis* cultivation
Mediterranean Sea	A large suitable area exists for warm-water species, especially during the winter months, when warmer temperatures and higher nutrient availability are favourable for growth. However, low nutrient levels and elevated summer temperatures may hinder growth during the warmer seasons, while salinity levels could present challenges for cold-water species. Competition for space with existing aquaculture and marine conservation efforts also poses challenges.	Warmer winter temperatures provide a favourable environment for growth; however, limited light and short photoperiods during this season are not conducive to optimal development. Additionally, low nutrient availability significantly constrains overall growth potential and poses a major challenge to successful cultivation.
Black Sea	Limited variation in salinity, along with seasonal temperature fluctuations, presents additional difficulties for large-scale cultivation. Some areas are suitable for cold-water species, but low salinity and cold temperatures can hinder the growth of both intermediate and cold-water varieties. While nutrient-rich regions offer potential, phosphate limitations in coastal zones may still act as a constraint.	Nutrient-rich areas can support *Asparagopsis* under specific conditions, though low salinity and cold temperatures create unfavourable conditions for its cultivation.
North Sea	Cold temperatures and strong currents challenge natural seaweed growth and productivity; however, these can be mitigated through controlled aquaculture methods. The extensive coastline and nutrient availability offer potential, though high wave exposure and competition for maritime space may limit the feasibility of large-scale cultivation.	Nutrient availability and colder waters create suitable conditions. However, high wave action and strong currents may pose challenges.
Baltic Sea	Low salinity and cold temperatures may restrict the growth of certain species. Nonetheless, shallow waters offer potential for cultivating cold-water species, particularly in areas with increasing nutrient availability.	*Asparagopsis* is not well-suited due to unfavourable salinity and temperature conditions, though controlled environments could mitigate these challenges.
Atlantic Coast	Some regions of Portugal, Spain, France, and Ireland offer favourable conditions, positioning this area as a potential hotspot for seaweed cultivation. The dynamic Atlantic coastline, rich in nutrients, presents promising prospects in specific locations. Site-specific studies will be necessary to assess commercial viability. Over 1 million km² of marine area is considered suitable for both cold and intermediate species. Certain zones may also support year-round cultivation; however, high wave heights and strong currents in some areas could hinder large-scale operations.	The Atlantic Coast offers ideal nutrient conditions and cooler temperatures, making it highly suitable for *Asparagopsis* cultivation. However, strong wave may present challenges for successful farming.

Source: Macias et al. (2025) ([133]).

([133]) Macias et al. (2025). Assessing the potential for seaweed cultivation in EU seas through an integrated modelling approach. *Aquaculture*, 594. https://doi.org/10.1016/j.aquaculture.2024.741353

APPENDIX C – Main seaweed species cultivated in the EU

Class	Species	Intermediate/cold
Brown	*Alaria esculenta*	Cold
Brown	*Alaria marginata*	Cold
Brown	*Alaria* sp.	Cold
Brown	*Ascophyllum nodosum*	Cold
Brown	*Fucus serratus*	Cold
Brown	*Fucus vesiculosus*	Cold
Brown	*Himanthalia elongata*	Cold
Brown	*Himanthalia* sp.	Cold
Brown	*Laminaria digitata*	Cold
Brown	*Laminaria hyperborea*	Cold
Brown	*Laminaria* sp.	Cold
Brown	*Saccharina latissima*	Cold
Brown	*Undaria pinnatifida*	Cold
Brown	*Undaria* sp.	Cold
Green	*Codium tomentosum*	Intermediate
Green	*Ulva intestinalis*	Intermediate
Green	*Ulva lactuca*	Intermediate
Green	*Ulva* sp.	Intermediate
Green	*Ulvella lens*	Intermediate
Red	*Falkenbergia* sp.	Intermediate
Red	*Asparagopsis* sp.	Intermediate
Red	*Calliblepharis jubata*	Intermediate
Red	*Chondrus crispus*	Intermediate
Red	*Chondrus* sp.	Intermediate
Red	*Gracilaria* sp.	Intermediate
Red	*Palmaria palmata*	Intermediate
Red	*Porphyra umbilicalis*	Intermediate
Red	*Vertebrata lanosa*	Intermediate

Source: Kotta et al. (2022) ([134]); van der Burg et al. (2013) ([135]); van der Molen et al. (2018); Vazquez Calderon & Sanchez (2022) ([136]).

([134]) Kotta et al. (2022). Progress in Polymeric Micelles for Drug Delivery Applications. Pharmaceutics, 14(8), 1636. https://doi.org/10.3390/pharmaceutics14081636
([135]) van der Burg, S., et al. (2013). A Triple P review of the feasibility of sustainable offshore seaweed production in the North Sea. Wageningen, Wageningen UR (University & Research centre), LEI Report 13-077. Available here.
([136]) Vazquez, Calderon, F. & Sanchez, L.J. (2022). An overview of the algae industry in Europe, Guillen Garcia, J. and Avraamides, M. editor(s), Publications Office of the European Union, Luxembourg, https://dx.doi.org/10.2760/813113

