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Commission

Algae and Climate

European Maritime and Fisheries Fund

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Abstract in English

The study builds on an extensive literature review, a survey, and in-depth interviews to investigate the potential of 10 microalgae and macroalgae production systems in contributing to animal feed requirements in the EU. It summarizes the current state of knowledge in terms of biomass, nutritional yields, costs and greenhouse gas (GHG) emissions. The report also compares production systems against land-based crops (e.g. soya) with similar nutritional properties. Finally, it assesses the EU potential for algae production that could be supported by current CO_2 point-source emissions and that could contribute to (today and in the future) animal’s feed requirements.

Overall, as algae production is an area where production and Research & Development are evolving in parallel, there is significant variability in values estimated for the criteria investigated. Follow-up research is required in particular on: (1) additional macro- and microalgae species, as well as additional land-based production systems; (2) post-harvest processing to support upscaling of biomass production in a sustainable manner and to remove unwanted minerals; and (3) improvement of nutritional value (e.g. digestibility and assimilation) of cultivable algae for animals.

Résumé en français

L’étude mobilise les résultats d’une revue de littérature, d’une enquête et d’entretiens pour analyser les contributions potentielles de 10 systèmes de production de micro- et macro-algues à l’alimentation animale en Europe. Elle présente les connaissances existantes sur la biomasse, les rendements en nutriments, les coûts et les émissions de gaz à effet de serre de ces systèmes. Et elle compare ces systèmes aux aliments produits par l’agriculture (par exemple, le soja) aux caractéristiques nutritionnelles équivalentes. Enfin, elle analyse le potentiel de production d’algues en Europe qui utiliserait les émissions ponctuelles de CO2 et contribuerait à l’alimentation animale.

D’une manière générale, dans un domaine ou production et recherche vont de pair, l’étude souligne la variabilité importante des estimations élaborées pour les principales variables analysées. Des travaux complémentaires seraient nécessaires en particulier pour : (1) analyser d’autres algues et systèmes de production à terre ; (2) identifier les processus d’après-récolte qui permettraient de produire à grande échelle d’une manière durable ; et (3) évaluer la valeur nutritionnelle (en particulier en ce qui concerne la digestibilité et l’assimilation des algues par les animaux.

Key words*:* #Algae #Cimate #GreenDeal #Bluebioeconomy #Marinepolicy #EuropeanCommission #DGmare #CINEA

ENGLISH EXECUTIVE SUMMARY

Introduction

On 11 December 2019, the European Commission announced the **European Green Deal** to transform the European Union (EU) into the **first climate neutral region of the world**. The EU Green Deal provides an action plan to: (1) boost the efficient use of resources by moving to a clean and circular economy; (2) cut pollution and pressures on ecosystems by decoupling economic growth from resource use; and (3) restore biodiversity by sustainably managing and preserving resources and ecosystems. The EU Green Deal builds on a series of sector and policy strategies that will support a just and inclusive ecological and climate transition.

Building on a momentum set prior to the adoption of the Green Deal, increasing attention is given to the role **marine ecosystems** and the **blue economy** can play, along with opportunities they can provide as a source of resources. In particular, major innovations taking place in the field of algae cultivation can support the development of the production of both: **macroalgae**, traditionally harvested from wild stocks on European coasts and now cultivated at sea and in land-based systems; and, **microalgae,** produced in open ponds and in closed systems such as photobioreactors. Today macro and microalgae occupy a production niche in Europe. And there is significant potential in algae production and utilisation that remains to be seized for a wide range of applications including human consumption and animal feed, biofertilizers, nutraceuticals, cosmetics, biomaterials and biofuel. Still, knowledge gaps remain on algae cultivation and utilisation in Europe, including on key constraints on algae cultivation and leverages to set to ensure its potential is fully seized.

Objectives

In this context, the European Commission launched a study to provide sound and up-to-date knowledge on the potential impacts of scaling-up the production of marine algae through aquaculture in the EU. The study addressed four key questions:

- Q1. What are the **biomass and protein yields** algae can provide, depending on the types of algae and the production technologies applied in marine waters and land-based systems?
- Q2. What are the **costs and greenhouse gas (GHG) emissions** of different algae production technologies? How do they compare with the costs and GHG emissions of land-based crops (e.g. soya) with similar nutritional properties? Under which conditions would algae production (in particular land-based systems fed by flue gases or process stream nutrients) be competitive?
- Q3. What could be the potential **total algae biomass production** in Europe as well as the resulting carbon dioxide captured, and amount of inputs used, to deliver this potential?
- Q4. Which share of (today and future) **animal and fish feed requirements** could be met by algae production? What are the main constraints on increasing the proportion of algae in animal feed?

How has the study been implemented?

Implemented by ACT*eon* (France – coordinator), the universities of Arhus and Copenhagen (Denmark), and TNO (the Netherlands Organisation for Applied Scientific Research), the study builds on the collection and critical analysis of a **wide range of technical, environmental, and economic data** related to different algae production technologies at different development stages (from pilot projects to large scale implementation in Europe and beyond).

It investigates the potential of **10 microalgae and macroalgae production systems** (see table below) in contributing to animal feed requirements in the EU. The cultivation systems selected represent a diverse range of production technologies, geographical relevance and algae species already present in the EU, that are documented with expected potential in terms of yields, costs and use for animal feed.

Information from the **scientific and grey literature** was complemented by **semi-structured interviews** with key experts and stakeholders of the algae value chains – from its production to its final use, in particular as a component of livestock feed – and an **online survey**. It summarizes the current state of knowledge in terms of biomass, nutritional yields, costs and greenhouse gas (GHG) emissions. The collected evidence has been organised in a **relational database** that has helped extracting quantitative results and answers to the questions above, identifying key knowledge gaps requiring research beyond the scope of the present study.

Macro-/Microalgae	Species	Cultivation methods
Coastal	Saccharina latissima	Rope system
	Alaria esculenta	Rope system
	Palmaria palmata	Rope system, pond/tank/raceway pond
	Asparagopsis sp.	Rope system
	Ulva sp.	Rope system, ponds
Land-based	Spirulina	Ponds
	Chlorella sp.	Photobioreactor
	Haematococcus pluvialis	Photobioreactor
	Nannochloropsis sp.	Photobioreactor
	Asparagopsis sp.	Photobioreactor

What biomass and protein yields can algae provide?

The global demand for food is rising. To meet growing demands, algae provide an alternative source of food and feed due to their protein, carbohydrate, and lipid content. Available evidence shows **large variations in algae composition** between algae species for both micro- and macroalgae. Reported nutritional values also vary significantly between studies focusing on the same production system, reflecting variations in cultivation conditions, seasons, and growth stages.

Overall, **microalgae** production systems have a high potential for feed applications due to their **high protein yield**[1]. Microalgae are also a promising sustainable source of lipids, omega-3 fatty acids and carbohydrates. Besides using these main components in animal diet supplementation, microalgae molecules can be used as ingredients for food after post-processing.

Macroalgae are also a promising source of protein, functional carbohydrates, minerals, and bioactive compounds even though their **nutritional yield is lower** when compared to microalgae. Within macroalgae production systems, land-based production of Ulva and Asparagopsis species performs in range with low yielding microalgae systems. Kelp

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[1] Nutritional yield can be defined as the tonnes of crude protein per area per year.

production at sea has the lowest protein yield per unit of surface area. When used as feed, macroalgae extracts have several beneficial properties that improve animal gut health.

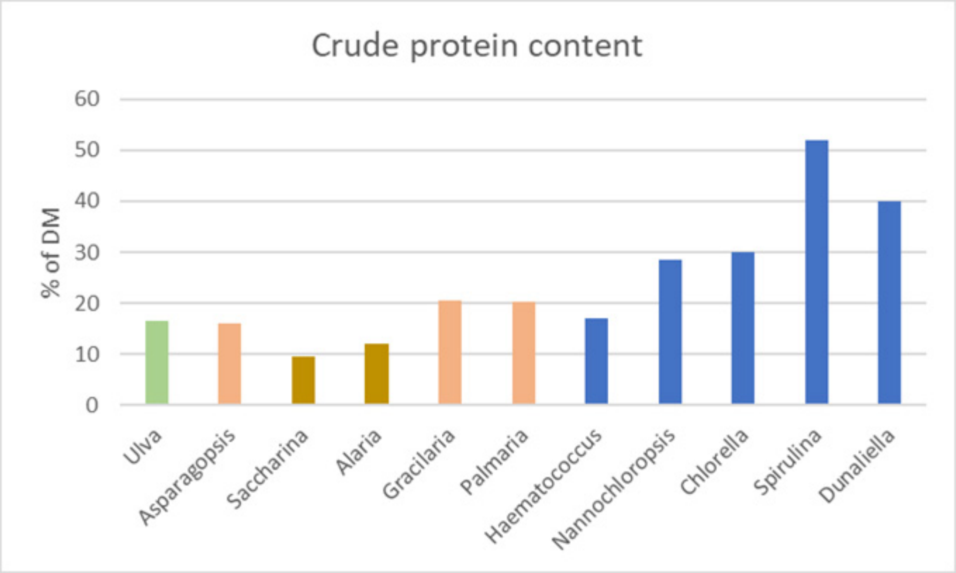

Figure 1 Average crude protein content of selected macro and microalgae. The colour of bars indicates different groups of macroalgae (red, green and brown), microalgae being in blue. Data are given in % of dry matter (DM).

What are the costs of the different types of algae production systems?

On average, **microalgae** cultivation systems tend to have **higher total costs than macroalgae** ones (EUR 27/kg dry weight and EUR 14/kg dry weight, respectively) as a result of high capital expenditures related to bioreactor configuration as well as high labour and electricity requirements. There are, however, **large differences in capital and operational expenses** depending on location, plant capacity, productivity, scale of operations and cost estimation assumptions[2] (see

Figure 2). Differences in capital expenditures are mainly related to differences in facility size, with economies of scale often occurring when scaling up production. Differences in operational expenditures are related to differences in input requirements and prices.

Algae have large water content and must be used immediately after harvest or stabilized by drying to maintain their quality. Depending on harvesting methods, drying techniques and related energy requirements, **drying costs** can be significant. On average, reported drying costs for macroalgae are higher than for microalgae (EUR 0.3/kg dry weight and EUR 0.9/kg dry weight, respectively). However, drying cost data is scarce, limited to a few sources only that vary according to the desired moisture content, the effect of salts on the heat of evaporation, the type of dryer and its efficiency, and the energy source costs.

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[2] Information on the cost of algae cultivation is scarce, with many missing data points regarding macroalgae cultivation land-based (*Asparagopsis* sp., *Alaria esculenta*) and macroalgae cultivation marine (*Palmaria palmata*).

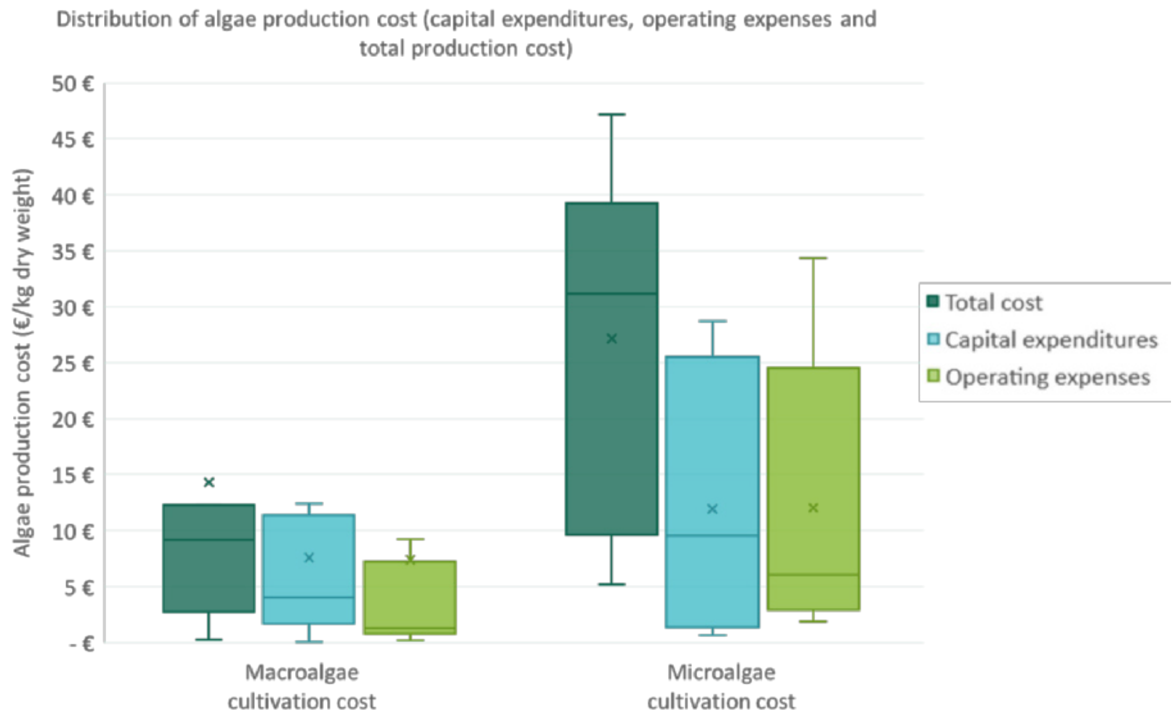

Figure 2 Distribution of algae production cost (capital expenditures, operating expenses and total production cost, in €/kg dry weight). The results for macroalgae are based on 11 observations for Saccharina and Ulva, while results for microalgae are based on 12 observations for Chlorella, Haematococcus pluvialis and Nannochloropsis sp.

What are greenhouse gas emissions from different types of algae production systems?

Algae production has several **positive effects on GHG emissions**. During growth, algae remove CO_2 from the atmosphere and converts it into biomass. **Flue gas from point source emitters** can serve as a **source of CO_2 for algae cultivation** to enhance growth, thereby reducing CO_2 emissions and contributing to climate change mitigation. At the same time, algae cultivation contributes to the emission of GHG emission. While algae capture carbon, **algae cultivation emits CO_2**, including emissions related to direct operations (direct emissions, scope 1), emissions related to purchased inputs or equipment (indirect emissions, scope 2) and emissions related to the end-use of algae products (indirect emissions, scope 3)[3].

Carbon capture

CO_2 fixation efficiency, i.e. the ratio of CO_2 fixed in the algae compared to the total CO_2 available, provides an indicator of the potential of algae to capture CO_2 and reduce emissions. Results show that **open systems** (raceway ponds) have a relatively **low fixation efficiency** (30%) compared to closed systems (60%). **Closed systems** allow for much **more efficient use of the CO_2** supplied, whereas in open systems significant CO_2 losses to the atmosphere occur. Reported differences in CO_2 fixation efficiencies can

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[3] The term “scope” refers to the GHG Protocol Corporate Standard, an international standard for developing and reporting a company-wide GHG inventory. It includes scope I (emissions from onsite processes and energy-related emissions from onsite fuel consumption), scope II (energy-related emissions associated to the production and delivery of the electricity, steam, heating, and cooling used for on-site operations) and scope III (emissions from upstream production and delivery of input to onsite system and downstream treatment processes emissions).

be attributed to differences in CO_2 sources, cultivation systems, CO_2 tolerance, flue gas composition and CO_2 tolerance capacity.

Carbon footprint

Evidence on the **total carbon footprint** shows a **highly variable footprint**[4] for both microalgae and macroalgae. The **total** carbon footprint accounts for direct and indirect emissions, avoided emissions through environmental mitigation, functional products and the substitution of products and fossil fuels, This footprint is higher for microalgae than for macroalgae - ranging from 21 to 1087 kg CO_2/kg dw and from 1.5 to 16 kg CO_2/kg dw of algae biomass, respectively.

Net effects

Information on net carbon footprints andbalancing carbon emissions with carbon capture, is only available for ***Saccharina latissima*** **produced offshore,** which is a technological mature cultivation system. The **net carbon footprint** for this system varies from –739 to 3131 kg CO_2e/ton dw of algae biomass, illustrating the opportunity for algae cultivation systems to deliver environmental benefits in the form of climate change mitigation services.

Does microalgae feed have the potential to become economically viable with additional revenues from CO_2 credit sales?

Microalgae can convert CO_2 emissions into biomass, making them a potential solution for climate change mitigation. Selling carbon credits on markets can potentially generate a second revenue stream and improve the profitability of microalgae production[5]. The analysis shows that additional revenues from carbon credit sales is not an effective solution for making algae feed production economically viable: **revenues from credit sales will always be marginal,** as the amount of carbon captured by algae is very low (1.8 kg CO_2/kg of dry weight biomass on average).

The algae feed price required to offset algae feed production costs was estimated at EUR 113/kg crude protein. Today, **algae feed is far from being competitive with soybeans meal** which price was EUR 0.92/kg of crude protein in 2021.

What is the potential for land-based marine algae production fed by flue gases?

Accounting for the availability of CO_2 sources (point source emitters), the suitability and convertibility of land use types, area requirements, and slope, the **potentially convertible land area** to algae production in Europe is **estimated at 106,960 km^2** (the equivalent of the area of a country like Bulgaria). Depending on assumptions, the potential of algae biomass production in Europe would range between **146 million and 392 million tons of dry weight per year**. Achieving this production level would help capturing CO_2 from 160 million to 719 million ton of CO_2 per year (which represents between 7% and 30% of the total CO_2 emissions in the EU-27 in 2020[6]). The resulting potential nutrient uptake would range from 4.83 million to 21.0 million ton of nitrogen

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[4] Excluding CO2 assimilation in the biomass.

[5] The main source of revenue from microalgae production is the sale of dry algae biomass (at an average price of EUR 31/kg of dry weight). However, the results of the literature review show strong price differences among the algae species, ranging from 25 (for *Chlorella*) euros to 300 (for *Haematoccocus*).

[6] Based on total net CO_2 emissions in EU-27 in 2020 (source: https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer)

per year (representing between 16% and 70% of the total annual nitrogen input from agriculture to the European Regional seas[7]).

The analysis has provided ballpark figures of potential inland marine algae production in the EU. It did not consider water and nutrient availability; the availability of pipelines for CO_2 distribution; geological conditions and groundwater levels; or existing land use regulations that might constraint algae cultivation.

Which share of animal and fish feed requirements could be met by algae production?

Using algae in animal diets can help reducing methane emissions from ruminant livestock. Several of the studied macroalgae species **accumulate critical minerals at levels exceeding the limit values set by the European Food Safety Association (EFSA)**. For example, *Palmaria palmata, Saccharina latissima* and *Asparagopsis taxiformis* have high to very high concentrations of iodine restricting the allowed inclusion rate in animal diets. No data on critical mineral contents was found for microalgae. For in-land cultivation systems, critical mineral contents can be assumed to depend entirely on water quality, given the known ability of macroalgae to accumulate such minerals.

To assess the potential of using algae in animal diets based on the animal species and potential of using anti-methanogenic algae the study relied on: (1) the content of essential and semi-essential amino acids; (2) critical minerals such as iodine, arsenic, cadmium, mercury and lead in the different species of seaweed in comparison to EU standards[1]. High content of critical minerals poses risk to human health and can negatively impact animal performance and; (3) the digestibility of the algae and the impact on animal performance and methane emission were also investigated.

Macroalgae

Asparagopsis taxiformis, which can only be grown in land-based systems in Europe being a non-indigenous species, is a potent inhibitor of enteric methane formation in ruminant animals. **Methane reduction of 30% in dairy cattle and to 50-75% in beef cattle could be achieved** without negative effects on animal performance. However, as it does not have nutritional value as such, considering its inclusion in the actual feed of monogastric and ruminant animals is not appropriate.

Palmaria palmata organic matter has the **highest digestibility for ruminants and monogastrics**, comparable to some terrestrial high-quality feeds. The red algae species, *Gracilaria sp*.[8] and *Palmaria palmata*, have the **highest protein content**, as well as amino acid profiles meeting the requirements for most animal species (except laying hens and poultry). They could be particularly relevant to consider as future protein feed for livestock. Whole tract and ideal digestibility of macroalgae appeared to be as high or higher for pigs as for cows, except for *Gracilaria spp*.

Microalgae

Chlorella sp., *Nannochloropsis sp.* and *Spirulina sp.* **can be fed to dairy cows, pigs, and chicken up to a certain percentage** without negative effects on feed intake or milk production. Preference for other feeds, however, indicates a **low palatability**. *Chlorella sp.* fulfils Essential Amino Acids (EAA) requirements for all animal species, except for laying hens where requirements were only met for Threonine and Valine.

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[7] Based on the mean annual nitrogen quantity over 2014-2018 (source: https://doi.org/10.1016/j.scitotenv.2022.160063 - data from the European environment Agency).

[8] No value for iodine concentration were found for *Gracilaria sp.*

Haematococcus pluvialis seems to have the best EAA profile and is a rich source of Leucine, Phenylalanine and Histidine. No data could be found on the nutritional value of *Dunaliella sp.* and *Nannochloropsis sp.* for any of the animal species.

Estimates for achievable recommended maximal dietary inclusion rates for different animal categories without compromising productivity or health have high uncertainty. Most information comes from scientific studies, mainly experiments carried out *in vitro* and results that are not always comparable. Very few *in vivo* studies targeting food-producing animals have been conducted. Additionally, standard methods for analysing feed composition are not well suited for algae, with lack of knowledge about the distinct carbohydrates present in algae and their digestibility.

FRENCH EXECUTIVE SUMMARY

Introduction

Le 11 décembre 2019, la Commission Européenne a officiellement lancé le **Pacte Vert** (ou ***Green Deal*****) européen dont l’ambition est de** faire de l'Union européenne (UE) la **première région climatiquement neutre du monde**. Le Pacte Vert propose un plan d'action visant à : (1) stimuler l'utilisation efficace des ressources via une économie propre et circulaire ; (2) réduire la pollution et les pressions sur les écosystèmes en dissociant croissance économique de l’utilisation des ressources ; et (3) restaurer la biodiversité en gérant et en préservant durablement les ressources et les écosystèmes.

S’appuyant sur différentes politiques et stratégies sectoriels, le Pacte Vert portera une attention particulière aux rôles que peuvent jouer les **écosystèmes marins** et l'**économie bleue** dans la transition écologique et climatique dans laquelle l’Europe s’engage. En particulier, différentes innovations contribueront au développement de la production d’algues, que ce soient les **macroalgues**, traditionnellement récoltées à partir de stocks sauvages sur les côtes européennes et cultivées aujourd’hui en mer et dans des systèmes terrestres, ou les **microalgues**, produites dans des bassins ouverts et dans des systèmes fermés comme des photobioréacteurs. Les macroalgues et les microalgues constituent une niche de production au potentiel et champs d’application considérables, que ce soient pour la consommation humaine et l'alimentation animale, les biofertilisants, les nutraceutiques, les cosmétiques, les biomatériaux et les biocarburants. Toutefois, les connaissances sur la culture et l'utilisation des algues restent incomplètes, notamment en ce qui concerne les contraintes auxquelles leur culture fait face dans un contexte européen, ainsi que les leviers à mettre en place pour s'assurer que le potentiel de production soit pleinement exploité.

Objectifs

Dans ce contexte, la Commission Européenne a lancé une étude visant à fournir des connaissances solides et actualisées sur les impacts potentiels de l'intensification de la production d'algues marines par l'aquaculture dans l'UE. L'étude s'est intéressée à quatre questions clés :

- Q1. Quels sont les rendements en biomasse et en protéines des algues, en fonction des types d'algues et des technologies de production adoptées dans les eaux marines et les systèmes terrestres ?
- Q2. Quels sont les coûts et les émissions de gaz à effet de serre (GES) des différentes technologies de production d'algues ? Où se situent-ils par rapport aux coûts et aux émissions de gaz à effet de serre des productions végétales (par exemple le soja) aux propriétés nutritionnelles similaires ? Sous quelles conditions la production d'algues (en particulier dans les systèmes terrestres alimentés par des gaz de combustion ou des nutriments issus des flux de production) serait-elle compétitive ?
- Q3. Quel pourrait être le potentiel de production totale de biomasse d'algues en Europe, ainsi que le dioxyde de carbone capturé et la quantité d’intrants utilisée pour atteindre ce potentiel ?
- Q4. Quelle part des besoins alimentaires des animaux d'élevage et des piscicultures pourrait être satisfaite par la production d'algues ? Quels sont les principaux obstacles à l'augmentation de la proportion d'algues dans l'alimentation animale ?

Comment l'étude a-t-elle été mise en œuvre ?

Mise en œuvre par ACT*eon* (France - coordinateur), les universités d'Arhus et de Copenhague (Danemark) et TNO (Organisation néerlandaise pour la recherche scientifique appliquée), l'étude s'appuie sur la collecte et l'analyse critique d'un **large éventail de données techniques, environnementales et économiques** relatives à différentes technologies de production d'algues à différents stades de développement (de projets pilotes à la mise en œuvre à grande échelle en Europe et au-delà).

Elle analyse le potentiel de **10 systèmes de production de microalgues et de macroalgues** (voir tableau ci-dessous) à contribuer aux besoins alimentaires de l'élevage de l'UE. Les systèmes sélectionnés représentent une diversité de technologies de production, de pertinence géographique et d'espèces d'algues déjà présentes et documentées dans l'UE et avec un fort potentiel en termes de rendements, de coûts et d'utilisation pour l'alimentation animale.

Pour compléter les informations tirées de la **littérature grise et scientifique**, des **entretiens semi-structurés** ont été menés avec des experts et acteurs clés des chaînes de valeur des algues - de la production à leur utilisation finale y compris en tant que composants d'aliments pour animaux. Une **enquête en ligne** a également été réalisée. L'étude résume l'état actuel des connaissances en termes de biomasse, de rendements nutritionnels, de coûts et d'émissions de gaz à effet de serre (GES). L'ensemble des données recueillies a été rassemblé dans une base de données relationnelle qui permet d'extraire des résultats quantitatifs et des réponses aux questions posées ci-dessus, identifiant les principales connaissances manquantes nécessitant des recherches complémentaires au-delà du cadre de la présente étude.

Macro-/Microalgues	Espèces	Système de culture
Littoral	Saccharina latissima	Système de cordes
	Alaria esculenta	Système de cordes
	Palmaria palmata	Système de cordes, bassin/réservoir/bassin de type « raceway »
	Asparagopsis sp.	Système de cordes
	Ulva sp.	Système de cordes, bassins
Systèmes terrestres	Spiruline	Bassins
	Chlorella sp.	Photobioréacteur
	Haematoccocus pluvialis	Photobioréacteur
	Nannochloropsis sp.	Photobioréacteur
	Asparagopsis sp.	Photobioréacteur

Quels rendements en biomasse et en protéines les algues peuvent-elles fournir ?

La demande mondiale en denrées alimentaires est en hausse. Pour répondre à cette demande, les algues constituent une **source alternative d'alimentation humaine et animale** au regard de leur teneur en protéines, carbohydrates et lipides. Les données disponibles montrent de **grandes variations dans la composition d'algues** de différentes espèces tant pour les microalgues que pour les macroalgues. Les valeurs nutritionnelles varient également de manière significative pour une même espèce selon le même système de production, les conditions de culture, les saisons et les stades de croissance.

D'une manière générale, les systèmes de production de **microalgues** présentent un potentiel élevé d'utilisations dans l'alimentation animale en raison de leur **rendement élevé en protéines**[9]. Les microalgues sont également une source intéressante de

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[9] Le rendement nutritionnel peut être défini comme les tonnes de protéines brutes par surface et par an.

lipides, d'acides gras oméga-3 et de carbohydrates composants clés dans l'alimentation animale, et possède d’autres molécules pouvant être utilisées comme ingrédients alimentaires après traitement ultérieur.

Les macroalgues sont également une source prometteuse de protéines, de carbohydrates fonctionnels, de minéraux et de composés bioactifs, même si leur **rendement nutritionnel est inférieur** à celui des microalgues. Parmi les systèmes de production de macroalgues, la production terrestre d'Ulva et d'Asparagopsis est comparable aux systèmes de production de microalgues à faible rendement. La production de varech en mer présente le rendement protéique le plus faible par unité de surface. Lorsqu'ils sont utilisés comme aliments pour animaux, les extraits de macroalgues ont plusieurs propriétés bénéfiques qui améliorent la santé intestinale des animaux.

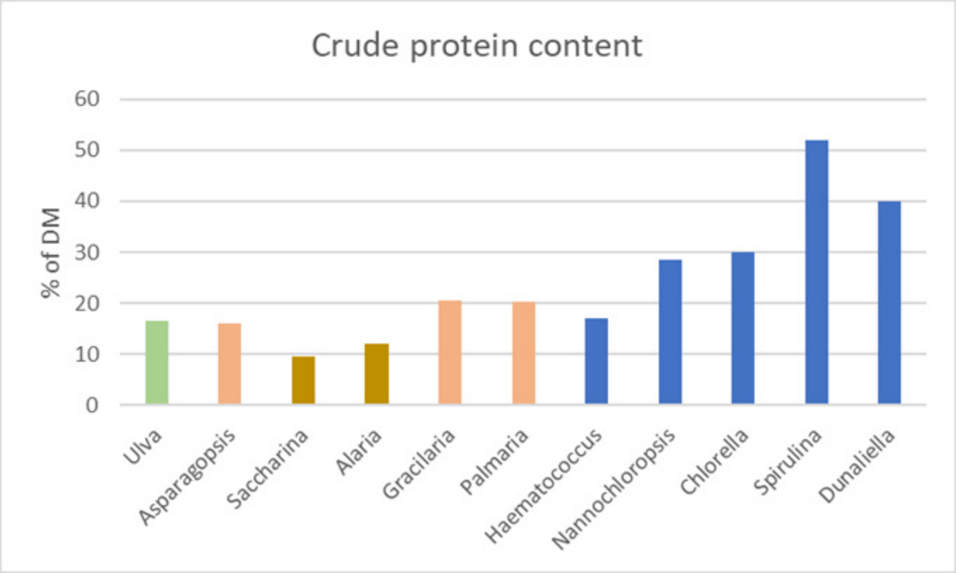

Figure 3 Teneur moyenne en protéines brutes des macroalgues et microalgues sélectionnées. La couleur des barres indique les différents groupes de macroalgues (rouge, vert et brun), les microalgues étant en bleu. Les données sont exprimées en % de matière sèche (MS).

Quels sont les coûts des différents types de systèmes de production d'algues ?

Les systèmes de culture des **microalgues** ont généralement des **coûts totaux plus élevés que ceux** des **macroalgues** (27 EUR/kg de matière sèche et 14 EUR/kg de matière sèche, respectivement) en raison de dépenses d'investissement élevées liées à la configuration des bioréacteurs et aux besoins élevés en main-d'œuvre et en électricité. Il existe toutefois de **grandes différences dans les dépenses d'investissement et d'exploitation** en fonction de la localisation, de la capacité de production de l'usine, de la productivité, de l'échelle et des hypothèses d'estimation des coûts[10] (voir Figure 3). Les différences en dépenses d'investissement sont principalement liées aux différences de taille des installations, des économies d'échelle étant souvent réalisées pour des systèmes de production de grande taille. Les dépenses d’exploitation sont généralement corrélées aux prix et quantités d’intrants.

Les algues ont une forte teneur en eau et doivent être utilisées immédiatement après la récolte ou stabilisées par séchage pour conserver leur qualité. En fonction des méthodes de récolte, des techniques de séchage et des besoins énergétiques associés, les **coûts**

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[10] Les informations sur le coût des algues cultivées sont rares, avec de nombreux points de données manquants concernant la culture de macroalgues terrestres (*Asparagopsis* sp., *Alaria esculenta*) et la culture de macroalgues marines (*Palmaria palmata*).

de séchage peuvent être importants. En moyenne, les coûts de séchage rapportés pour les macroalgues sont plus élevés que pour les microalgues (0,3 EUR/kg de matière sèche et 0,9 EUR/kg de matière sèche, respectivement). Cependant, les données sur les coûts de séchage sont rares, limitées à quelques références seulement, et varient en fonction de la teneur en eau souhaitée, de l'effet des sels sur la chaleur d'évaporation, du type de séchoir et de son efficacité, ainsi que de la source d'énergie et de ses coûts.

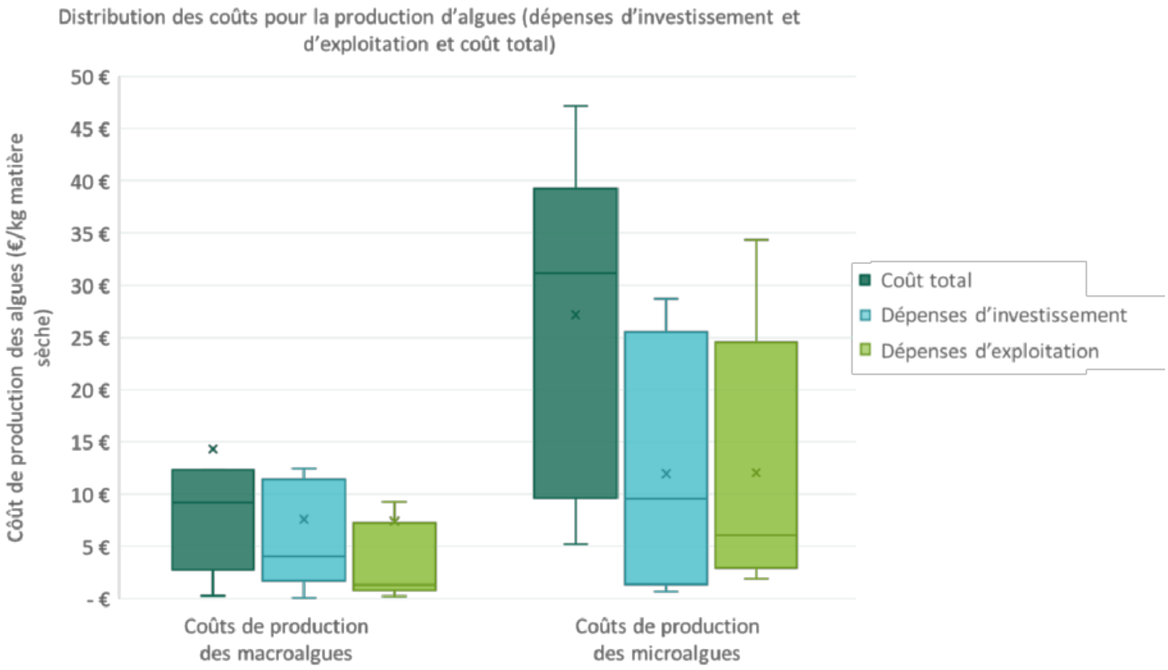

Figure 4 Distribution des coûts pour la production d'algues (dépenses d'investissement et d'exploitation et coût total, en €/kg de matière sèche). Les résultats pour les macroalgues sont basés sur 11 observations pour Saccharina et Ulva, tandis que les résultats pour les microalgues sont basés sur 12 observations pour Chlorella, Haematoccocus pluvialis et Nannochloropsis sp.

Quelles sont les émissions de gaz à effet de serre des différents types de systèmes de production d'algues ?

La production d'algues a plusieurs **effets positifs sur les émissions de GES**. Pendant leur croissance, les algues accumulent le CO_2 de l'atmosphère et le transforment en biomasse. Les **gaz de combustion** émis par certaines activités peuvent servir de **source de CO_2 pour la culture des algues** afin d'améliorer leur croissance, réduisant ainsi les émissions de CO_2 et contribuant à l'atténuation du changement climatique. Dans le même temps, la **culture d'algues émet du CO_2**, que ce soit par les émissions liées aux opérations directes (émissions directes, « Scope I »), les émissions liées aux intrants ou aux équipements achetés (émissions indirectes, « Scope II ») ou les émissions liées à l'utilisation finale des produits à base d'algues (émissions indirectes, « Scope III »)[11].

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[11] Les « Scope » font référence au GHG Protocol Corporate Standard. Il s'agit d'une norme internationale pour l'élaboration et la déclaration d'un inventaire des GES à l'échelle des entreprises. Il comprend le Scope I (émissions provenant des procédés sur site et émissions liées à l'énergie provenant de la consommation de carburant sur site), le Scope II (émissions liées à l'énergie associées à la production et à la fourniture de l'électricité, de la vapeur, du chauffage et du refroidissement utilisés pour les opérations sur site) et le Scope III (émissions provenant de la production en amont et de la fourniture d'intrants au système sur site et émissions provenant des procédés de traitement en aval).