APPENDIX D – Hindering factors for an *Asparagopsis* supply chain

Hindering Factors	Context
Political	There is substantial political will through the EU Green Deal and the EU Algae Initiative. Both provide a strong foundation for algae cultivation by aligning with the EU's goals of sustainability and carbon reduction. The Green Deal targets climate neutrality by 2050, with algae seen as playing a key role in reducing methane emissions. The Algae Initiative supports the growth of algae-based industries through research and innovation. Additional initiatives across the EU underscore growing political and financial support for algae-based solutions. Several member states have introduced national roadmaps: *France 2030* promotes algae-based industries; Denmark's *National Algae Roadmap* focuses on scaling algae farming for bioenergy and livestock feed; Germany's *Bioeconomy Strategy* includes algae as a key component in the transition to a circular economy; Spain's *Algae R&D Projects* support algae research in agriculture; and Ireland's *National Marine Planning Framework* leverages coastal resources to foster sustainable marine industries.
Economic	The high costs of algae cultivation and processing continue to limit scalability and investment returns. Additionally, the market for *Asparagopsis* is constrained by low awareness of its benefits among both farmers and consumers. Addressing these barriers will require cost-reducing technologies – such as automated farming systems and remote monitoring – alongside subsidies and financial incentives. National governments and industry bodies can contribute by promoting awareness and incentivising adoption, for example through carbon credit schemes. Investment at the local level in processing hubs and marine biomass infrastructure could also help resolve logistical challenges. Other factors hindering production include financial constraints, particularly the high upfront capital investment required for cultivation systems, especially offshore. Access to affordable aquaculture land is limited, and the lack of economies of scale increases production costs. Market uncertainty, limited private investment, and a lack of industry standardisation exacerbate these challenges. Regulatory barriers – such as protracted approval processes and environmental assessment requirements – can further delay market entry and inflate costs ([137]).
Social	Social acceptance is vital to the success of marine-based feed additives like *Asparagopsis*. Concerns about incorporating marine-derived ingredients into livestock diets often stem from perceptions that they are unnatural. Public education campaigns should emphasise the environmental benefits of algae-based feeds, particularly their role in reducing methane emissions and promoting sustainability. Building trust through collaboration with stakeholders – including farmers and industry groups – is essential. Demonstration projects involving early adopters in the livestock sector can raise awareness and highlight added value opportunities such as carbon credits or premium pricing for low-emission products. At the consumer level, education campaigns can help shift perceptions and increase acceptance ([138]).

([137]) Kuech, A., Breuer, M., & Popescu, I. (2023). Research for PECH Committee – The future of the EU algae sector, European Parliament, Policy Department for Structural and Cohesion Policies, Brussels. Available here.
([138]) EIT studies. EIT food strategic agenda 2021-2027.

Hindering Factors	Context
Technological	Scientific research on marine algae cultivation is advancing, supported by initiatives like Horizon Europe, which funds studies on aquaculture systems and farming techniques. These efforts aim to address challenges in scaling up algae production across Europe's varied maritime regions, including gaps in knowledge around *Asparagopsis* cultivation and insufficient upscaling technologies from seeding to harvesting and processing. Investments in R&D, start-ups, and supporting ecosystems are essential to fill these gaps and facilitate wider industry adoption. A major barrier remains the lack of infrastructure for large-scale production, transportation, and processing. A dedicated logistics network for marine biomass – accounting for perishability and ensuring timely delivery to processing facilities – is urgently needed ([139]).
Environmental	The ecological impacts of algae cultivation, particularly those linked to by-products like bromoform, raise concerns. Regional, seasonal, and climatic variations – as well as potential ecological risks such as invasive growth or competition with native species – must be assessed. Environmental impact assessments are necessary to identify suitable maritime zones and to evaluate species resilience. These studies, and the permits they require, depend on national and regional authorities. Land-based alternatives offer more controlled conditions that reduce ecological risks, such as marine disruption or invasive spread. However, land-based systems come with high energy, water, and infrastructure costs, making large-scale production expensive. While they offer significant sustainability benefits, addressing economic and logistical barriers will be key to their viability ([140]).
Legal	The lack of harmonised regulations for algae across EU member states hampers the development of algae-based feed additives. To overcome this, regulatory frameworks should be unified at the EU level, and approval processes streamlined. This would require coordinated action from EU institutions, while implementation and enforcement remain with national authorities. The focus should be on aligning policy frameworks with broader sustainability targets set by the Paris Agreement and COP26. Achieving this will require a coordinated approach encompassing regulatory simplification, financial support, and the development of a stable, demand-driven market for algae-based products across the EU ([141]).

([139]) The EU Blue Economy Report published in 2021 by the European Commission explores potential for technological advancements in marine industries. Algal Research Journal discusses breakthroughs in aquaculture technologies.
([140]) UNEP FI and GIZ's "Nature-based Solutions in Oceans and Coastal Ecosystems" published in 2023 evaluates ecological considerations of algae farming.
([141]) EU Farm to Fork Strategy. EFSA Feed Additive Guidance process for approving novel additives.