Capture du carbone

L'efficacité de fixation du CO_2, c'est-à-dire le rapport entre le CO_2 fixé dans les algues et le CO_2 total disponible, est un indicateur du potentiel des algues à capturer du CO_2 et à réduire les émissions. Les résultats montrent que les **systèmes ouverts** (bassins de type « *raceway* ») ont une **efficacité de fixation** relativement **faible** (30 %) par rapport aux systèmes fermés (60 %). Les **systèmes fermés permettent une utilisation** beaucoup **plus efficace du CO_2** disponible en comparaison aux systèmes ouverts pour lesquelles les pertes de CO_2 dans l'atmosphère sont importantes. Les différences observées d'efficacités de fixation du CO_2 peuvent être attribuées à des différences dans les sources de CO_2, les systèmes de culture, la tolérance au CO_2 et la composition des gaz de combustion.

Empreinte carbone

Les données relatives à l'**empreinte carbone totale de la production d'algues** qui tiennent compte des émissions directes et indirectes et des émissions évitées grâce à l'atténuation des effets sur l'environnement ou à la substitution de produits et de combustibles fossiles, montrent que l'**empreinte carbone totale**[12] **est très variable,** tant pour les microalgues que pour les macroalgues, mais **plus élevée pour les microalgues** que pour les macroalgues - allant respectivement de 21 à 1 087 kg CO_2 /kg matière sèche et de 1,5 à 16 kg CO_2 /kg matière sèche.

Effets nets

Les informations sur les empreintes carbone nettes, qui établissent le rapport entre les émissions de carbone et la capture du carbone, ne sont disponibles que pour les systèmes de culture de ***Saccharina latissima*** technologiquement matures et **produits en mer**. L'**empreinte carbone nette** de ce système varie de -739 à 3131 kg CO_2 /tonne de matière sèche, illustrant la capacité de contribuer à l'atténuation au changement climatique des systèmes de culture d'algues.

Les aliments pour animaux à base de microalgues peuvent-ils devenir économiquement viables grâce aux recettes supplémentaires générées par les ventes de crédits de CO2 ?

De par leur capacité à transformer les émissions de CO_2 en biomasse, les microalgues représentent une solution potentielle pour atténuer le changement climatique. La vente de crédits carbone sur les marchés pourrait potentiellement générer une deuxième source de revenus pour les producteurs d'algues et améliorer leur rentabilité financière[13]. L'analyse montre que des revenus supplémentaires provenant de la vente de crédits carbone ne constituent pas une solution intéressante pour améliorer la viabilité financière de la production d'aliments pour animaux à base d'algues : les **revenus provenant de la vente de crédits carbone seront toujours négligeables,** la quantité de carbone capturée par les algues étant généralement très faible (en moyenne 1,8 kg CO_2 /kg de matière sèche).

Le prix d'aliments pour le bétail à base d'algues permettant de compenser les coûts de production a été estimé à 113 EUR/kg de protéines brutes. Ainsi, les **aliments pour algues sont aujourd'hui loin d'être compétitifs par rapport au tourteau de soja**, dont le prix était de 0,92 EUR/kg de protéines brutes en 2021.

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[12] A l'exclusion de l'assimilation du CO_2 dans la biomasse.

[13] La principale source de revenus de la production de microalgues est la vente de la biomasse d'algues sèches (à un prix moyen de 31 euros/kg de matière sèche). Cependant, les résultats de l'analyse bibliographique montrent de fortes différences de prix entre les espèces d'algues, allant de 25 (pour *Chlorella*) à 300 (pour *Haematoccocus*) euros.

Quel est le potentiel de production d'algues marines terrestres alimentées par des gaz de combustion ?

En tenant compte de la disponibilité des sources de CO_2 (émetteurs ponctuels), de l'adéquation et de la convertibilité des types d'utilisation des terres, des exigences en matière de superficie et de la pente, la **superficie potentiellement convertible** pour la production d'algues en Europe est **estimée à 106 960 km ^{2}** (l'équivalent de la superficie d'un pays comme la Bulgarie). Selon les hypothèses retenues, le potentiel de production de biomasse algale en Europe se situerait entre **146 millions et 392 millions de tonnes de matière sèche par an**. Atteindre ce niveau de production permettrait de capturer de 160 à 719 millions de tonnes de CO_2 par an (ce qui représente entre 7 % et 30 % des émissions totales de CO_2 dans l'UE-27 en 2020[14]). L'absorption potentielle d'éléments nutritifs qui en résulterait serait comprise entre 4,83 millions et 21,0 millions de tonnes d'azote par an (représentant entre 16% et 70% de l'apport annuel total d'azote provenant de l'agriculture dans les mers régionales européennes[15]).

L'analyse a fourni des chiffres indicatifs sur la production potentielle d'algues marines continentales dans l'UE. Elle n'a pas pris en compte : la disponibilité de l'eau et des nutriments ; la disponibilité des pipelines pour la distribution du CO_2 ; les conditions géologiques et le niveau des eaux souterraines ; ou les réglementations existantes en matière d'utilisation des sols qui pourraient entraver la culture d'algues.

Quelle part des besoins alimentaires des animaux et des poissons pourrait être couverte par la production d'algues ?

L'utilisation d'algues dans l'alimentation du bétail peut contribuer à réduire les émissions de méthane des ruminants. Plusieurs des espèces de macroalgues étudiées **accumulent des minéraux critiques à des niveaux dépassant les valeurs limites** fixées par l'Autorité européenne de sécurité des aliments (EFSA). Par exemple, *Palmaria palmata*, *Saccharina latissima* et *Asparagopsis taxiformis* présentent des concentrations d'iode élevées, voire très élevées, qui limitent le taux d'incorporation autorisé dans les régimes alimentaires des animaux. Aucune donnée sur les teneurs critiques en minéraux des microalgues n'est aujourd'hui disponible. Pour les systèmes de culture en milieu terrestre, les teneurs critiques en minéraux dépendront directement de la qualité de l'eau utilisée, étant donné la capacité des macroalgues à accumuler ces minéraux.

Pour évaluer le potentiel d'utilisation des algues dans l'alimentation animale en fonction de l'espèce animale et le potentiel d'utilisation d'algues anti-méthanogènes, l'étude s'est appuyée sur : (1) la teneur en acides aminés essentiels et semi-essentiels ; (2) les teneurs de minéraux critiques tels que l'iode, l'arsenic, le cadmium, le mercure, le plomb dans les espèces d'algues en comparaison aux normes existantes pour les minéraux dans l'UE . Une teneur élevée en minéraux critiques présente un risque pour la santé humaine et peut avoir un impact négatif sur les performances des animaux ; et, (3) la digestibilité des algues et l'impact sur la performance animale et l'émission de méthane.

Macroalgues

Asparagopsis taxiformis, une espèce non indigène qui ne peut être cultivée que dans des systèmes terrestres en Europe, est un puissant inhibiteur de la formation de méthane entérique chez les ruminants. L'intégration de cette algue dans la ration animale entrainerait ainsi une **réduction du méthane de 30 % à 50-75 %** chez les bovins

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[14] Sur la base des émissions nettes totales de CO_2 dans l'UE-27 en 2020 (source : https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer)

[15] Sur la base de la quantité moyenne annuelle d'azote sur la période 2014-2018 (source : https://doi.org/10.1016/j.scitotenv.2022.160063 - données de l'Agence européenne pour l'environnement).

laitiers et les bovins de boucherie, respectivement, sans effets collatéraux négatifs sur les performances des animaux. Toutefois, cette algue n’ayant pas de valeur nutritionnelle particulière, il n'est pas envisagé de l’inclure dans l'alimentation des animaux monogastriques et des ruminants.

La matière organique de *Palmaria palmata* présente la **digestibilité la plus élevée pour les ruminants et les animaux monogastriques**, comparable à celle de certains aliments terrestres de haute qualité. Les espèces d'algues rouges, *Gracilaria sp*.[16] et *Palmaria palmata*, ont la **teneur en protéines la plus élevée**, ainsi que des profils d'acides aminés répondant aux besoins de la plupart des espèces animales (à l'exception des poules pondeuses et de la volaille). Ces algues pourraient être particulièrement intéressantes à considérer comme futurs aliments protéiques pour le bétail. La digestibilité de l'ensemble du tube digestif et la digestibilité optimale des macroalgues semblent aussi être élevées, voire plus élevées, pour les porcs que pour les vaches, à l'exception de *Gracilaria sp.*

Microalgues

Bien dosées dans les rations alimentaires, *Chlorella sp.*, *Nannochloropsis sp.* et *Spirulina sp.* **peuvent être consommées par les vaches laitières, les porcs et les poulets** sans effets négatifs sur l'ingestion d'aliments ou la production de lait. La préférence des animaux pour d'autres aliments indique toutefois une **faible appétence**. *Chlorella sp.* répond aux besoins en acides aminés essentiels (AAE) de toutes les espèces animales, à l'exception des poules pondeuses pour lesquelles seuls les besoins en thréonine et en valine seraient satisfaits. *Haematococcus pluvialis* semble avoir le meilleur profil en 'AAE et est une source riche en Leucine, Phénylalanine et Histidine. Aucune donnée n'a pu être trouvée sur la valeur nutritionnelle pour des espèces animales de *Dunaliella sp.* et *Nannochloropsis sp.*.

Les estimations des taux d'incorporation alimentaire maximaux recommandés pour différentes catégories d'animaux, sans compromettre la productivité ou la santé, sont très incertaines. La plupart des informations proviennent d'expériences réalisées *in vitro* et dont les résultats ne sont pas toujours comparables. Très peu d'études *in vivo ont* été menées sur des animaux. En outre, les méthodes standard d'analyse de la composition des aliments sont peu adaptées aux algues, en raison du manque de connaissances sur les différents carbohydrates présents dans les algues et sur leur digestibilité.

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[16] Aucune valeur de concentration en iode n'a été trouvée pour *Gracilaria sp.*

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

CAPEX	Capital expenditures
CLC	Corinne Land Cover
CP	Crude protein
DE	Digestible energy
DHA	Docosahexaenoic acid
DOI	Digital object identifier
DM	Dry matter
DW	Dry weight
EAA	Essential amino acids
EC	European Commission
EPA	Eicosapentaenoic acid
FAO	Food and Agriculture Organization
FCR	Feed conversion ratio
FW	Fresh weight
GHG	Greenhouse gas
ME	Metabolizable energy
MS	Member State
NRC	National Research Council of the USA
NE	Net energy
OM	Organic matter
OPEX	Operating expenses
PBR	Photobioreactor
PBS	Phycobilisomes
RMDIR	Recommended maximal dietary inclusion rate
ROP	Rope systems
RP	Raceway pond
SID	Standardized ileal digestible
TAG	Triacylglycerols
PUFA	Polyunsaturated fatty acid
STDD	Standardized total tract digestible
TGA	Triacylglycerols
VL-PUFA	Very-long-chain polyunsaturated fatty acids
WEI+	Water Exploitation Index plus
WHO	World Health Organization

1 INTRODUCTION

1.1 Background

The European Commission (EC) has launched a study to provide sound and up-to-date knowledge on the potential impacts of scaling up the production of algae through aquaculture in the EU. The main questions the study addresses include:

- What biomass and nutritional yields can algae provide, how does it depend on the types of algae and the production technologies applied in marine or land-based cultivation systems?
- What are the costs and greenhouse gas (GHG) emissions of different types of algae production technologies? How do they compare with the costs and GHG emissions of land-based crops (e.g. soya) with similar nutritional properties? Under which conditions would algae production (in particular land-based systems fed by flue gases) be competitive?
- What could be the potential total algae production in Europe? What will be the resulting carbon dioxide captured and input (fertiliser, freshwater and land in particular) used?
- Which share of (today and future) animal feed requirements could be met by algae production? What are the main constraints (e.g. required post-harvesting processes with potentially high costs) that would need to be addressed to ensure algae production is recognised as source of animal feed and its potential fully seized?

1.2 Approach

The study was launched in December 2021 with a 12-month duration and is implemented by ACTeon (France – coordinator), Aarhus University (Denmark), the University of Copenhagen (Denmark), and TNO (the Netherlands Organisation for Applied Scientific Research). The study is structured into a series of tasks presented in Figure 5. The tasks are interconnected and task 6 has a transversal role by collecting data from all other tasks for the preparation of the relational database.

A wide range of scientific and grey literature was collected and reviewed with the aim to collect data on algae composition, yields, costs, greenhouse gas emissions, nutritional properties, and nutrition potential for selected production systems. National statistics databases were consulted to collect georeferenced data to estimate land-based algae production potential. The information was complemented by interviews with key experts via semi-structured interviews and an online survey. Collected data was structured in an interactive relational database that sets links and relations between data sets ensuring traceability between original references and database sources.

Key results of the study include:

- Description and estimation of key characteristics (algae composition, carbon uptake, costs, greenhouse gas emissions and break-even prices) for selected algae production systems.
- Estimation of the proportion of animal diets that could be met by algae and the methane reducing potential of algae.
- Maps of potential feed production for three case studies, including Denmark, France and the Netherlands.
- A relational database summarizing all project results.

1. Examination of production systems

- Selection of 10 key cultivation types (combination of technology and algae species)
- Data on algae composition and carbon uptake

2. Examination of costs and GHG emissions

- Estimation of cultivation costs and GHG emissions
- Benchmark against alternative feed sources

3. Estimation of carbon break-even price

- Estimation of break-even carbon price
- Comparison to past, current and future dynamics of carbon prices

4. Mapping of geographic potential for land-based marine algae cultivation

- Mapping and estimation of potential algae cultivation and resulting carbon capture
- 3 case studies (NL, France, Denmark) and extrapolation to the EU

5. Potential animal feed requirements that could be met by algae

- Identification of the species-dependent potential for inclusion of algae in animal diets
- Evaluation of the potential to employ anti-methanognic algae in methane mitigating strategies

6. Prepare database of results

- Development of a relational database integrating all data
- Developement of a user-guide

Figure 5 Overall approach

2 EXAMINATION OF PRODUCTION SYSTEMS

2.1 Introduction

The overall aims of this section are to:

1. Estimate the nutritional yield per unit area of at least 5 species for cultivation in marine waters, (coastal or offshore) and 5 species for land-based cultivation (either saltwater or freshwater) that are fit for human and animal nutrition. The nutritional yield was defined as a minimum and registered as the volume of crude protein (based on biomass nitrogen content) per unit area per year.
2. Collate additional available information on costs, GHG emissions, challenges, and constraints to cultivation/large-scale development, that can support consecutive tasks.

Activities included literature review and interviews with experts and stakeholders involved in algae production and processing. The activities have focused on the prioritization of production systems to be considered throughout the study, the identification of key projects and studies to be considered in the data collection and analysis.

As a first step, production techniques and algae species were prioritized based on literature review (see Section 2.2). The final list of selected production systems and the justification for their selection was validated at the interim meeting. For the selected production systems, data on nutritional yields and carbon uptake were collected (see Section 2.4 and Section 2.5). To facilitate data extraction, template tables for data extraction have been developed, tailored for entering the necessary output format of data into the relational database.

When data turned out to be scarce or missing, different sources from literature and interviews were used to arrive at an estimate of key parameters and variables. Review of evidence show that production volume, size, location, and species vary significantly between different combinations of cultivation method/species, and between studies. The expert assessment to give values for a range of estimates (from so-called conservative to base to optimistic scenarios) has only partly mitigated this issue. When comparing different scenarios and cultivation techniques, particular attention has been given to key assumptions and methodologies. This is because differences reported in the performance of different cultivation systems can be due to real (actual) performance, rather than differences resulting from variations in starting points, assumptions, and methodologies.

In parallel to the literature review, discussions were ongoing with the consultants of EurA, supporting the development and facilitation of the EU4Algae coalition to identify how best to mobilise (future) members of the coalition to provide and consolidate evidence available in the literature, in particular for production systems that are experiencing rapid developments in Europe and elsewhere (Taylor, 2022). An online survey was distributed to all members of the EU4Algae coalition (see Annex 11.6). Results of the online survey are presented in Section 2.6. Phone or online interviews with experts were carried out in parallel and the results of the interviews are presented in Section 2.7. Section 2.8 presents data on nutritional values and carbon uptake that are included in the relational database. Key messages, uncertainties and further research are discussed in Section 2.9.

2.2 Selected production systems

A 'Production system' has been defined as the combination of a cultivation system and a specific algae species. Among the candidate systems and species, 10 combinations of cultivation systems (Table 1) and algae species (Table 2) have been selected for the study and have been presented to the EC for comments prior to validation. The selection has been based on the following criteria:

- Established cultivation in the EU.
- Documentation for biomass composition.
- Production yields and costs in the EU.
- High production yields.
- Diversity in production technologies (coastal/offshore/land-based).
- Diversity in geographic relevance of cultivation (species native or not, adapted to climate).
- Inclusion of both macro- and microalgae.

As some of the selected macroalgae species are cultivated in both coastal/off-shore systems and land-based systems, the selected algae species are presented and categorised as macro- or microalgae. The selection includes: 6 macroalgae species whereof all may be cultivated in coastal/off-shore systems, while 4 hereof are also cultivated in land-based systems; 5 microalgae species all cultivated in land-based systems.

2.2.1 Selection of cultivation systems

The following cultivation systems have been selected following a first screening of the literature available to identify systems for which some information was available and could be used to make estimates of key parameters and variables (see Table 1). Proposed cultivation systems cover the potential for cultivation of as many species as possible and systems with similarities have been combined into one category, to hereby limit the number of combinations of data input for the relational database. For example, 'rope systems' covering all coastal/offshore macroalgae cultivation systems with algae seeded on ropes/lines and deployed at sea, regardless of e.g. the system infrastructure, the stocking density and/or the seeding method applied.

Table 1 Cultivation systems selected for data extraction

Cultivation systems	Marine/In-land	Macroalgae /Microalgae	Open / closed	Salt / fresh	Details
Rope system	Marine / Coastal	Macroalgae	Open	Salt	Spores/gametophytes of algae seeded on ropes or lines, deployed directly into the coastal of offshore cultivation system, or reared in a hatchery prior to deployment.
Ponds/raceway ponds/tanks	Land-based	Macro- and microalgae	Open	Salt	Shallow artificial ponds/tanks typically open and out-door with natural light, if raceway ponds: circular water movement by paddle wheel, if tank: potential aeration.
Photo-bioreactors	Land-based	Macro- and microalgae	Closed	Salt/fresh	Closed cultivation system designed for growing photoautotrophic organisms using artificial light sources or solar light.

2.2.2 Selection of algae species

On a global scale it is estimated that 10 000 species of macroalgae (seaweeds) exist, represented by the phylogenetically different brown, green and red algae. Only relatively few species are exploited commercially, hereof most in Asia (FAO, 2020). Where the majority of seaweeds produced in Asia are cultivated, 68% of European macroalgae producers rely on wild harvested seaweeds, constituting more than 99% of the seaweeds produced (Araújo et al. 2021). Europe, however, is moving towards increased cultivation of kelps in marine systems, but also various species in systems on land in open and closed systems.

From the most commonly cultivated species in Europe, we have selected 5 species (of which one species in two different systems) that will be considered in the study based on their present scale of production, and their immediate future potential in animal feed (including as a zootechnical feed ingredient to reduce enteric methane production in ruminants), human food, ingredients for food and cosmetics, as well as for food supplements and nutraceuticals (Table 2).

The two most cultivated seaweed species in Europe are *S. latissima*, and *A. esculenta* with a production of 376 and 107 wet tonnes annually, respectively (Araújo et al. 2021). The two kelps are cultivated using similar systems in the marine environment, but have different yields and they also differ in application, where *A. esculenta* primarily is used for food, and *S. latissima* is used for both food and feed purposes. An important difference between the two kelp species is that they differ in iodine content, with *A. esculenta* having a significantly lower iodine content (171 to 1070 µg g^{-1} dw) as compared to *S. latissima* (1556–7208 µg g^{-1} dw) (Roleda et al. 2018). Thus, *A. esculenta* is potentially facing less barriers in the value chains for food and feed purposes.

Data on production yields, cost and biomass composition exist from relevant studies (Bak et al. 2018; Fernand et al. 2017; Zhang et al. 2022) and reports (Wegeberg et al. 2013; Bak 2019; Roleda et al. 2018). Both kelp species offer a means for coastal and offshore marine cultivation with a potential for emission capture and utilisation of CO_2 and nutrients entering the marine systems from land (Zhang et al. 2022). Both kelps have potential for cultivation in the North Sea, and for *S. latissima* also, to a limited extent in the western Baltic (Boderskov et al, 2021).

Ulva sp. are the third most produced seaweed species in Europe (50 wet tonnes annually) (Araújo et al. 2021). Ulva species are typically cultivated in land-based systems due to their more fragile morphology, albeit cultivation in marine systems is progressing (Steinhagen et al, 2021). Land-based cultivation of Ulva offers a means for emission capture and utilisation of CO_2 and nutrients from land-based point sources, such as CO_2 emitting industries and land-based fish production. Established value chains based on Ulva include food, feed, fertiliser, nutraceuticals, and cosmetics end products. Ulva is a cosmopolitan species complex with potential for cultivation in the North Sea, Baltic, Black Sea and the Mediterranean and in land-based systems independent of immediate access to marine water.

Palmaria palmata is a North Atlantic red alga in high demand from the food industry due to its rich flavour and relatively high protein content (Grote et al, 2019). At present, the bulk of *Palmaria palmata* biomass on the market derive from wild harvest (Araujo et al, 2021), but optimised aquaculture strategies are progressing for coastal/off-shore cultivation as well as for land-based production in connection to fish farms (Grote et al, 2019 and Schmedes et al, 2020).

Gracilaria sp. are red algae species being cultivated in ponds, land-based systems and in cages (in marine coastal systems). The species has potential for cultivation in the North Sea, Baltic, Black Sea and Mediterranean, with the caveat that in some EU countries, certain *Gracilaria* species are considered invasive, and thus only closed land-based systems with focus on biosecurity can apply in these cases (Abreu et al. 2011). *Gracilaria* sp. has high potential for nutrient bioremediation in various systems on land and in cages in the marine environment. Value chain perspectives are i.e. food, feed, hydrocolloids and protein through biorefining (Kazir et al. 2019).

Asparagopsis sp. are red algae species complexes. Both originate from Australasia, and the species *Asparagopsis* taxiformis is predominantly found in tropical and subtropical waters, whereas the species *Asparagopsis* armata is found in warm temperate waters. Both are introduced non-indigenous species in Europe and are found i.e. in the southern North Atlantic (Madeira, Azores, Canary Islands)) and *Asparagopsis* armata also at the British Isles and in the Mediterranean Sea[17].

Both species can be cultivated in open ponds/tanks (under the environmental conditions i.e. temperature they are adapted to) and in closed land-based systems – photobioreactors – where cultivation conditions are fully controlled and can be optimised. Production yields are described from both by de Mata et al. (2008) and Shuenhoff (2006) – see i.e. review by Zanolla et al. (2022) and also mentioned by Araujo et al. (2021). Cultivation of Asparagopsis species in photobioreactors is happening in pilot scale in Sweden (VoltaGreetech), Denmark (Maripure) aiming for large-scale commercial production.

Asparagopsis sp. are cultivated in Europe to a limited extent, but the interest and development has been increasing dramatically since Asparagopsis sp. showed potential to significantly reduce the ruminal methane production in cattle, and with that the climate footprint of agriculture (Glasson et al. 2022 and Kinley et al. 2020). Data on production yields, costs and value chain potential will be accessible through literature and expert interviews from both land-based systems and coastal cultivation. Several other macroalgae species such as *Undaria* sp., *Chondrus crispus*, *Porphyra* sp. and *Codium* sp. are also being exploited in Europe, however provision of these species is primarily through wild harvest, not cultivation (Araújo et al, 2021), and for this reason these species are not prioritised in this report. China is the world's largest macroalgae producer (Chopin and Tacon, 2020). For a number of reasons however, information has not been gathered for cultivation of macroalgae in China for this specific report: major divergence in the conditions for seaweed production between China and Europe: Most species cultivated in Chinese waters are not relevant for cultivation in Europe since the species are non-indigenous – and in some cases potentially invasive. The technology is not (yet) developed for cultivation of sterile marine seaweed crops, that are guaranteed not to spread into the natural environment, as is developed for agricultural crops such as potatoes, tomatoes, tobacco and maize. The costs of seaweed production are not comparable between China and EU, as the cost of labour in China is considerably lower than in the EU, and therefore mechanisation is not imperative for a feasible business case.

The regulatory framework for seaweed cultivation in China is also not comparable to the EU frameworks, i.e. 1) seaweed cultivated in the sea in China can be fertilised by adding nutrients directly to the sea, whereas in European waters, all European countries are obliged by the Water Framework Directive to reduce the emissions of nutrients to European coastal waters, and a direct fertilisation of seaweeds would never be accepted; 2) non-indigenous seaweed species may be imported and cultivated in Chinese waters, whereas in Europe cultivation in the sea of non-indigenous species will not be permitted. Still, valuable knowledge may be extracted on cultivation technology and impacts of cultivation in industrial scale, and efforts were made to include this information by identifying and repeatedly contacting the top 10 Chinese algae producers, the attempts were not successful.

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[17] (Algaebase.org)

It is estimated that an order of 100 000 microalgae species exists, of which about 200 species are used in various applications, though the latter number includes seaweeds (Enzing et al. 2014). From a biological perspective, the microalgae division includes diatoms (Bacillariophyceae), green algae (Chlorophyta), dinoflagellates (Dinophyceae), red algae (Rhodophyta) and Euglenoids (Euglenophyta) (Lee, 2008 and Enamala et al. 2018). In this study, cyanobacteria (Cyanophyceae or blue-green algae) are also referred to as microalgae, given the importance of the much-used species *Spirulina*. All microalgae are eukaryotes, whereas cyanobacteria are prokaryotes lacking a membrane-bounded nucleus.

Concerning the purpose of this study, the logical classification is to distinguish between the main types of storage molecule used. Here, a division can be made between biochemical storage in the form of lipids, carbohydrates (starch) and proteins, although each microalga could store, and/or be manipulated to store, lipids, carbohydrates, and proteins in response to environmental variability. *Nannochloropsis* sp. was selected to represent one of the microalgae with lipids as storage molecules. *Nannochloropsis* can store up to 60% lipids in the form of triacylglycerols (TAG) and the ω-3 long-chain polyunsaturated fatty acid (PUFA) and eicosapentaenoic acid (EPA) (Ma et al. 2016). The most studied applications include biofuels, feed, and functional food. Recent studies (Sarker et al. 2020) found it an attractive option for fish aquaculture feed. *Nannochloropsis* is cultivated in photobioreactors to avoid contamination and using saltwater. In Europe, 25 companies produce 21 tonnes of *Nannochloropsis* annually (Araújo et al, 2021).

Haematococcus pluvialis is a green alga which grows in fresh water and store up to 35% lipids as major components. To date, *Haematococcus pluvialis* has the highest reported concentration of astaxanthin at 4% dry weight with the higher purity of astaxanthin produced in any microalgae (can reach 95% of the total carotenoids) (Butler et al. 2017). Astaxanthin is mainly incorporated in dietary supplements, nutraceuticals, cosmetics, as well as feed additives in the aquaculture and agriculture sectors, although 99% of the astaxanthin on the market is chemically synthetised. In Europe, 17 companies produce 66 tonnes of *Haematococcus* annually (Araújo et al. 2021).

Chlorella sp. was selected as representative of microalgae using carbohydrates as storage molecules, as it can store up to 60% starch of DM (Cheng et al. 2017). *Chlorella* belongs to the green algae (Chlorophyceae), and it was considered for use as a protein supplement in human diet. *Chlorella* sp. production was estimated at 2000 tonne dw/yr by 70 producers in 2003 (Vigani et al. 2015) and is used as human food supplement, animal feed and cosmetics. Cultivation of *Chlorella* sp. is done mainly in photobioreactors to avoid contamination requiring fresh or salt water. In Europe, 30 companies produce 82 tonnes of *Chlorella* sp. annually (Araújo et al. 2021).

Spirulina is the commonly used name for species belonging to the genus *Arthrospira* sp. *Spirulina* was selected as the representative for cyanobacteria, as it can accumulate up to 60-70% of proteins of DM, including all the essential amino acids, vitamins, minerals, etc. (Soni et al. 2017). *Spirulina* is commonly cultivated in open raceway ponds that have lower costs than photobioreactors. Cultivation requires fresh water and CO_2. Commercial production of *Spirulina* is targeted in industrialised countries for natural food and health food market and the extraction of high value biochemicals. Developing countries are in search of a rich source of protein, produced under local conditions and using marginal land, and for treating animal and human waste (Ahsan et al. 2008 and Vigani et al. 2015). *Spirulina* production was estimated at 5000 tonnes dw/yr in 2012 by 15 producers (Vigani et al. 2015). In Europe, 222 companies produce 142 tonnes of *Spirulina* annually, of which the 147 tonnes are produced in France (Araújo et al, 2021).

Dunaliella sp. is a green bi-flagellated, pear-shaped cell, halophilic microalga. This microalga is a natural source of carotenoids (up to 16% of the dry matter) for human use as well as for animal feed (shrimps) and it is used as nutritional, colorant ingredient in food, feed, and cosmetic industries. *Dunaliella* sp. is commonly cultivated in open ponds that have lower costs than photobioreactors. Cultivation requires high salinity water (less risk of contamination), high light intensity and CO_2. The global production of *Dunaliella* sp. was estimated to 1200 tons dry weight per year in 1996, where the major producers of *Dunaliella* sp., mainly for beta-carotene, where located in Israel, China, United States, and Australia. In Europe, 8 companies produce 2 tonnes of *Dunaliella* sp. annually (Araújo, 2021), as source of natural healthy food and for the extraction of high value biochemicals.

Table 2: Species selected for the data extraction, with production system and species combination selected marked in bold and ranked in prioritised order from 1 = highest priority to 5 (C = Coastal, L = land-based). Five production systems from coastal (C) or land-based (L) systems were selected. Note that production systems with a priority lower than 5 for either coastal or land-based, do not have a priority number (Gracilaria and Dunaliella)

Species	Macro / Microalgae	Production method	Selection/priority argument	Production system priority
Saccharina latissima **(Laminariales, Phaophyceae)**	Macroalgae	Rope system	Most cultivated macroalgae species in Europe.	C1
Alaria esculenta **(Laminariales, Phaophyceae)**	Macroalgae	Rope system	Second most cultivated macroalgae species in Europe. Iodine content lower than other kelps.	C2
Palmaria palmata **(Rhodophyceae)**	Macroalgae	Rope system, pond/tank/raceway pond	High demand from food industry. Strong efforts to develop efficient coastal production.	C3
Asparagopsis sp. **(Rhodophyceae)**	Macroalgae	Rope system / photobioreactor	High interest as methane reducing feed additive. Cultivation activities increasing.	C4 / L5
Ulva sp. **(Chlorophyceae)**	Macroalgae	Rope system, pond/tank/raceway pond, photobioreactor	Cosmopolitan species with potential for cultivation in various systems marine and land-based, and thus with large potential across EU.	C5
Gracilaria sp. **(Rhodophyceae)**	Macroalgae	Pond/tank/raceway pond	Cosmopolitan species with potential for cultivation in various systems marine and land-based, and thus with large potential across EU.	Not in priority top 10
Spirulina **(Spirulinales, Cyanophyceae)**	Microalgae	Photobioreactor	Protein-rich	L1
Chlorella sp.	Microalgae	Photobioreactor	Carbohydrate-rich	L2

(Chlorellales, Trebouxiophyceae)				
Haematococcus pluvialis **(Chlamydomonadale, Chlorophyceae)**	Microalgae	Photobioreactor	Astaxanthin	L3
Nannochloropsis sp. **(Eustigmatales, Eustigmatophyceae)**	Microalgae	Photobioreactor	Lipids, carotenoids	L4
Dunaliella **(Chlamydomonadales, Chlorophyceae)**	Microalgae	Raceway pond/ Photobioreactor	Protein	Not in priority top 10

2.3 Data collection and methodology

Data on the composition of micro- and macroalgae was extracted from the existing literature using standard searching tool and keywords relevant for the information needed in relation to specific species, algae groups, production, productivity, and elements of composition. The literature search was not an exhaustive review of all existing literature. The number of papers included in the data search was defined by 1) number of key papers to limit variation of data while securing a realistic range of values, 2) and limitations on available, existing, published knowledge, in particular regarding the tissue concentrations of critical elements and species with a short track record in cultivation such as *Asparagopsis* sp., and also regarding productivity for the specific combinations of species and cultivation systems.

Specifically for microalgae, reviews not older than ten years were included (as review papers include the most relevant information from previous years). Two to four review papers were selected per microalgae species; each relevant component's maximum and minimum concentrations were considered as listed in these papers.

If necessary and possible, values were recalculated to fit units defined in the database. In cases where values were missing to recalculate to standardised units, assumptions were made regarding dry matter (DM) content of 1:10 DM:FW (Fresh Weight), if other necessary information was not given to allow for re-calculations, data were not included. Quality assessment of data was performed as part of calculation of results for nutritional yield, feed requirements and mapping of the geographical potential for cultivation and carbon capture.

Base scenarios were defined as the average of values in the database, the highest concentration was defined as the ‘optimistic scenario’, and the lowest concentrations were defined as the ‘pessimistic scenario’. The following exceptions were made: For ash content and the concentrations of critical minerals (Iodine, Hg, Cd, As), a high concentration is not positive and may be limiting for the inclusion of algae in feed. For this reason, the definitions of ‘optimistic’ and ‘pessimistic’ were inversed, for the concentrations of ash and the mentioned the specific minerals.

2.4 Results on algae composition and nutritional yield

2.4.1 Algae nutritional yields

The nutritional yield, defined as crude protein produced per area per year, varied with a factor of nearly 2000 between the highest yielding species and system: *Spirulina* in raceway ponds (71.5 tonnes crude protein/ha/y), and the lowest yielding species and system, *Alaria esculenta* on ropes in the sea (0.04 tons crude protein/ha/y). Generally, the microalgae systems had the highest nutritional yields, see Figure 6. This is a consequence of the microalgae in general having both higher areal biomass production yields and higher crude protein contents in comparison with macroalgae. The nutritional yield of macroalgae produced in land-based systems was markedly higher than the nutritional yield of macroalgae produced in coastal systems (Figure 7), as *Ulva* and *Asparagopsis* produced in land-based systems achieved nutritional yields at a level comparable to the microalgae (Table 3).