APPENDIX E – Discussing microalgae as a feedstuff or additive to feedstuff – Summary of main and recent research papers

Title	Author(s)	Year	Abstract/conclusions/content	Algae type	Animal & method	Inclusion rate/amount (g/kg BW or g/day)	Impact on methane emissions (reduction)	Animal health/welfare	Risks & safety/general concerns or comments
Micro- and Macroalgae Combination as a Novel Alternative Ruminant Feed with Methane-Mitigation Potential	Eslam et al.	2023	This study was conducted to explore an alternative high-quality feed source and to reduce methane production using a combination of the minimum effective levels of *Euglena gracilis* (EG) ([142]) and *Asparagopsis taxiformis* (ATA 24-hour *in vitro* batch culture system was used for the experiment. Chemical analysis showed that EG is a highly nutritious material, containing 26.1% protein and 17.7% fat. The mixtures of 1% AT with either 10% or 25% EG demonstrated a greater methane-reducing potential than individual supplementation of these algae, decreasing methane yield by 29.9% and 40.0%, respectively. This combined approach offers a dual benefit: it provides a high-quality alternative feed while reducing CH_4 emissions using lower levels of AT. These findings suggest a promising strategy for sustainable livestock production. The results of this *in vitro* study should serve as a foundation for future *in vivo* trials to confirm the efficacy of the EG and AT mixture.	Euglena gracilis (EG)	Holstein cows In vitro	10% and 25% of the diet replacing concentrate mixture	Reduced by 4% and 11% respectively	No adverse effects	
				Asparagopsis taxiformis (AT)	Holstein cows In vitro	1% and 2.5% of the diet as feed additive	Reduced by 21.3% (1%) and 80.1% (2.5%)	No adverse effects	
				Combination (EG + AT)	Holstein cows In vitro	AT 1% + EG 10% AT 1% + EG 25%	Reduced by 29.9% Reduced by 40%	No adverse effects	
Strategies Used to Reduce Methane Emissions from Ruminants:	Królicze wska et al.	2023	The main and important objective of this paper is to critically discuss the current strategies proposed to reduce methane emissions from livestock (see also Table 6.3.2 Other mitigation strategies for methane emissions in ruminants)						
				Algae			Reduced by 9–98% depending on species/dose		Excess bromoform and iodine may pose risks to milk safety and animal health. Chronic exposure linked to tumours.

([142]) Euglena gracilis (EG) is a freshwater microalga known for its high protein and fat content. However, there is limited research on EG's impact on ruminal fermentation and methane production. EG is commercially produced by Euglena Co., Ltd. in Japan, which has large-scale facilities for its cultivation on Ishigaki Island. Further research could enhance EG's use as a sustainable feed with greater methane reduction potential.

Title	Author(s)	Year	Abstract/conclusions/content	Algae type	Animal & method	Inclusion rate/amount (g/kg BW or g/day)	Impact on methane emissions (reduction)	Animal health/welfare	Risks & safety/general concerns or comments
Controversies and Issues									Environmental concerns over bromoform toxicity and CO_2 emissions from algae farming. Disruptions to marine biodiversity and GHG offset considerations required. Land-based systems still in development. Requires careful monitoring in feed systems.
Enteric methane mitigation through *Asparagopsis taxiformis* supplementation and potential algal alternatives	Wasson et al.	2022	Several studies, both *in vitro* and *in vivo*, have demonstrated the effectiveness of *Asparagopsis taxiformis* in reducing enteric methane (CH_4) emissions by over 80%. However, questions remain regarding its sustainability, impact on animal productivity and product quality, and overall commercial viability. These concerns do not disqualify the practice of using macroalgae as a feed additive for methane mitigation, but they must be addressed before large-scale commercial implementation can occur. Multiple *in vitro* studies have also shown the methane reduction potential of non-bromoform-containing macroalgae species. However, effective inclusion levels in these cases are typically much higher than those required for *A. taxiformis* (i.e. less than 0.5% of dietary dry matter). In some animal studies, supplementation with *A. taxiformis* has been associated with reduced dry matter intake and productivity, as well as increased accumulation of minerals such as iodine in animal-derived products. Therefore, to be practical and acceptable, methane mitigation through macroalgae is likely to require low dietary inclusion rates. This review aims to highlight both the potential benefits and the challenges of using macroalgae as a methane mitigation strategy in livestock systems. It focuses on rumen manipulation via feed additives – specifically macroalgae – as a potentially viable approach. The aim of this paper is twofold: (1) to evaluate the practicality and use of *A. taxiformis* as a methane-reducing feed additive for ruminants, and (2) to explore the potential of other bioactive algal compounds to reduce CH_4 emissions or enhance animal performance. A growing body of research indicates that low-level inclusion (≤ 1% of dietary dry matter) of *A. taxiformis* can substantially reduce, or even eliminate, enteric CH_4 production. See Annex Table Summary 1 for a compilation of relevant studies.						
			Demonstrated that *Asparagopsis taxiformis* inclusion with Flinders grass hay reduced CH_4 production by 99% in vitro.						
			Machado et al., 2014	*Asparagopsis taxiformis*	Cattle In vitro	20% OM	Reduced by 98.9%	No direct animal health impact reported	Most effective species for methane mitigation; highest molar concentration of propionate. Further research needed in vivo.
			Confirmed the antimethanogenic effect, with bromoform being the primary compound responsible for this effect.						
			Kinley et al. (2016) Machado et al. (2016) Machado et al. (2018)	*Asparagopsis taxiformis*	In vitro	At doses below 2% substrate DM			
			Demonstrated that *A. taxiformis* was effective at reducing in vitro methane production at even lower inclusion rates (0.5 mg/g of DM).						