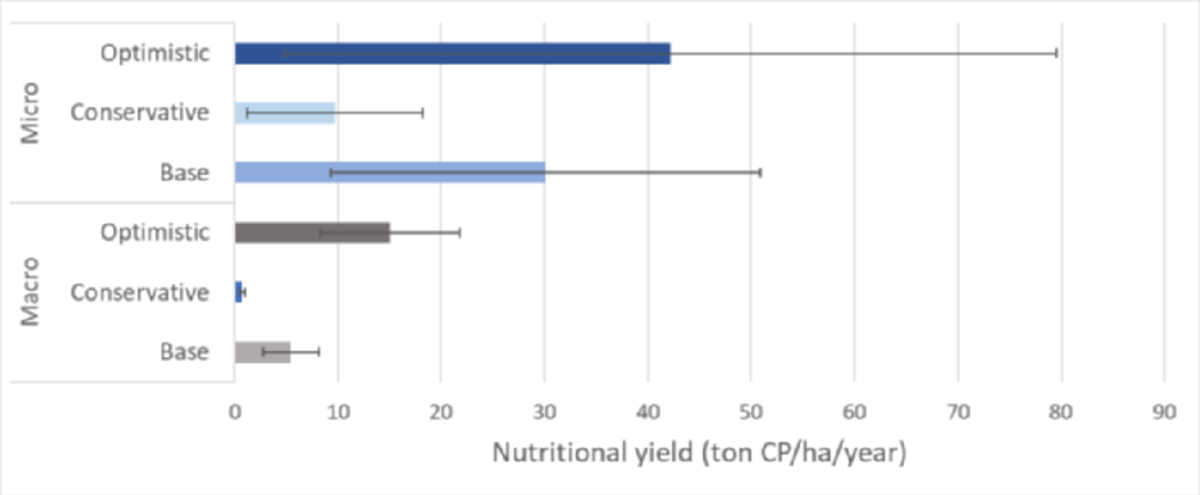

Figure 6 The nutritional yield of macroalgae versus microalgae including the base, conservative and optimistic scenarios across species. Data are presented as average +/- SE (n =4)

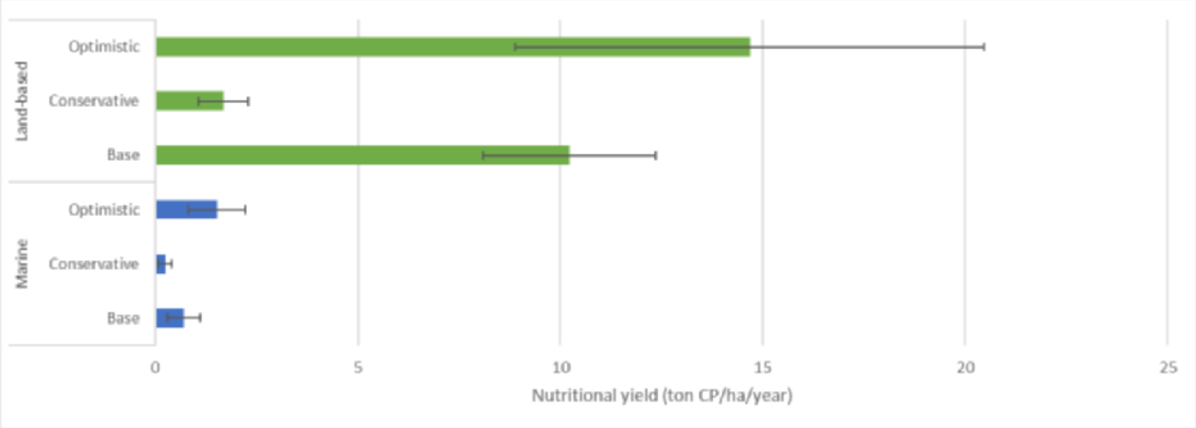

Figure 7 The nutritional yield of macroalgae produced in coastal versus in land-based systems, including the base, conservative and optimistic scenarios across species. Data are presented as average +/- SE (n =4)

The kelp species cultivated on rope systems at sea, in general had the lowest nutritional yields, see Table 3. Calculation of the nutritional yield based on assuming both optimistic/conservative scenarios for biomass yield and content of crude protein, however, contains a bias as these two parameters tend to be inversely correlated.

Table 3 The nutritional yield (tons crude protein (CP) per hectare per year) of the different algae species and production systems, calculated from the relational database 'base values' of areal production and content of crude protein

Species	Production system	Yield/total footprint area (t_dw/ha_tot/yr) (land or sea)	Crude protein content (% dm)	Nutritional yield (tons CP/ha/y)
Ulva	Raceway ponds/ponds	38.68	16.42	6.35
Ulva	Photobioreactor	14.28	16.42	2.35
Asparagopsis	Marine rope system	137.93	16.00	13.23
Saccharina	Marine rope system	1.84	9.59	0.18
Alaria	Marine rope system	0.33	12.12	0.04
Haematococcus	Photobioreactor	32.18	17.00	5.47
Nannochloropsis	Photobioreactor	49.10	28.50	13.99
Spirulina	Raceway ponds	137.50	52.00	71.50

2.4.2 Macroalgae composition

Macroalgae are a promising source of crude protein, functional carbohydrates, minerals, and bioactive compounds, such as pigments/antioxidants (Holdt and Kraan 2011). In contrast to microalgae, the macroalgae generally only contain low concentrations of lipids, but larger amounts of minerals (ash). Growth conditions (light, nutrient availability, temperature, salinity), species, ecotype and life cycle, to a large extent determine the macroalgae growth rate and specific composition, leading to a large variability in composition between and within species (Boderskov et al. 2016 and Schiener et al. 2015), which is also reflected in the database compiled for this study.

The macroalgae composition of amino acids and lipids is generally beneficial in a nutritional perspective (Holdt and Kraan 2011) which is described in detail in Section 6 and in Supplementary Table 6.1. In general, an aspect of concern is the ability of algae to accumulate critical minerals, which for some species may be exceeding limit values in existing food and feed regulations (Cherry et al. 2019, Holdt and Kraan 2011 and Makkar et al. 2016). This is also discussed in detail in Section 6 and Supplementary Table 6.2.

2.4.2.1 Macroalgae carbohydrates/polysaccharides

The carbohydrate content in macroalgae differs in quantity and quality across species and seasons. It derives from two major sources: structural carbohydrates (predominantly found in the cell walls, and generally sulphated) and storage carbohydrates (stored inside the cells). The dominant carbohydrates differ between the different phylogenetic groups of macroalgae: the red, green, and brown macroalgae. The major structural carbohydrates in red algae are carrageenan and agar, in green algae, such as Ulva species, it is ulvane, whereas in brown algae it is alginate (Percival 1979). The structural carbohydrates of macroalgae are used as gelling agents (hydrocolloids) in the industry, mainly in food, feed, and cosmetics.

Macroalgae also contain a varying amount of starch in the cell walls. The storage carbohydrates are i.e., floridian starch in the red algae, starch in the green algae, and laminarin and mannitol in the brown algae (Percival 1979). Under nutrient limitation and unlimiting light conditions, carbohydrates typically constitute a major fraction of the macroalgae biomass. In particular, the sulphated polysaccharides have several beneficial functional properties that to an increasing degree are exploited in the pharma- and biotech industries (Holdt and Kraan 2011), as well as in the feed industry for improving animal gut health (Berri et al. 2017, Corino et al. 2019).

2.4.2.2 Macroalgae lipids

The lipid content in macroalgae is generally very low – less than 1-5% of DM (Holdt and Kraan 2011). As for microalgae, the composition of the lipid fraction is significantly higher -and with a relatively high concentration of omega-3 fatty acids (Holdt and Kraan 2011).

2.4.2.3 Macroalgae protein

The protein concentration in macroalgae varies, as for the carbohydrates, with species and season. The major determining factors being nitrogen availability (directly correlated) and growth rate (inverse correlation). The amino acid composition of macroalgae protein is generally complying with FAO recommendations (Juul et al. 2021, Kraan 2013 and Marinho et al. 2015). Generally, red, and green macroalgae contain more protein than brown algae (Holdt and Kraan, 2011).

2.4.2.4 Macroalgae high value components

In addition to the functional carbohydrates and protein, macroalgae contain various high value components, such as pigments, polyphenols, and other antioxidants (Holdt and Kraan 2011). In this study fucoxanthin (a bioactive brown pigment), carotenoids (red/orange pigments and antioxidants) and polyphenols were included.

2.4.2.5 Macroalgae minerals/ash

The ash content of macroalgae is very variable and typically ranges between 17 and 55% of DM depending on species and growth conditions (Holdt and Kraan 2011). Macroalgae are efficient in taking up heavy metals and critical minerals, and in particular the contents of Arsenic and Iodine can be limiting for applications of certain brown algae for food and feed purposes (Makkar et al 2016). Post-harvest processing in the form of blanching and fermentation, however, has been documented to reduce the content of specific metals and iodine (Bruhn et al 2019, and Nielsen et a. 2020).

2.4.2.6 Macroalgae composition results

The overall composition of the algae included in the study emphasizes the differences in composition between macroalgae and microalgae, with the macroalgae having a generally higher content of carbohydrate (47-72% versus 10-35% of DM) (Figure 8) and ash (11-36% versus 6-12% of DM) (Figure 9), and a lower content of crude lipid (1-9% versus 12-40% of DM) (Figure 10) and protein (9-20% versus 17-52% of DM) (Figure 11), as compared to the microalgae.

Among, and also within, the macroalgae species, a large variation in composition was observed, with the largest variation observed in the lipid content, as i.e. a factor of 20 in lipid composition of *Gracilaria*, and a factor of 800 difference between the highest and lowest lipid content reported for *Asparagopsis* (Figure 12). The large variation reflects differences in growth conditions and life stages. In controlled, land-based cultivation scenarios, conditions can be optimised towards greater stability in composition (Hafting et al. 2012). Where the DM content of microalgae is most commonly not provided, there is a difference between the macroalgae with *Asparagopsis* representing the lowest DM content of 8%, and *Palmaria* (Figure 13).

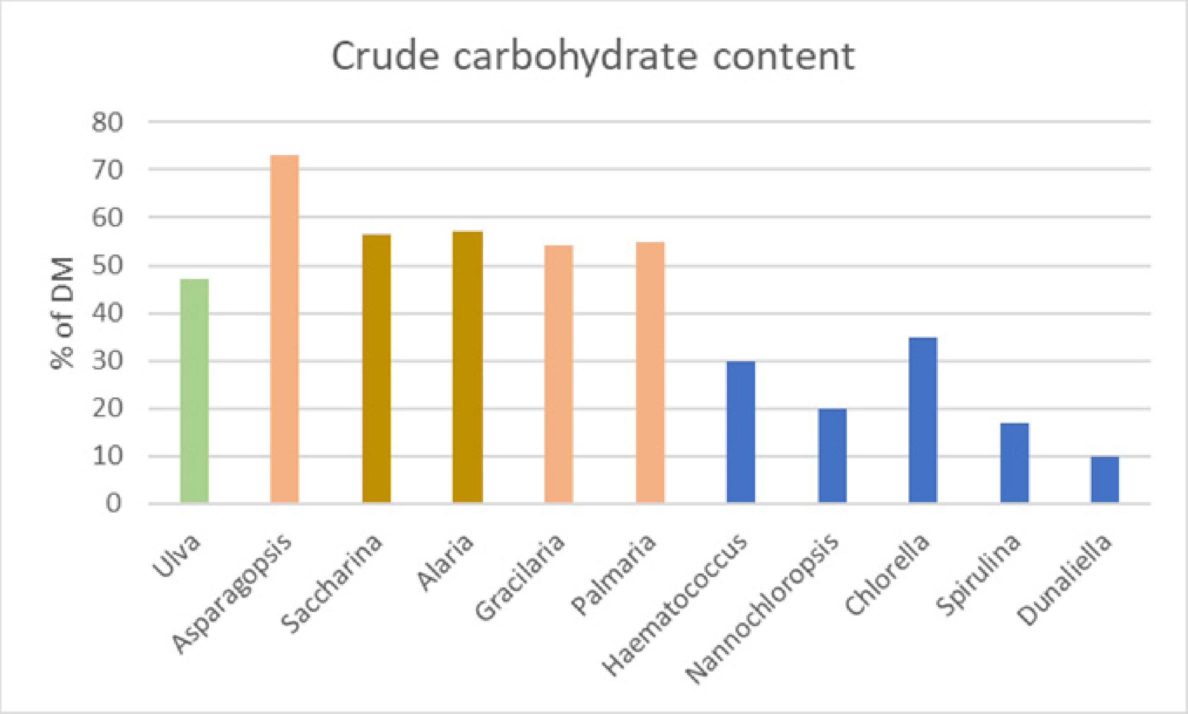

Figure 8 Base scenario values of the crude carbohydrate content of the algae selected or this study. Colour of bars indicate group of macroalgae – red, green, and brown, and microalgae in blue. Data are given as % dry matter (DM)

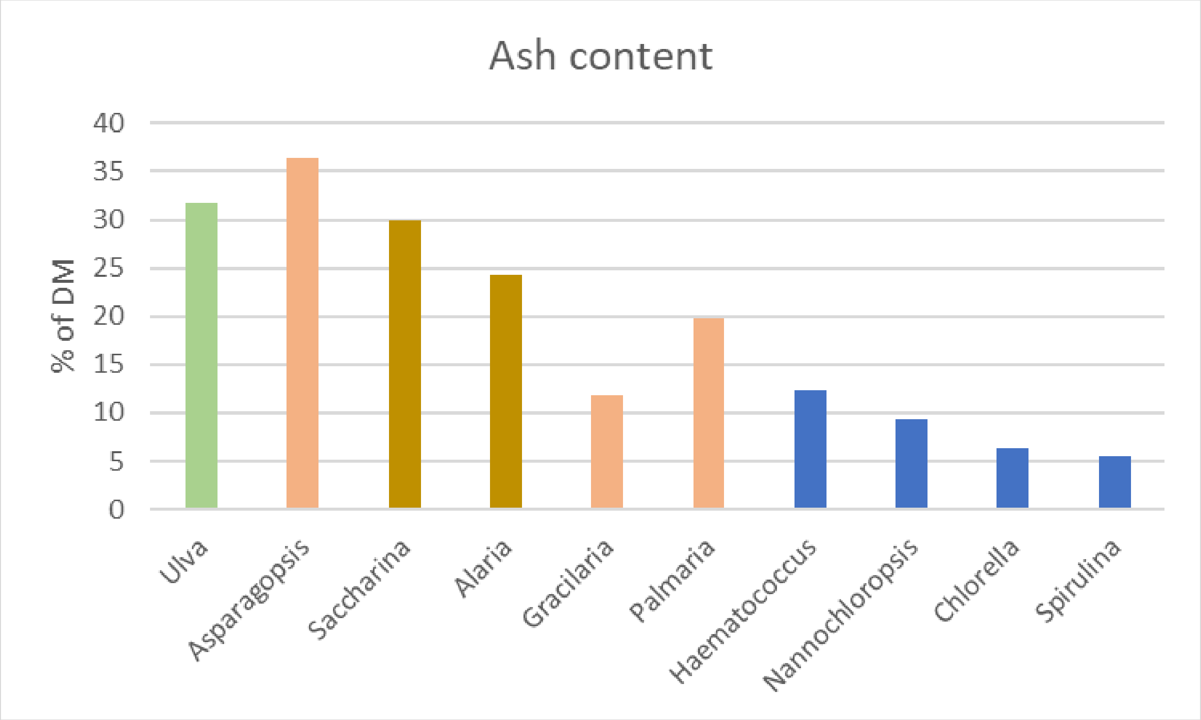

Figure 9 Base scenario values of the ash content of the algae selected or this study. Colour of bars indicate group of macroalgae – red, green, and brown, and microalgae in blue. Data are given as % dry matter (DM)

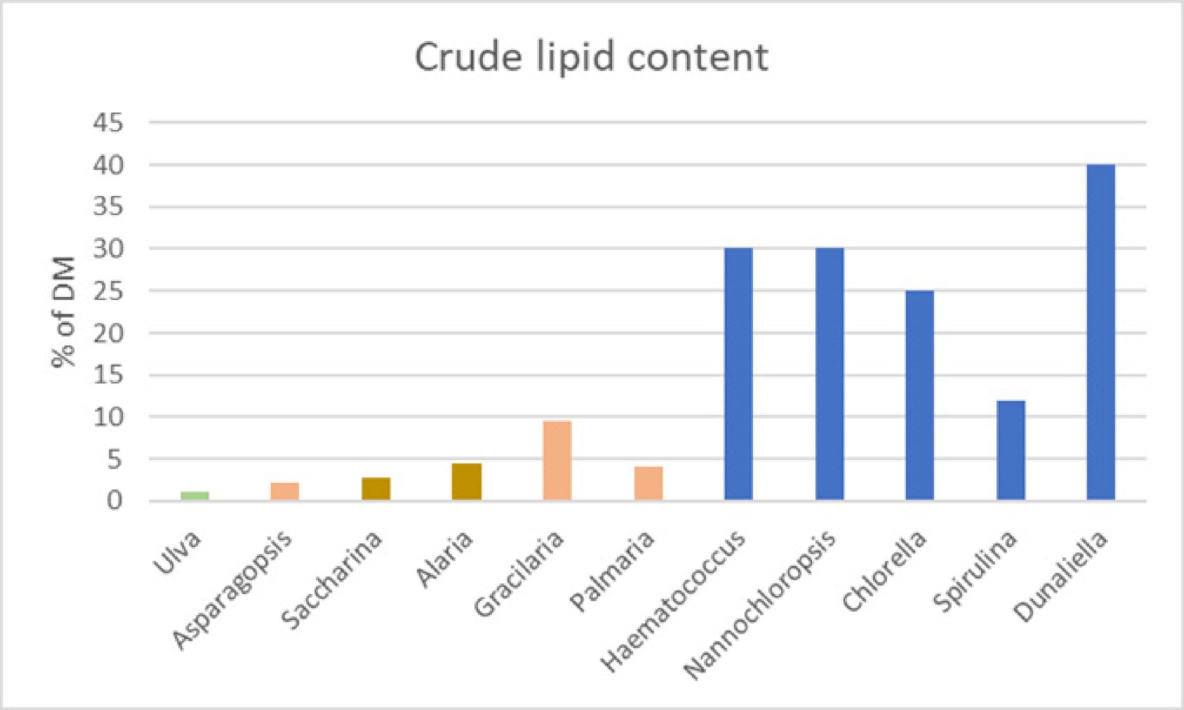

Figure 10 Base scenario values of the crude lipid content of the algae selected or this study. Colour of bars indicate group of macroalgae – red, green, and brown, and microalgae in blue. Data are given as % dry matter (DM)

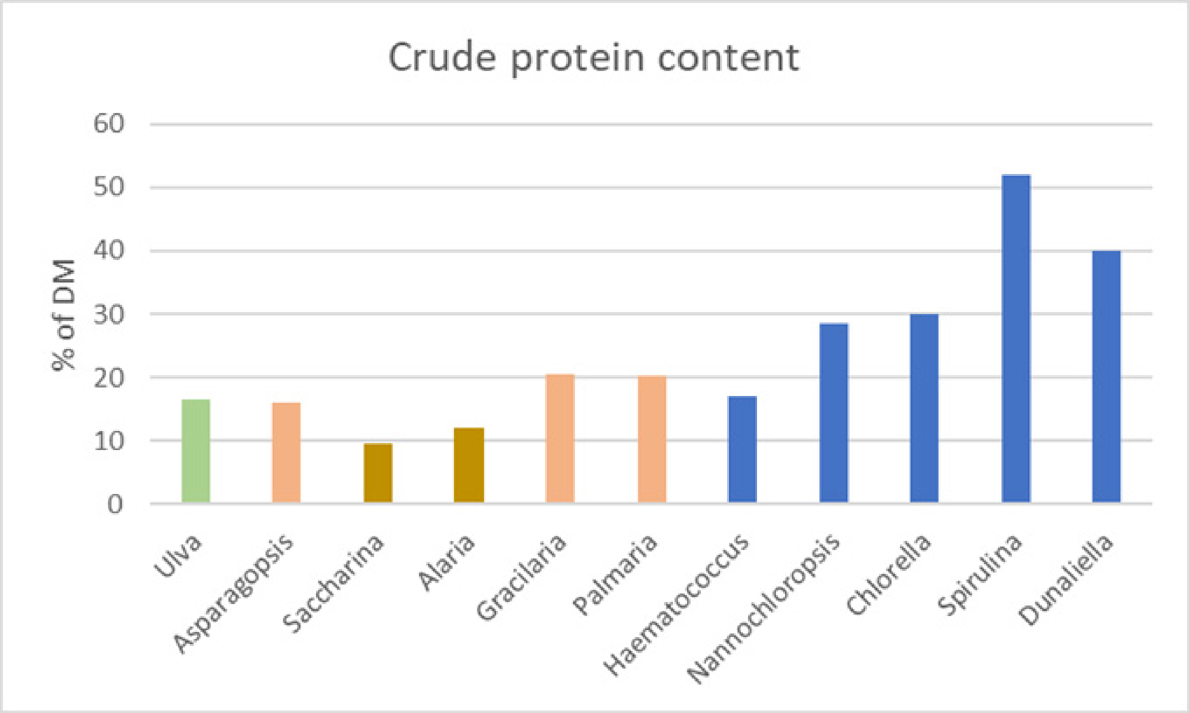

Figure 11 Base scenario values of the crude protein content of the algae selected or this study. Colour of bars indicate group of macroalgae – red, green, and brown, and microalgae in blue. Data are given as % dry matter (DM)

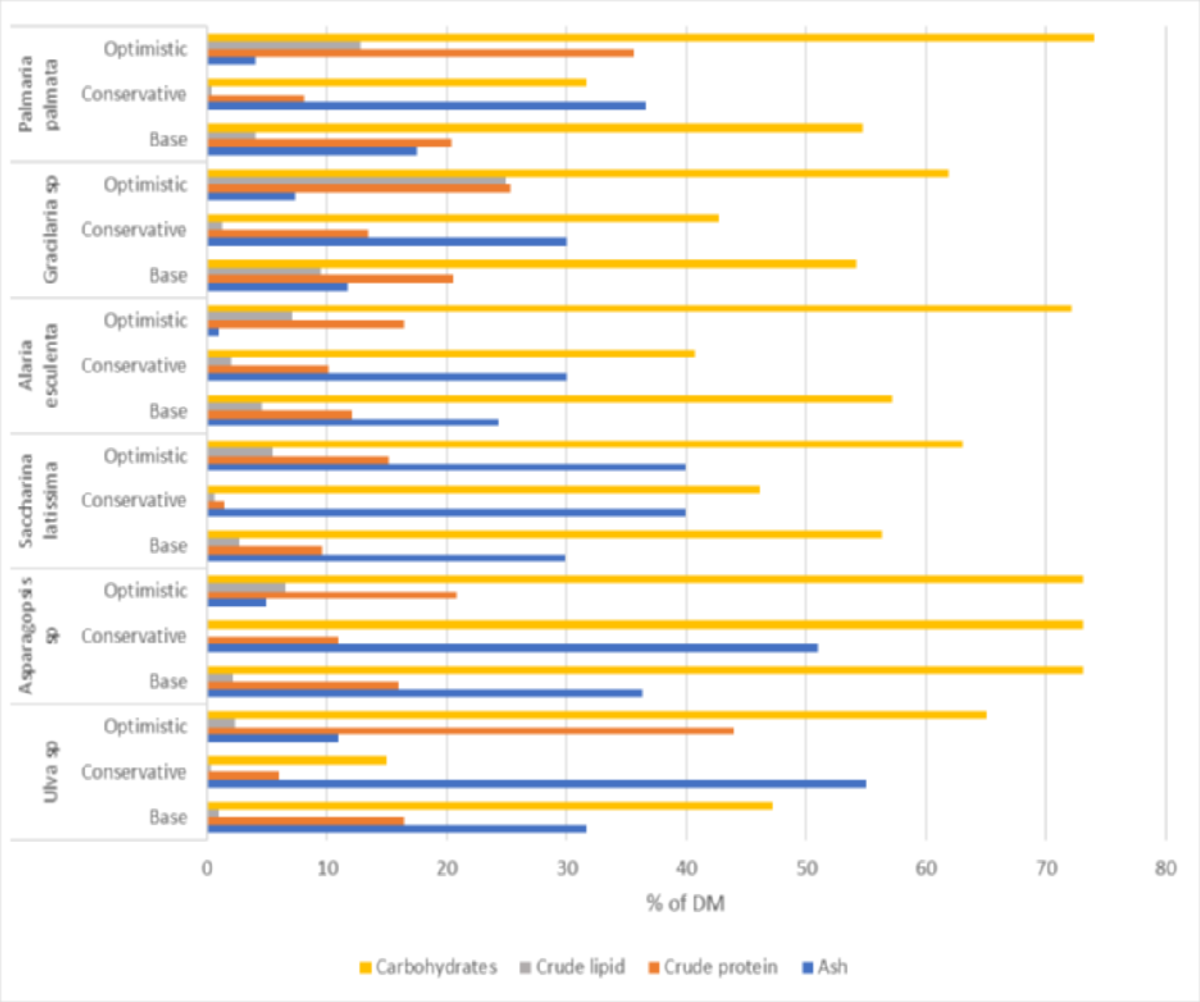

Figure 12 Main macroalgae composition (carbohydrates, crude lipid, crude protein and ash) illustrating the large variation between the optimistic, base and conservative scenarios

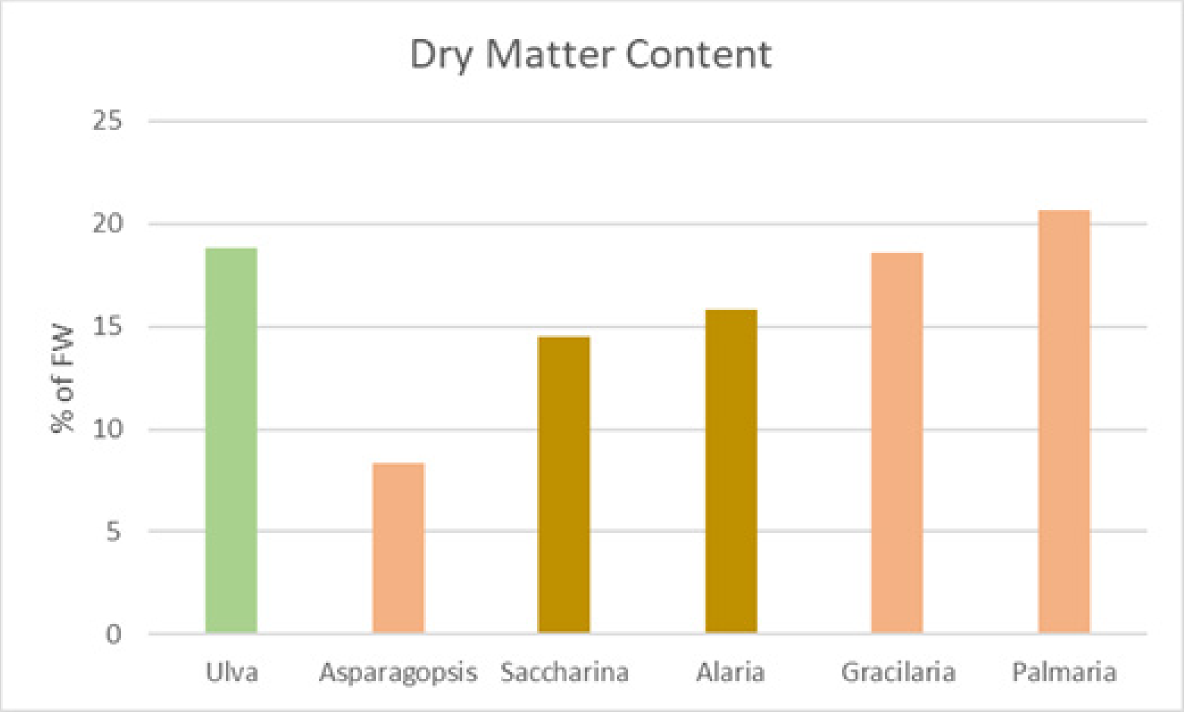

Figure 13 Base values of the dry matter content of the macroalgae selected or this study. Colour of bars indicate group of macroalgae – red, green, and brown. Data are given as % fresh weight (FW)

2.4.3 Microalgae composition

Microalgae are a promising sustainable source of lipids, omega-3 fatty acids, proteins, and carbohydrates. Lipids and carbohydrates are the main components of microalgae, and both are a source of energy storage, while proteins are of central importance in the chemistry and composition of microalgae. Proteins are involved in growth, repair and maintenance of the cell and serve as cellular motors, chemical messengers, regulators of cellular activities, etc. (Safi, Zebib, Merah, Pontalier, & Vaca-Garcia, 2014).

Growth conditions such as nutrient limitation, temperature and light intensity significantly influence the growth rate and chemical composition of every microalgae strain. Microalgae species have been shown to accumulate carbohydrates and lipids even when cultivated under nitrogen limitation (Reitan, Øie, Jørgensen, & Wang, 2021) and (Chen et al., 2013).

Besides the main microalgae components (lipids, proteins, and carbohydrates), the interest in using these and other microalgae molecules is increasing. The use of microalgae molecules as a functional food has risen recently due to their nutritional and bioactive potential. Compounds such as polysaccharides, fatty acids, bioactive peptides, and pigments are becoming more relevant as feed and food additives (Reitan et al., 2021). The potential applications depend on the type of metabolites found in each microalgae species. Thus, in addition to being used in human diet supplementation, it can be used as ingredients for animal feed, pharma, cosmetics, pigments, biofuels, bioplastics, etc. (Morais Junior et al., 2020).

2.4.3.1 Carbohydrates (polymeric and non-polymerics)

Microalgae differ in carbohydrate composition (quantity and quality) depending on species and cultivation conditions. Although most of the microalgae carbohydrates are starches (energy storage of microalgae and fermentable to produce bio-ethanol), a few carbohydrates such as glucans and polysaccharides sparked some commercial interest (biological and rheological) for feed, food, pharma and cosmetics industries (Costa, Lucas, Alvarenga, Moreira, & de Morais, 2021).

Specific microalgal glucans (polysaccharides) can activate the immune system or exert antioxidant and hypocholesterolemic effects (Reitan et al., 2021). Microalgal polysaccharide-enriched extracts and even whole cells from some microalgae modulated the gut microbiome and stimulated the immune system (Carballo et al., 2019).

Microalgal-based carbohydrates possess a specific advantage compared to their synthetic or traditional alternatives in the food and nutraceutical industries despite high production costs. The functionality of microalgal carbohydrates in food products is not restricted to their health attributes, as they also possess techno-functional properties and can function as a texturizer or stabilizer in food products (Ravindran & Rajauria, 2021).

2.4.3.2 Lipids and other liposoluble components

Microalgal lipids are divided into three main categories, namely those used as biofuel (with 14–20 carbon chains), as food (containing 20 carbon chains) and pigments. Some microalgae demonstrated a dual potential, namely the ability to produce lipids and value-added products (i.e. carotenoids) under the influence of various physicochemical stresses on microalgae. Some species of microalgae can synthesize, very-long-chain polyunsaturated fatty acids (VL-PUFA, >20C) such as docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), those have significant applications in food and health (Minhas, Hodgson, Barrow, & Adholeya, 2016)(Minhas, Hodgson, Barrow, & Adholeya, 2016)(Minhas, Hodgson, Barrow, & Adholeya, 2016) while short saturated carbon chains find applications in biodiesel production. Omega-3 fatty acids such EPA and DHA are the most relevant compounds in fish oil for human consumption. This point is important because fish do not synthesize DHA and EPA, therefore the only way to enrich these compounds in fish is by accumulating them in a proper algal paste and incorporate them in the fish feed, thus making them available to humans.

The importance of algal lipids is based on their polyunsaturated fatty acids, their anti-inflammatory effects, their modulation of lipid pathways and their neuroprotective action., Microalgae also produce metabolites such as carotenoids (lutein, zeaxanthin, and astaxanthin), very long-chain polyunsaturated fatty acids (VC-PUFA), and vitamins that are widely used in nutraceuticals industries such as food additives.

2.4.3.3 Proteins and peptides

Protein nutritional quality is determined by its amino acid profile. For most microalgae, the amino acid profile compares well with the standard profile for human nutrition proposed by World Health Organisation (WHO) and Food and Agricultural Organisation (FAO). Furthermore, regardless of the extraction procedure, microalgae proteins can be excellent emulsifiers, comparable to and even better than commercial ingredients (Safi et al., 2014).

Besides the amino acid profile, some proteins have value themselves. Phycobiliproteins (PBPs) are fluorescent peptides of various colours, including fuchsia, purple-blue and cyan, that allow the capture of light energy in auxiliary photosynthetic complexes called phycobilisomes (PBS). PBPs have several highly preserved structural and physicochemical characteristics. (Dagnino-Leone et al., 2022). Due to the bright colouration and high solubility in water, PBPs are suitable in various fields, such as foods, cosmetics, and pharmaceuticals.

Phycocyanin is a non-toxic, water-soluble PBP from microalgae that exhibits antioxidant, anti-inflammatory, hepatoprotective, and neuroprotective effects. In addition to these health benefits, this pigment has been used in dietary nutritional supplements and natural colourant applications in the food, nutraceutical, cosmetic, and biotechnology industries (Mobin & Alam, 2017; Morais Junior et al., 2020). Other physiological performances of phycocyanin also attract much attention, for instance, the antioxidant, anticarcinogenic, anti-inflammatory and immunomodulatory activity (Michele Greque de Morais, 2018).

2.4.3.4 Results

The main results from the literature study on composition are depicted in Figure 14. This shows the content of protein, lipids, carbohydrates and ash, respectively. This is done for the base, optimistic and conservative scenarios as described. Comparing the base, optimistic and conservative scenarios, a significant variation in microalgae composition is observed. For example, the amount of protein can vary with around 20%-points between the optimistic and conservative scenarios.

The total ash content in microalgae is generally below 10%, much lower than for macroalgae. For microalgae, nutrients are generally added as commercial fertilizer. Through this, the macro-minerals can be more accurately controlled, and the build-up of undesired minerals can be minimized. Given this low amount of macro minerals in the feed and the high recycle of nutrients, the concerns for Iodine, Sr, Hg, etc., that play a role in some macroalgae are far less in microalgae. These have therefore been addressed in less detail in the database and are restricted to *Chlorella sp.*

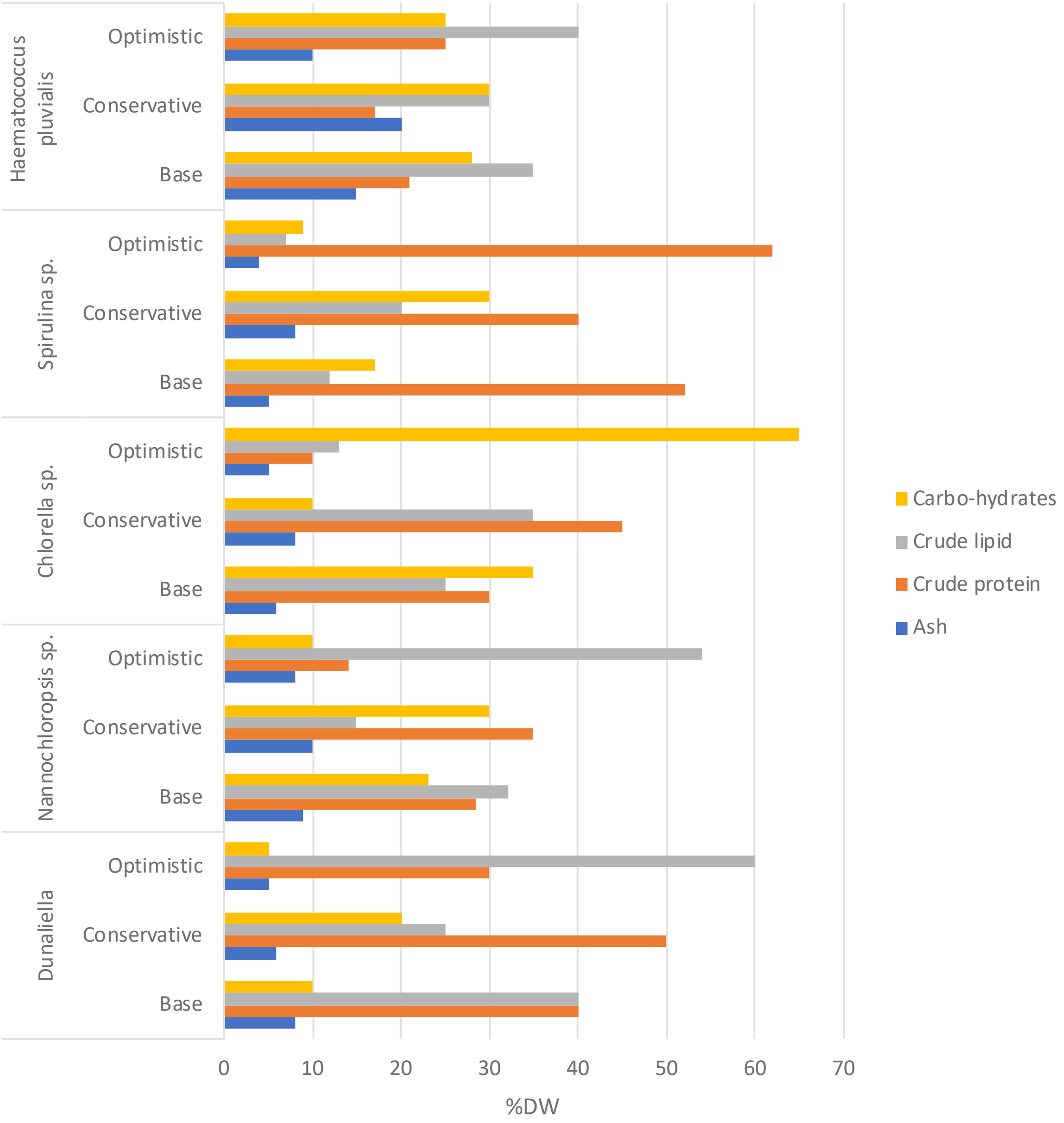

Figure 14 Main microalgae composition (ash, protein, lipid, and carbohydrate) at the base, conservative and optimistic scenarios

The chemical composition of microalgae varies with species, classes, and growing conditions with high variance even within day and night. *Haematococcus pluvialis* shows two well-defined growing stages (green and red) based on growing and stress conditions. The green and red stages are based on the accumulation of astaxanthin, which is also related to the ratio between protein: carbohydrates: lipids; For the green stage the ratio is 0.5:0.2:0.3 while the red stage is 0.2:0.4:0.35 (Shah, Liang, Cheng, & Daroch, 2016) see Figure 15. In the green stage, during favourable growth conditions, most Haematococcus strains are rich in protein (29–45%). For simplification, only the green stage, in which the content of bioactive components is the highest, is considered in the rest of this report.