Title	Author(s)	Year	Abstract/conclusions/content	Algae type	Animal & method	Inclusion rate/amount (g/kg BW or g/day)	Impact on methane emissions (reduction)	Animal health/welfare	Risks & safety/general concerns or comments
			Chagas et al. (2018)	*Asparagopsis taxiformis*	In vitro	0.5 mg/g of DM			
			Demonstrated that in vivo supplementation of *A. taxiformis* (0.5 to 3% OM basis) in sheep reduced CH_4 emissions 50 to 80% over 72 days.						
			Li et al. (2018)	*Asparagopsis taxiformis*	Sheep In vivo	0.5 to 3% OM basis	Reduced by 50 to 80% over 72 days		
			Asparagopsis armata, reduced methane intensity (g/kg milk yield) by 60% and CH_4 yield by 43% when fed at 1% OM to lactating dairy cows.						
			Roque et al. (2019)	*Asparagopsis armata*	Lactating dairy cows		Reduced by 43% Reduced methane intensity (g/kg milk yield) by 60%	DMI decreased by 38%	
			Established no decrease in bromoform concentration from *A. taxiformis* that had been freeze dried and stored at -20°C for 20 weeks.						
			Romanazzi et al. (2021)						
Benefits and risks of including the bromoform containing seaweed *Asparagopsis* in feed for the reduction of methane production from ruminants	Glasson et al.	2022	The seaweeds *Asparagopsis taxiformis* and *Asparagopsis* armata included at low levels in the feed of cattle and sheep inhibit methanogenesis by up to 98%, with evidence of improvements in feed utilisation efficiency. This review focuses on the relevant ruminal biochemical pathways, degradation, and toxicological risks associated with bromoform (in *Asparagopsis*, and the effects that production of *Asparagopsis* and its use as a ruminant feed ingredient might have on atmospheric chemistry. Greenhouse gas emission management strategies including methanogenesis inhibitors provide an effective measure, with *Asparagopsis* (bromoform) the most promising performer to date. However, methane production utilises excess [H] generated during rumen fermentation and subsequent H_2 production, and, like methane emissions but to a lesser degree, energy lost as H2 emissions represent a feed utilisation inefficiency, and excessive H_2 has potential to reduce the efficiency of rumen fermentation. Alternative [H] sinks have been identified but more research is required to verify and optimise feed formulations to increase productivity across different production systems. Our modelling analyses in this review demonstrate that the risk of *Asparagopsis* contributing to ozone depletion is very small relative to the collective total of all natural and anthropogenic sources of bromine.						
				Asparagopsis taxiformis			Up to 98%, with evidence of improvements in feed utilisation efficiency	Animal health is not compromised at the minimum effective feed inclusion levels (at or near the minimum effective feed	Product quality is not compromised (at or near the minimum effective feed inclusion levels) Large-scale aquaculture of *Asparagopsis* and its application in methane mitigation strategies for ruminants at or near minimum effective inclusion levels, may not negatively impact ozone depletion. Research to develop effective production and management