Protein content during red stage cultivation of *Haematococcus comprises* amino acid composition mainly composed of aspartic acid, glutamic acid, alanine, and leucine, 46.0% of which belonged to essential amino acids. In the green stage, carbohydrate content approximates 15–17%, about half of the red stage. In the red stage, under conditions of stress (e.g., nutrient starvation, light stress, high acidity, temperature variations etc.), *Haematococcus* accumulates higher content of carbohydrates (starch). Under prolonged stress conditions, starch is consumed in the cell.

Next to the main components discussed above, other high-value, and bioactive components are present in microalgae that are relevant for specific applications and may also vary with conditions. Astaxanthin, β-carotene, and lutein are promising microalgal pigments (lipidic) with high market potential. The above pigments are vital for the survival of a cell because they form the basic and functional components of photosynthesis in the thylakoid membrane (Minhas et al., 2016). For instance, *Haematococcus pluviali*s (microalgae) in the red phase can produce significant amounts of astaxanthin, lutein, and fatty acids, which are valuable antioxidants in nutrition, aquaculture, therapeutics, and cosmetics. Natural astaxanthin significantly reduces oxidative and free-radical stress compared to synthetic astaxanthin (Kumar, Kumar, Kumari, & Panwar, 2022).

The total carotenoids in the green phase are about 0.5% of the total dry cell, while it is between 2 and 5% in the red phase. The carotenoid fraction of green cells consists mainly of lutein, violaxanthin (75-80%), and β-carotene (10-20%). In the red stage, the total carotenoids are mainly astaxanthin (80-99% of the total carotenoids. *Haematococcus* can accumulate up to 5% of astaxanthin and is considered the best natural source of this high-value carotenoid. The biosynthesis of astaxanthin of *Haematococcus* is a complex process directly related to the accumulation of triacylglycerols (TGA’s).

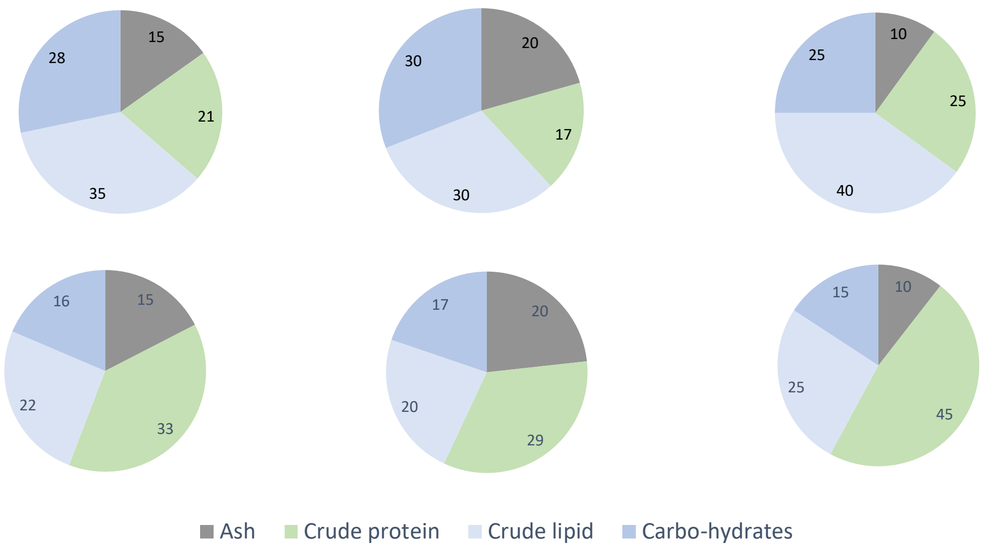

Figure 15 *Haematococcus pluvialis* green (top) and red (bottom) growing stages composition (ashes, proteins, lipids, and carbohydrates in %wt) at the base, pessimistic and optimistic cases at left, centre and right figure, respectively

An overview of the relevant bioactive species in microalgae and the base scenario content is depicted in Table 4.

Table 4 High value and bioactive components content in microalgae

Algae species	**Carotenoids**	**Carotene**	**Lutein**	**Astaxanthin**	**Violaxanthin**	**Phycobiliprotein**	**Polyphenols**	**Antioxidant activity**
	% DM	%c of atotenoids				% DM	Galic acid eq (mg/g)	%
Dunaliella	11	90						
Nannochloropsis sp.		6		6				
Chlorella sp.								
Spirulina sp.						16	10	50
Haematococcus pluvialis (green stage)	0.5	17	56	0				
Haematococcus pluvialis (red stage)	3.5	3.3	0.5	81-99				

The whole algae composition is listed in the database. The water content (dry matter content) is not listed because, for microalgae, this is not well defined. It depends very much on the dewatering technology and the amount of remaining interstitial water. The composition includes the above primary components, bioactive/high-value components. It lists the lipid composition (Polyunsaturated, Monounsaturated, Saturated, Omega 3 Fatty acids and eicosapentaenoic acid/EPA). It also lists the essential amino acid content and the content of individual amino acids.

2.5 Carbon uptake by macro- and microalgae

CO_2 enrichment is primarily done to enhance the growth of algae. At the same time, it is a means for fixating carbon and thereby reducing (local) CO_2 emissions. Of importance here is the CO_2 fixation efficiency, which is the ratio between the amount of carbon fixed in the algae relative to the amount of carbon in the CO_2 produced by the point source. Several factors play a role here. There is the cultivation system type (open or closed) and algae type (seasonal and photosynthetic efficiency) growth conditions, and integration between the capture system and cultivation media.

The subject of integration of CO_2 source and algae farm and the assessment of the CO_2 fixation efficiency at industrial scale is a subject that is largely underexposed and for which explicit literature is scarce. However, Zheng (Zheng, Xu, Martin, & Kentish, 2018) gives a very useful overview of technologies and their characteristics which are summarized in Table 5.

Table 5 Characteristics of CO_2 sources for land-based algae cultivation (Adapted from (Zheng et al., 2018)

CO_2 source	CO_2 price USD/ton CO_2	Characteristics
Atmospheric CO_2	0	Very low concentration, very high gas volumes
Raw flue gas	0	High volumes, contaminants temperature control
Commercial purified CO_2	3-55	Low availability
Captured CO_2 from flue gas	29-111	High availability
Bicarbonate addition	380	Very high addition efficiency
CO_2 containing solvents	10-35	Very high addition efficiency, low technology readiness level

Atmospheric CO_2 levels [0.0387% (v/v)] are not sufficient to support high microalgal growth rates and productivity due to mass transfer limitations. Industrial exhaust gases such as flue gas contain up to 15 % (v/v) CO_2, which can be potentially poisonous (inhibiting) to some microalgae. CO_2 enrichment reduces the pH of the culture medium, and thus, the CO_2 addition/pH needs to be controlled by within a certain range in order to optimize growth, as too low pH will negatively affect the growth rate and viability of the algae. The maximum (inhibition) and minimum (limitation) concentrations of CO_2 vary from one species to another and are not well documented in scientific literature. Direct contact of flue gas and growth medium requires a large scrubber and has higher estimated costs than an amine capture system(Kadam, 1997). Furthermore, it avoids absorption of SO_x and NO_x and other contaminants that could be present in the flue gas. An additional issue is that the flue gas is of elevated temperature,(Lam, Lee, & Mohamed, 2012).

CO_2 can also be captured from a flue gas stream or an industrial stream, after which it becomes available as a pure (or purified) stream. A common method for CO_2 capture is amine scrubbing, but depending on stream size, concentration and pressure, a variety of other methods could be applied (Feron & Hendriks, 2005; Lam et al., 2012). For algae specifically, sorbents are mentioned (Lam et al., 2012). Integration of capture and algae cultivation is also suggested in the literature. This included membrane capture (Lam et al., 2012) or amine capture (Könst, Mireles, van der Stel, van Os, & Goetheer, 2017). (bi)Carbonate addition can increase the CO_2 capture rate and capture efficiency (Lam et al., 2012). Integrated systems with alkaline absorption have been proposed that could have high capture efficiencies of 70% or 95% even with direct flue gas injection (Acien Fernandez, Gonzalez-Lopez, Fernandez Sevilla, & Molina Grima, 2012) but require alkaline-resistant algae species.

Captured CO_2 can be added directly, but it can also be liquified by compression and cooling, after which it can be stored under cryogenic conditions. This method allows for matching the CO_2 demand by growth, thereby increasing CO_2 fixation efficiency. CO_2 capture and optional liquefaction are associated with significant energy demand. For example, typically a power plant equipped with CO_2 capture requires 10-40% more energy input to deliver the same amount of power (for Natural Gas Combined Cycle plants, the range is 11–22%, for Pulverized Coal plants, 24–40% (Metz, Davidson, De Coninck, Loos, & Meyer, 2005)). Liquified CO_2 can also be transported by truck, allowing for geographical disconnection of the CO_2 source and algae farm, supplying multiple farms with CO_2 from a single point source, or combining different CO_2 sources for a single algae farm.

The addition of CO_2 to the water in the pond or photobioreactor can be done with various methods, including sparging, bubbling and membrane addition (Zheng et al., 2018). Having a concentrated captured stream allows for much more efficient mass transfer than sparging flue gas and, thereby, allows for a higher CO_2 fixation efficiency, still keeping in mind the pH range optimal for growth of the specific algae species (Acien Fernandez et al., 2012). The non-absorbed CO_2 is lost to the atmosphere.

The algae will take up CO_2 only when exposed to light, during the daytime, and in contrast, when in darkness, during nighttime, the algae will even respirate part of the CO_2 absorbed. Some CO_2 will be lost from the pond/bioreactor also. Both growth of algae and CO_2 point source intermittency and variability will differ with the source type. Large industrial processes are mostly operated continuously throughout the year resulting in a steady CO_2 supply. District heating systems will have a low load in summer and high in winter periods, which is counter-cyclic with algae production, so it can be concluded that this is not a promising match.

Power plants are operated according to the electricity price merit order, which may vary from base load operation to peak power supply. The capture of CO_2 from these power plants and other point sources is associated with an energy demand and with costs. Storage of CO_2 through compression or liquefaction could allow for an optimal match between CO_2 release to match the day/night difference and would also allow for the distribution of captured CO_2. Cryogenic CO_2 with an on-demand supply is very often considered as the CO_2 source in algae cultivation, especially for small-scale operations. Liquification of CO_2 to cryogenic conditions is however associated with additional energy demand and costs. Many studies on algae cultivation are for a single location. The effect of day/night and summer winter cycles on CO_2 fixation (as well as productivity) is a topic that is seldomly addressed, and it could be argued that, this is quite different with latitude (Maurya et al., 2022).

Table 6 presents an overview of the CO_2 capture efficiencies reported in literature. For seaweed, the literature is extremely scarce. The CO_2 uptake of *Oedogonium* a green seaweed, was measured by Cole et al., (2014), comparing it to *Ulva* sp. in ponds, using pure CO_2 sparging during the day using a pH-control strategy. Over a 4-week growth period, they found an uptake and biological conversion efficiency of 11.5% of the $CO_{2,}$ the rest of the CO_2 likely being lost to the atmosphere with smaller amounts also respirated during the night time. For (semi) closed system, the authors refer to literature on microalgae systems.

For microalgae, the CO_2 uptake efficiency reported in the literature for photobioreactors is in the range of 32%-to 50% (Cole et al., 2014). The controlled CO_2 addition kept a pH of 7 thatfavoured the growth of *Nannochloropsis* sp and photosynthetically fixed CO_2 converted into biomass at a fixation efficiency of 40%. Laurens (2017), mentions a typical value of 30% for all algae, cultivation systems and integration methods. CO_2 fixation rates vary significantly. The lowest value of 4.2% is found for continuous bubbling, while a maximum biological conversion of 60% of the available CO_2 was estimated by Galès et al. (2020).

The general view from literature is that the CO_2 fixation rate is mostly affected by the system type, rather than algae type or species. The main division observed was between open and (semi) closed systems. In open systems (raceway ponds), lots of the CO_2 supplied is lost to the atmosphere. Here a base scenario of 30% uptake is considered with variations between 5% and 60%. Closed systems (photobioreactors) allow for much more efficient use of the CO_2 supplied and the CO_2 fixation efficiency chosen, with on average 60% for the base scenario, varying between 25% and 90%. As indicated, this does not take into account mismatch between seasonal variation in algae growth, so especially for high-latitude regions, the data used could be overestimated.

Table 6 Overview of the CO_2 fixation efficiency from literature

Open systems (raceway ponds)	**CO_2 fixation efficiency**	**Reference**
Macroalgae, open ponds, 4 weeks period	11.5%	(Cole et al., 2014)
Open ponds, various studies	10-30% (20% avg)	(K. Kumar, Mishra, Shrivastav, Park, & Yang, 2015)
Microalgae, open photobioreactors	32.5%-50%	(Cole et al., 2014)
***Cyanobacteria,* photobioreactor, continuous bubbling**	8.1%	(Acien Fernandez et al., 2012)
Chlorococcum littorale, continuous bubbling	4.2%	(Acien Fernandez et al.,
***Nannochloropsis,* open raceway pond, pH control**	40-60%	(Galès et al., 2020)
Base scenario	30%	
Conservative scenario	5%	
Optimistic scenario	60%	
(Semi) closed systems (photobioreactors)		
Micro algae, direct injection	70-90%	(Acien Fernandez et al.,
***Chlorella sp.*, bubble column**	35%	(Lam et al., 2012)
Chlorella sp., bioreactor	24%	(Lam et al., 2012)
Scenedesmus obliquus, glass-made vessel	61.8%	(Lam et al., 2012)
***Microalgae,* closed photo-bioreactors**	50%	(Cole et al., 2014)
***Spirulina*, raceway pond in greenhouse, on-demand supply of pure CO_2**	78%	(Cheng et al., 2018)
Base scenario	60%	
Conservative scenario	25%	
Optimistic scenario	90%	

Next to the CO_2 fixation efficiency, the share of CO_2 supplied from the point source is relevant. CO_2 fixated in the algae can come either from the point source or from the atmosphere, and the ratio indicates which amount of CO_2 fixated originates from the point source. Here a straightforward approach is concluded. For photobioreactors and raceway ponds, it is assumed the reactors are equipped with a CO_2 supply. For this, it can be taken that 100% of the carbon originates from the point source. This is a logical assumption since the CO_2 supply will increase the CO_2 concentration in the growth medium, which will prevent any uptake of CO_2 from the atmosphere. For marine systems without CO_2 supply, all the CO_2 used (100%) originates from the excess fossil CO_2 in the atmosphere.

For all algae cultivation systems, unexplored sources of N and P from either industrial wastewater (land-based systems) or emission to natural waters from agricultural land

and WWTS (offshore cultivation) are assumed (Maurya et al., 2022; Zhang, Boderskov, Bruhn, & Thomsen, 2022). Sources to nutrient supply are not considered a limiting factor and are therefore not further addressed in the current review study.

2.6 Online survey

To gather additional updated qualitative and quantitative inputs and information not yet published, a survey was addressed to members of algae related fora in the EU, including EU4Algae. The total number of respondents was 35. The respondents represented 13 European countries, with the majority coming from the Netherlands, Spain, UK, France, and Germany. One respondent was from outside the EU (Canada).

Most of the respondents had a background in a company/business organisation (55.9%), an academic/research institution (26.5%) or a non-governmental organisation (8.8%). Most represented micro-organisations (1-9 employees) (44.1%), followed by large organisations (26.5%) or small organisations (23.5%). The final 10% of the respondents represented either Business associations, Microalgae cultivation or Start-up companies.

The organisations behind the respondents represent all aspects of the algae value chain, with the majority working with Research and Development, and production/cultivation of algae, but also including representatives from the processing into and sales of end-products, technology/service provisioning and consulting. The work of most respondents is mainly related with the macroalgae subsector (42.9%), less with microalgae (34.3%) and 22.9% work with both types of algae. Out of 35 respondents, 30 were available for further questions. The full outline of the survey is in Annex 11.6.

2.6.1 Target algae species, production methods and challenges

The respondents were asked quantitative and qualitative questions focusing on target species and production systems selected for the Algae and Climate study. The questions addressed production yields, costs, carbon uptake, nutrient and freshwater needs, present applications and challenges related to production, up-scaling, post-harvest processing and markets. Of the 10 target species, answers were received for 5 species, with one or two responses per species, and none with answers to all questions, see Figure 16.