Title	Author(s)	Year	Abstract/conclusions/content	Algae type	Animal & method	Inclusion rate/amount (g/kg BW or g/day)	Impact on methane emissions (reduction)	Animal health/welfare	Risks & safety/general concerns or comments
								inclusion levels)	protocols, and strategies for the aquaculture and processing of *Asparagopsis* targeting maximum bioactivity (e.g. by minimising bromoform losses) is needed
Effects of the macroalga *Asparagopsis taxiformis* and oregano leaves on methane emission, rumen fermentation, and lactational performance of dairy cows	Stefenoni et al.	2021	This study comprised two *in vitro* and two *in vivo* experiments. Experiment 1 aimed to establish the effect of AT on methane (CH_4) emissions *in vitro*. Two *in vivo* experiments (Experiments 2 and 3) involving lactating dairy cows were conducted to evaluate the antimethanogenic effects of AT and oregano (in Experiment 3). A further experiment (Experiment 4) investigated the stability of bromoform ($CHBr_3$) in AT over time. In Experiment 3, twenty Holstein cows were used in a replicated 4 × 4 Latin square design over four 28-day periods. Treatments consisted of a basal diet (control), or the basal diet supplemented (on a dry matter basis) with 0.25% AT (LowAT), 0.50% AT (HighAT), or 1.77% oregano (*Origanum vulgare* L.) leaves. Enteric gas emissions were measured using the GreenFeed system (C-Lock Inc., Rapid City, SD), and rumen samples were collected for fermentation analysis using the ororuminal technique. In the *in vitro* Experiment 1, AT (at 1% of dry matter) reduced CH_4 yield by 98% relative to the control. In Experiment 3, HighAT reduced average daily CH_4 emissions and CH_4 yield by 65% and 55%, respectively, during experimental periods 1 and 2, but had no effect in periods 3 and 4. This variability in response across periods was likely due to a decline in $CHBr_3$ concentration in AT over time, as observed in Experiment 4, where up to an 84% decrease occurred over four months of storage. In Experiment 3, AT increased hydrogen (H_2) emissions, and as expected, the proportion of acetate among total volatile fatty acids in the rumen decreased, while the proportions of propionate and butyrate increased with HighAT compared to the control. HighAT also reduced dry matter intake, milk yield, and energy-corrected milk yield. Milk composition was largely unaffected by treatment, except that lactose percentage and yield were reduced with HighAT. Iodine and bromide concentrations in milk increased under the HighAT treatment. However, $CHBr_3$ concentrations and organoleptic properties of the milk did not differ between the control and HighAT treatments. Oregano supplementation had no effect on CH_4 emissions or lactational performance in Experiment 3. Overall, inclusion of AT at 0.50% in the diet of dairy cows can significantly mitigate enteric CH_4 emissions, although it may also reduce feed intake and milk production. The CH_4 mitigation effect of AT diminished in the latter half of Experiment 3, likely due to degradation of $CHBr_3$ over time.						
				Asparagopsis taxiformis (AT)	Dairy cows In vitro & in vivo	1% DM (in vitro) 0.25%, 0.50%, 1.77% DM (in vivo)	In vitro: reduced by 98% In vivo: reduced CH4 by 65% (HighAT) in periods 1 and 2	Decreased DMI, milk yield, and energy-corrected milk yield in HighAT group	Bromoform residue in milk; Iodine and bromide concentrations increased in milk with HighAT. AT had significant methane mitigation but also decreased milk yield and DMI. Bromoform concentration decreased over time in AT.
Red seaweed (*Asparagopsis taxiformis*) supplementation reduces enteric	Roque et al.	2021	The red macroalga (*Asparagopsis* sp.) has been shown to reduce ruminant enteric methane (CH_4) production by up to 99% *in vitro*. The objective of this study was to assess the effect of *Asparagopsis taxiformis* on CH_4 production (g/day per animal), yield (g CH_4/kg dry matter intake [DMI]), and intensity (g CH_4/kg average daily gain [ADG]); as well as on ADG (kg gain/day), feed conversion efficiency (FCE; kg ADG/kg DMI), and carcass and meat quality in growing beef steers. 21 Angus–Hereford beef steers were randomly assigned to one of three treatment groups: 0% (Control), 0.25% (Low), and 0.5% (High) *A. taxiformis* inclusion, based on organic matter intake. Steers were fed three diets – high- , medium-, and low-forage total mixed rations (TMRs) –						

Title	Author(s)	Year	Abstract/conclusions/content	Algae type	Animal & method	Inclusion rate/amount (g/kg BW or g/day)	Impact on methane emissions (reduction)	Animal health/welfare	Risks & safety/general concerns or comments
methane by over 80 percent in beef steers			representing life-stage diets for growing beef steers. Over a 147-day period, the Low and High *A. taxiformis* treatments reduced enteric CH_4 yield by 45% and 68%, respectively.						
				Asparagopsis spp	Angus-Hereford beef steers	0%, 0.25%, 0.5% of OM intake Steers were fed 3 diets: high, medium, and low forage total mixed ration (TMR)	Reduced CH_4 yield: 45% (Low), 68% (High). Low forage TMR: CH_4 yield reduced 69.8% (Low) and 80% (High).	No differences in carcass/meat quality, or consumer taste.	Increased H_2 yield by 336% (Low) and 590% (High). Increased CO_2 yield by 13.7% (High). No bromoform or iodine residues. Viable for reducing ruminant carbon footprint. Low forage TMR enhances CH_4 mitigation. No adverse effects on meat quality. Improved FCE reduces production costs. Localized cultivation suggested for sustainability.
Safety and Transfer Study: Transfer of Bromoform Present in *Asparagopsis taxiformis* to Milk and Urine of Lactating Dairy Cows	Muizelaar et al.	2021	This study investigated the transfer of bromoform ($CHBr_3$) present in *Asparagopsis taxiformis* (AT) to milk, urine, faeces, and animal tissues when incorporated into the diets of dairy cows. Twelve lactating Holstein-Friesian cows were randomly assigned to three treatment groups: a target dose (low), twice the target dose (medium), and five times the target dose (high). Following a 7-day adaptation period, cows were fed AT for up to 22 days. $CHBr_3$ was detected in urine on days 1 and 10 across all treatment groups (10–148 µg/L). On day 1, $CHBr_3$ was also found in the milk of most cows in the low and medium groups (9.1 and 11 µg/L, respectively), and in the milk of one cow in the high group on day 9 (35 µg/L). By day 17, bromoform was no longer detectable in either milk or urine. No $CHBr_3$ concentrations above the detection limit were found in faeces or collected tissues. Two cows in the low-dose group were sacrificed for further examination; their rumen walls displayed abnormalities, and histological analysis revealed signs of inflammation. Feed refusal and selective avoidance of AT were observed in several animals. In conclusion, under the conditions of this study, $CHBr_3$ does not appear to accumulate in animal tissues but may be transiently excreted in urine and milk.						
				Asparagopsis taxiformis	Lactating Holstein-Friesian dairy cows	Low, Medium, High (target doses: low = 1x, medium = 2x, high = 5x)	Strongly decreases CH_4 emissions (up to 99% in other studies)	Reduced voluntary feed intake at all treatment levels; some cows refused or selectively avoided feed. Bromoform detected in milk, urine, but not in tissues.	Potential toxicological effects of bromoform, especially inflammation of rumen wall papillae in some cows. Further studies needed to assess long-term effects of *A. taxiformis* on the rumen and bromoform metabolism in dairy cows

Title	Author(s)	Year	Abstract/conclusions/content	Algae type	Animal & method	Inclusion rate/amount (g/kg BW or g/day)	Impact on methane emissions (reduction)	Animal health/welfare	Risks & safety/general concerns or comments
								Rumen wall abnormalities.	
Mitigating the carbon footprint and improving productivity of ruminant livestock agriculture using a red seaweed	Kinley and al.	2020	We investigated the marine red macroalga *Asparagopsis taxiformis* as a feed ingredient to substantially reduce enteric methane emissions in beef cattle fed a high-grain diet, while also evaluating its effects on livestock production performance. *Asparagopsis* was incorporated into the diets of Brahman–Angus cross steers at 0.00%, 0.05%, 0.10%, and 0.20% of feed organic matter. Emissions were measured fortnightly over 90 days using respiration chambers. Steers were weighed weekly prior to feeding; feed intake was recorded daily. Rumen fluid samples were collected alongside emissions data to assess rumen function. Faecal samples were analysed for bromoform residues, and meat, organs, and fat were collected post-slaughter for residue testing and sensory evaluation. Enhancements in the quality of *Asparagopsis* – through optimised cultivation and processing – could further reduce effective inclusion levels, minimise mineral exposure, and improve supply chain efficiency. The findings suggest that enteric methane emissions can be almost entirely eliminated by incorporating *Asparagopsis* into the high-grain TMR of feedlot beef cattle.						
				Asparagopsis taxiformis	Brahman-Angus cross steers	0.00%, 0.05%, 0.10%, 0.20% of diet OM	Reduction by 40% (0.10%), 98% (0.20%).	No bromoform residues detected in meat, fat, or organs. Improved weight gain by 53% (0.10%) and 42% (0.20%). No negative effects on DMI, feed conversion, or rumen function.	Supports global emissions targets; creates new economies and enhances livestock productivity.

Source: Technopolis.

Note: Ordered by year of publication, from most recent to less recent.

APPENDIX F – Summary of in vivo seaweed studies in which enteric CH4 emissions was measured

TABLE 1 Summary of *in vivo* seaweed studies, in which enteric CH_4 emission was measured. .

Seaweed	Animal	n (design)	Study duration (d)	Seaweed inclusion level	$CHBr_3$intake (mg/d)	CH_4 g/kg of DMI (Δ%)	DMI (Δ%)	Productivity[1] (Δ%)	$CHBr_3$ residue[2]	Reference
A. taxiformis	Sheep	5 (Ctn)	72	0.5% OM	0.07	n.s.	n.s.	-	n.s.	Li et al., 2018
A. taxiformis	Sheep	5 (Ctn)	72	1.0% OM	0.14	-52	n.s.	-	n.s.	Li et al., 2018
A. taxiformis	Sheep	5 (Ctn)	72	2.0% OM	0.16	-62	n.s.	-	n.s.	Li et al., 2018
A. taxiformis	Sheep	5 (Ctn)	72	3.0% OM	0.18	-81	n.s.	-	n.s.	Li et al., 2018
Ascophyllum nodosum	Dairy cows	7 (Ctn)	112	113 g/h/d	–	n.s.	n.s.[a]	n.s.	–	Antaya et al., 2019
A. armata	Dairy cows	12 (3 × 3 LS)	21	0.50% OM	0.44	-26	-10	n.s.	n.s.	Roque et al., 2019
A. armata	Dairy cows	12 (3 × 3 LS)	21	1.0% OM	0.62	-67	-38	-11.6[b]	n.s.	Roque et al., 2019
A. taxiformis	Beef cattle	5 (Ctn)	60	0.05% OM	0.1	-9	n.s.	n.s.	n.s.	Kinley et al., 2020
A. taxiformis	Beef cattle	5 (Ctn)	60	0.10% OM	0.25	-38	n.s.	51[c]	n.s.	Kinley et al., 2020

A. taxiformis	Beef cattle	5 (Ctn)	60	0.20% OM	0.45	-98	n.s.	42[c]	n.s.	Kinley et al., 2020
A. taxiformis	Beef cattle	6 (Ctn)	147	0.25% OM	0.87	-51	-8	n.s.	n.s.	Roque et al., 2021
A. taxiformis	Beef cattle	6 (Ctn)	147	0.50% OM	1.58	-75	-14	n.s.	n.s.	Roque et al., 2021
A. taxiformis	Dairy cows	20 (4 × 4 LS)	28	0.25% DM	–	n.s.	n.s.	n.s.	n.s.	Stefenoni et al., 2021
A. taxiformis	Dairy cows	20 (4 × 4 LS)	28	0.5% DM	–	-34	-7	-6.5[b]	n.s.	Stefenoni et al., 2021
A. taxiformis	Dairy cows	8 (Ctn)	19	67 g/h/d	0.08	-	-5	15[b]	9.1 µg/L[d]	Muizelaar et al., 2021
A. taxiformis	Dairy cows	2 (Ctn)	19	133 g/h/d	0.17	-	-9	-5[b]	11 µg/L[d]	Muizelaar et al., 2021
A. taxiformis	Dairy cows	2 (Ctn)	19	333 g/h/d	0.42	-	-14	-4[b]	35 µg/L[d]	Muizelaar et al., 2021

CH_4, methane; $CHBr_3$, Bromoform; Ctn, Continuous design; DM, dry matter basis; OM, organic matter basis; DMI, dry matter intake; Δ%, treatment response over control; (-), not quantified; n.s., not statistically significant; LS, Latin square.
[1]Reported as average daily gain or milk yield.
[2]Reported CHBr3 residue in milk or meat products.
[a]Total DMI = estimated pasture DMI + partial total mixed ration DMI.
[b]Milk.
[c]Average daily gain.
[d]Highest single day CHBr3 concentration in milk reported during the study.

Source: Wasson et al. (2022) ([143]).

([143]) Wasson, D.E., Yarish, C., Hristov, A.N. (2022). Enteric methane mitigation through *Asparagopsis taxiformis* supplementation and potential algal alternatives, *Front. Anim. Sci.,* 3. https://doi.org/10.3389/fanim.2022.999338

APPENDIX G – Summary of relevant ruminant animal studies using synthetic halogenated methane analogues or *Asparagopsis* for methane reduction purposes, including inclusion level, measured results, and citation

Table 1
Summary of relevant ruminant animal studies using synthetic halogenated methane analogues (HMAs) or *Asparagopsis* for methane reduction purposes, including inclusion level, measured results, and citation (organised by bioactive).

HMA	Animal	Treatment size (n)	Treatment duration (days)	Inclusion level* (mg·kg^{-1} LW day^{-1}	CH_4[a] (Δ%)	H_2 (Δ%)	Change in VFAs (Δ%)	Acetate: Propionate (Δ%)	Productivity (Δ%)	Ref.
BCM	Cattle[b]	4 × 4 LS	28	5.5[c]	–	–	↓	–	–	[42]
BCM	Cattle	4 × 4 LS	28	10.9	↓100[d]	–	n.s.	↓33[d]	↑31[e].	[48]
BCM	Cattle	6	28	0.66	↓29	–	n.s.	↓5	n.s.[e]	[37]
BCM	Cattle	5	28	0.66	↓93	–	–		n.s.[e]	[30]
BCM	Cattle	5	90	0.66	↓38	–	–	–	–	[30]
BCM	Cattle	12	85	0.66	–	–	–	–	n.s.[e]	[30]
BCM	Goats[f]	9	70	0.66	↓32	–	n.s.	↓31	↑36[g]	[47]
BCM	Cows	4 × 4 LS	14[h]	9.0	↓85	–	–	–	–	[49]
BCM	Goats	3	33[i]	4.0	↓91	↑ > 650	n.s.	↓33	–	[39]
$CHCl_3$	Sheep	3	98	3.3	↓89[j]	↑ > 250[k]	↓26	↓31	–	[46]
$CHCl_3$	Cows	3	42	3.71	↓38	–	–	↓30	n.s.	[45]
$CHCl_3$	Cattle[b,l]	4	30[m]	1.69	↓58	↑3.16g[n]	↓10	↓32	–	[41]
$CHCl_3$	Cattle[b,o]	4	30[m]	1.69	↓55	↑1.73g[n]	↓16	↓32	–	[41]
$CHCl_3$	Cattle[b]	8	21[p]	1.04	↓40	↑1.2g[n]	n.s.	↓35	n.s.	[40]
A. taxiformis	Sheep	5	72	0.07[q]	n.s.	–	↓6	↓34	–	[10]
A. taxiformis	Sheep	5	72	0.14[q]	↓52	–	↓19	↓45	–	[10]
A. taxiformis	Sheep	5	72	0.16[q]	↓62	–	↓25	↓42	–	[10]
A. taxiformis	Sheep	5	72	0.18[q]	↓81	–	↓29	↓45	–	[10]
A. taxiformis	Cattle	5	60	0.10[q]	↓9	n.s.	n.s.	↓14	n.s.	[9]
A. taxiformis	Cattle	5	60	0.25[q]	↓38	↑380[r]	n.s.	↓29	↑51	[9]
A. taxiformis	Cattle[b]	5	60	0.45[q]	↓98	↑1700[r]	n.s.	↓35	↑42[s]	[9]
A. taxiformis	Cattle	6	147	0.87[q]	↓50.6	↑318[r]	–	–	n.s.	[12]
A. taxiformis	Cattle	6	147	1.58[q]	↓74.9	↑497[r]	–	–	n.s.	[12]
A. armata	Cows	3 × 3 LS	21	0.44[q]	↓26.4	↑163[r]	–	–	n.s.	[11]
A. armata	Cows[f]	3 × 3 LS	21	0.62[q]	↓67.2	↑236[r]	–	–	↓11.6[g]	[11]
A. taxiformis	Cows[f]	4 × 4 LS	28	–[t]	n.s.	↑234[r]	n.s.	n.s.	n.s.	[13]
A. taxiformis	Cows[f]	4 × 4 LS	28	–[t]	↓34.4	↑627[r]	n.s.	↓11.7	↓6.5[g]	[13]

Abbreviations: dash (–) = not quantified; n.s. = not significant; LS = latin square experimental design; LW = live weight; BCM = Bromochloromethane; VFAs = Volatile Fatty Acids, $CHCl_3$ = chloroform.

[*] Calculations are based on average dry matter intakes (DMI) and animal weights.

[a] Percent reduction in eructed CH_4 over control animals.

[b] Meat.

[c] Units of g day^{-1}.

[d] 6 h post-dose.

[e] Live weight gain.

[f] Dairy.

[g] Milk yield (kg $animal^{-1}$ day^{-1}).

[h] Plus 14-day recovery period.

[i] Test animals exposed to each of 3 doses (0.4, 1.6, and 4.0 mg kg^{-1} day^{-1}) in succession with each treatment lasting 11 days.

[j] Measurements from harvested rumen fluid.

[k] Based on the lowest measure value of H_2 in Fig. 1 of [46].

[l] Hay:concentrate diet.

[m] Test animals exposed to each of 3 doses (0.65, 1.04, and 1.69 mg kg^{-1} day^{-1}) in succession with each treatment lasting 11 days.

[n] g kg^{-1} DMI.

[o] Hay diet.

[p] Test animals exposed to each of 3 inclusion levels (0.4, 1.6, and 4.0 mg kg^{-1} day^{-1}) in succession with each treatment lasting 11 days.

[q] Bromoform, except in [10] which is total HMAs.

[r] Expressed as % of control.

[s] Average daily weight gain (ADWG, kg day^{-1}).

[t] *A. taxiformis* added at 0.25 and 0.5% dry weight (dw), respectively, bromoform was not quantified in fed *Asparagopsis*.

Source: Glasson et al. (2022) ([144]).

([144]) Glasson, C.R.K., Kinley, R.D., de Nys, R. et al. (2022). Benefits and risks of including the bromoform containing seaweed *Asparagopsis* in feed for the reduction of methane production from ruminants. *Algal Research,* 64, https://doi.org/10.1016/j.algal.2022.102673

APPENDIX H – Summary of methane alternatives

Solution type	Inclusion rate or amount	Potential impact on methane emissions	Animal health/welfare	Risks and safety - General comments or recommendations
Saponins	Varied High doses (>5% DMI)	Reduction by 6–50%	• potential toxicity at high doses	• toxicity varies by source, dose and diet • select feed ingredients carefully • efficiency depends on plant source
Lipids		14% reduction in long-term emissions	• reduces fibre digestibility, DMI, and milk fat synthesis • decreases weight gain in growing animal • more suited for lactating animals	• requires careful balance of diet • higher lipid levels can reduce digestibility and increase nutrient excretion • regional costs vary and oilseed production can have high upstream GHG emissions • consider offsetting benefits against environmental impact
Plant Essential Oils		Reductions vary (up to 90% in vitro, inconsistent in vivo)	• long-term ruminal adaptation may diminish effects • high doses can reduce feed intake and alter fermentation • garlic oil can impact meat and milk flavour • encapsulation can mitigate effects but increases costs	• consumer acceptance challenges due to flavour • regulatory frameworks for maximum allowed limits are needed. • application costs are high, and more research is needed for sustainable and effective use without disrupting microbial balance
Probiotics		Potential 20% reduction with certain strains	• improves gastrointestinal health and fermentation	• feasibility of in vivo application needs more research • practical impacts need further exploration
Rumen Defaunation	Varies based on defaunation method (natural or chemical)	10–13% reduction	• can reduce organic matter digestibility • but potential decrease in food intake	• potential difficulty in maintaining protozoa-free animals in industrial systems • increases bacterial population density • improves protein supply

Solution type	Inclusion rate or amount	Potential impact on methane emissions	Animal health/welfare	Risks and safety - General comments or recommendations
Vaccination	Not specified, it depends on the vaccine type	Mixed results: in vitro shows reductions of up to 70%, in vivo results are inconsistent	• non-invasive method • minimal direct animal health impact	• challenges in producing effective vaccines and maintaining results over time • promising in theory but effectiveness varies greatly based on protocol
Chemical intervention		20–35% reduction in with 3-NOP ([145])	• considered safe generally when used correctly • potential metabolic effects	• potential toxicity of 3-NOP metabolites • one of the most promising additives though more research is needed
Genetic selection	Breeding strategy	Long-term reduction of methane emissions by selecting low methane emitters	• genetic selection does not directly affect animal welfare • may impact productivity traits	• requires many animals for effective selection • slow process • promising long-term strategy without additional chemical inputs
Forage management	Dependent on forage type and harvest timing	Potential reduction improving forage quality and digestibility	• positive effect on feed intake and productivity • improves forage nutritional value	• requires region-specific adjustments, it is highly farm-specific • may be costly depending on forage system • most effective when combined with other strategies

Source: Króliczewska et al. (2023) ([146]).

([145]) NOP (3-nitrooxypropanol) is a chemical compound that acts as a methane inhibitor for ruminant livestock, such as cattle, sheep, and goats. It is a synthetic feed additive that helps reduce methane emissions by targeting the microbial processes in the rumen responsible for methane production.
([146]) Króliczewska et al. (2023). Strategies Used to Reduce Methane Emissions from Ruminants: Controversies and Issues. *Agriculture*, 13(3). https://doi.org/10.3390/agriculture13030602

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