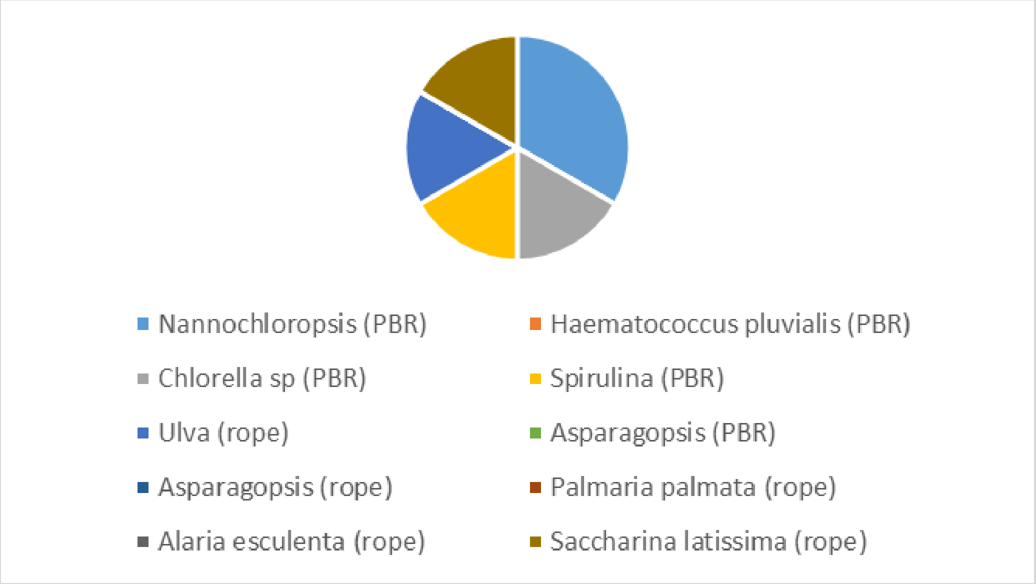

Figure 16 Distribution of the responses to specific questions to the species and production systems used in the Algae and Climate study. Of the 10 target species, answers were received for 5 species (Nannochloropsis (2 respondents), Chlorella (1 respondent), Ulva (1 respondent), Spirulina (1 respondent) and Saccharina (1 respondent)

2.6.2 Production and costs of the target species

In summary, the respondents describe the total annual production of *Saccharina latissima* to be 344 tons DM/y (indicated as latest FAO statistics from 2020) and slightly less than described for 2019 (Araújo et al. 2021), and the area production potential of *Ulva* from rope systems to be in the range of 25-40 ton DM/ha/y (this may be a misinterpretation of the question, since only small scale R&D production of Ulva on ropes exist, and the total European aquaculture production is reported to be 50 tonnes DM/y (Araújo et al. 2021). The Spirulina areal production potential was given as 40-60 tons DM/ha/y, which is within range with the total European production of 144 tons DM/y (Araújo et al. 2021). Market prices for *Spirulina* and *Nannochloropsis* were reported of up to 200 Euro/kg, and estimated production costs of Spirulina of 20 Euro/kg DM, with capital expenses (CAPEX) of 8 euro/kg DM ad operating expenses (OPEX) of 12% of the cost per kg DM (depending on energy prices) (Table 7).

Table 7 Production size, market price and production costs according to respondents of the on-line survey

Species	System	Production in Europe	Market price	Cost price	CAPEX	OPEX	Main market
Saccharina latissima	Rope system	344 tons DM in 2020 (official FAO stat) total	-	-	-	-	-
Ulva	Rope systems	~ 25-40 tons DM/ha/y	-	-	-	-	-
Spirulina	PBR	40-60 tons DM/ha/y	Variable, up to 200 Euro/kg	ca 20 € per kg DM (for algal paste	8 € per kg DM	12% per kg DM*	EU
Nanno-chloropsis	PBR	Limited, in open pond systems	Up to 200 Euro/kg	-	-	-	-

*dependent on energy prices

2.6.3 Uses of the algae biomass

The present use of the different algae was indicated as predominantly food, specialty chemicals for use in nutra-, pharma- and cosmeceuticals, feed for aquaculture, and fewer indications of use for feed for livestock and other, and for bio-energy (Figure 17), which is in accordance with the uses summarised for algae produced in Europe (Araújo et al. 2021).

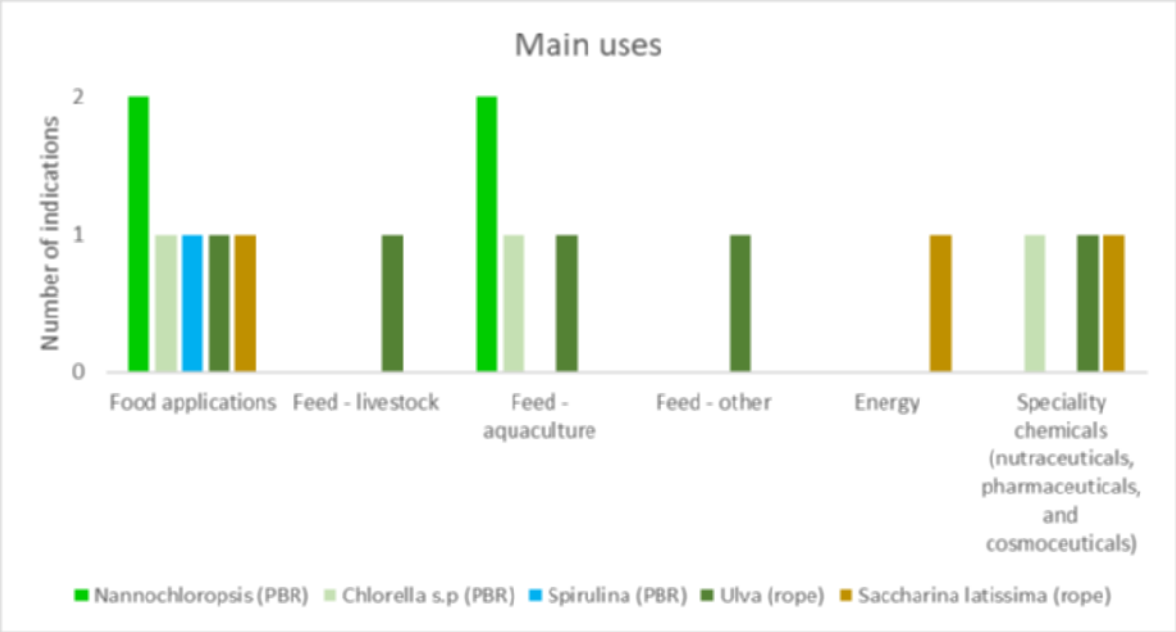

Figure 17 The main uses of the target algae species as indicated by the respondents

2.6.4 Resource needs - uptake of CO_2, nutrients and freshwater needs

The respondents' inputs on the CO_2 uptake potentials and specific resource needs of the target species, was higher than the acknowledged average CO_2 uptake of approximately 1.2 kg CO_2/kg algae dry matter (DM). Specific nutrient resource needs are given to produce *Spirulina*. Notably, the nutrient ‘fertilizer’ for land-based production of both micro- and macroalgae need not to be in the form of mineral fertilizers, but can constitute nutrient-rich waste streams from aquaculture or industry production (Molazadeh et al 2019; Neori et al 2003; Nielsen et al 2012 and Sode et al 2013).

The responses regarding resource needs for the different production systems Table 8, emphasize that where rope cultivation systems at sea do not require nutrients nor freshwater inputs, cultivation in PBR systems do require inputs of nutrients and freshwater, in particular when cultivating freshwater species. The freshwater needs described cover both process water and cooling water, with cooling water needs at the double of the process water needs but depending on location. Post-harvest processing methods are only described for the microalgae, including dewatering by filtration and/or centrifugation, drying by drum, belt, spray or freeze drying, and extraction of high value components through organic solvents (ethanol or hexane) or super critical CO_2.

Table 8 CO_2 uptake, resource needs and post-harvest processing techniques used according to respondents of the online survey

Species	System	CO_2 uptake (kg/kg DM)	Nitrogen fertilizer needed (kg N/kg DM)	Phosphate fertilizer needed (kg P/kg DM)	Fresh water required (m3/kg DM)	Post-harvest processing
Saccharina latissima	Rope system	-	0	0	0	-
Spirulina	PBR	1.8	0.006-0.010	0.001	Process water <0.050 m^3 per kg DW. Cooling water 0.1 m^3 per kg but depending on location	Harvesting/dewatering: Filtration and/or centrifugation. Drying (drum, belt, spray, freeze). Extraction (Ethanol, Super critical CO_2)
Nanno-chloropsis	PBR	1.8	-	-	-	Harvesting/dewatering (filtration and or centrifugation). Drying (spray). Extraction (Ethanol, hexane,)

2.6.5 Challenges

Regarding the experienced challenges in relation to different links of the production chain - production, up-scaling, post-harvest processing and market - of the target algae species, the input from the respondents point to regulations, costs, and technology as being the major challenges. Also, the social awareness and acceptance was commonly indicated as a challenge in the microalgae production chains.

Where high cost was indicated as the main challenge to production, up-scaling, and market of *Saccharina* cultivated on ropes, regulations was more often indicated as a challenge faced in production and scaling up of *Nannochloropsis, Spirulina* and *Ulva*. Climate was indicated as a challenge to the production and post-harvest processing of *Ulva* on ropes, which can be interpreted as temperate regions of Northern Europe being too cool and dark to be able to produce and dry *Ulva* outdoor as is possible in warmer, more sunny climates. Technology was indicated as a challenge for production and upscaling of *Chlorella* and for production of *Ulva* on ropes.

Partnerships, access to financial resources and knowledge gaps were pointed out as challenges in single cases in the microalgae production: partnership in the production of *Nannochloropsis*, access to financial resources in the production of *Chlorella*, and partnership and knowledge gaps in the post-harvest processing of *Chlorella*. This could indicate a need for strengthening networks and science-industrial cooperation in developing of the microalgae production chain.

2.6.6 Looking ahead – recommendations from survey respondents

The respondents provided several useful recommendations for future focus points in the species selection, production, post-harvest processing and applications of algae biomass.

Of all respondents, 76.5% have contributed to identifying a total of 38 macro- and microalgae species and 3-4 production methods that – in their opinion - should receive future attention for biomass production and carbon capture, in addition to the target species of this survey and study, see Table 9.

2.6.6.1 Macroalgae species recommendations

Eighteen macroalgae species were suggested by the respondents for future focus in addition to the target species of the survey. Six brown algae species belonging to the Laminariales and Fucales were mentioned as future focus species for production. Rope cultivation is developed or in development for *Laminaria digitata*, *L. ochra* and *Macrocystis pyrifera*, but cultivation protocols still need developing for the Fucales: *Himanthalia elongata*, *Ascophyllum nodosum* and *Fucus* sp.

For the suggested nine red algae species some are already in cultivation in the sea in the tropics *(Kappaphycus*), on land in ponds (*Gracilaria* and *Porphyra*) or in PBR in the sea in the south Atlantic (*Asparagopsis*).

For strengthening the cultivation potential in areas in addition to the European Atlantic and the North Sea, species are identified for cultivation in the more low-saline Baltic Sea: *Fucus vesiculosus* and *Furcellaria lumbricalis,* whereas for the warm and saline Mediterrenean Sea, *Kappaphycus*, and the three green macroalgae *Caulerpa lentillifera* and *C. racemosa* and *Codium* sp. were suggested.

Regarding *Ulva*, the most cultivated green macroalgae in Europe (Araújo et al 2021) and already a target species in the survey, the respondents call for focus on additional cultivation systems – raceway ponds and ponds, arguing that on-land cultivation of seaweeds secure controlled environment and high-quality biomass, and that land-based cultivation of *Ulva* is very promising with raceway ponds constituting one of the most productive systems. The suggested macroalgae should primarily address markets for food, agar and bio-stimulants.

2.6.6.2 Microalgae species recommendations

Twenty microalgae species were also suggested by the respondents for future focus, and again the respondents argued for developing the production of algae in raceway ponds and ponds – both open and closed. Regarding the microalgae, heterotrophic production and fermentation was suggested as also contributing to climate change mitigation despite the heterotrophic nature of the production. The suggested microalgae should primarily address markets within aquaculture feed and speciality chemical for nutra-, pharma- and cosmeceuticals (omega-3 fatty acids and pigments (fucoxanthin, betacaroten, and phycocyanin)).

A respondent's comment on the carbon capture potential of algae is that 'direct air capture from atmosphere needs to be considered. New algae strains capable of taking up CO_2 were identified. Photobioreactors will not serve the purpose of reducing CO_2 from atmosphere. This logic is questionable as high-pressure CO_2 needs to be injected in the reactors at high concentrations because of dense cultures. This needs to be evaluated.

Table 9 Algae species and production methods suggested by the respondents for future focus in addition to the ten defined target species of this study and survey

Species	Cultivation method	Argument	Potential product
Macroalgae			
Brown algae			
Ascophyllum nodosum	Rope/intertidal cultivation	Potential in bio-stimulants and other applications	Bio-stimulants
Fucus vesiculosus		Potential for cultivation in the Baltic Sea	
Himanthalia elongata	Ropes		Food
Laminaria digitata	Ropes	All the rope system cultivation options are relevant for future resources	
Laminaria ochra	Ropes		
Macrocystis sp.	On arrays/offshore	Cultivation potential depends on geography (site)	Bio-stimulants
Red algae			
Asparagopsis sp.			
Durvillaea antarctica		Traditional food from Chile -> nutrients and chunky texture fur multiple applications	
Furcellaria lumbricalis		Potential for cultivation in the Baltic Sea	
Gracilaria sp.	Ponds		Agar production
Kappaphycus sp.		Potential for cultivation in the Mediterranean Sea	
Hypnea spinella			
Hydropuntia cornea			
Polysiphonia sp.		Taste and gastronomic properties	Food
Porphyra/Pyropia	Still needs cultivation knowledge for the Atlantic species	Huge market potential	Food
Green algae			

Caulerpa lentillifera		Potential for cultivation in the Mediterranean Sea	Nutritious and appealing texture and appearance
Caulerpa racemosa		Potential for cultivation in the Mediterranean Sea	
Codium sp.		Potential for cultivation in the Mediterranean Sea	Flavour for food
Ulva	Raceway systems	On-land cultivation of seaweeds and in particular of Ulva is very promising and raceway is one of the most productive systems Ulva - landbased cultivation -> controlled environment -> high quality biomass	
Ulva	Ponds		
Microalgae			
Characiopsis sp.			
Diacronema lutheri	Raceway pond	Cheapest and the most environmentally friendly	Aquaculture
Dunaliella	Ponds		Beta-carotene
Euglena cantabrica			
Galdieria sp.			Phycocyanin
Isochrysis galbana			
Munda sp.			
Nannochloropsis sp.	Open ponds	The study is missing completely for the open ponds that are, at the moment, the widest used system for algae cultivation on large scale	
Nostoc commune			
Odontella cf. aurit			
Pavlova sp.			Omega 3
Phaeodactylum tricornutum			Fucoxanthin
Porphyridium cruentum			
Rhodomonas sp.	Raceway ponds	Good nutritional profile	Aquaculture copepods

Skeletonema			Bivalve feed
Scenedesmus rubescens			
Schyzochytrium spp	Heterotrophic micro-algae, bioreactor	This is a very efficient way of producing algae, with a proven benefit on several Sustainable Development Goals 2 (hunger), 3 (health & wellbeing), 12 (responsible consumption and production), 13 (climate action) and 14 (life below water	
Spirulina	Covered ponds -> fewer resources needed (no pipes)		
Tetraselmis chui			
Tisochrysis lutea	Raceway ponds		Aquaculture, fucoxanthin, omega3

2.6.6.3 Cultivation systems recommendations

For the land-based production systems, recommendations included 1) combining open ponds and PBR in southern Europe in connection to heat producing industries for water temperature management, and flue gas filtering (CO_2 capture), optionally coupled to salt water use; 2) aquaculture and hydroponic co-cultivation, arguing that this should be less resources intense especially in freshwater and fertilisers; and finally to support development of laminar systems or fully automated tubular PBR systems.

For the marine production systems, the recommendations included 1) developing offshore platforms allowing cultivation at scale with less impact on existing wild populations, and potentially combined with offshore wind farms or other infrastructure (two large Horizon EU lighthouse projects will focus on this in the coming 4 years[18]). Coexistence between low trophic aquaculture, i.e., offshore cultivation of seaweeds, and off-shore wind farms, and hereby concentrating off-shore activities, might also help to ensure space for genuinely protected Marine Protected Areas; 2) Mariculture with deep sea water irrigation system(s) as a way to increase the growing season, accelerating growth by bringing up nutrient rich water (restore overturning circulation by mimicking natural upwelling, and 3) a future development of seeding technologies is recommended, as well as development of cultivation on nets, mats, ropes and in floating cages. This point is also supported by the seaweed expert interviews.

2.6.6.4 Post-harvest processing technology recommendations

Regarding post-harvest processing, the respondents recommended future focus on developing microalgae harvesting via ultra- or micro-filtration in order to recover and reuse as much water as possible.

2.6.6.5 Recommendations to applications of the algae biomass and novel markets

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[18] 1. OLAMUR https://cordis.europa.eu/project/id/101094065 and 2. ULTFARM https://cordis.europa.eu/project/id/101093888

For potential uses in feed, the use of formulations containing mixed strains was mentioned for improving quality, and it is also suggested to focus less on specific species and more on the QPS approach, developed by the EFSA Scientific Committee to provide a ‘harmonised generic pre-evaluation to support safety risk assessments of biological agents intentionally introduced into the food and feed chain, in support of the concerned scientific Panels and Units in the frame of market authorisations’. Increased exploitation of invasive species such as *Sargassum* is suggested, but this may be controversial due to EU and national regulations in the context of non-indigenous / invasive species and biodiversity protection.

The respondents foresee novel markets within 1) Food and food additives food (gastronomy, bio and vegan markets) and food additives, replacement of food ingredients (proteins, lipids, antioxidants) or enrichment of foods (i.e. omega 3 in olive oils), 2) Biomaterials, bioplastics and packaging; 3) Feed, methane reducing feed additive and pet food, 4) Agriculture, as biostimulants replacing industrial fertilisers, or agricultural plastics as alternatives to mulch films, 5) Speciality chemicals for cosmetics, health care and nutrition, and finally 6) within markets for carbon sequestration and carbon credits. This is in part also supported by the algae expert interviews, except that they generally express more scepticism towards the market of carbon sequestration and carbon credits.

2.6.7 Final remarks

In addition to the scheduled questions, the respondents were asked to provide their final remarks as an option to communicate urgent topics of concern or interest to the EC. The following topics were raised:

1. More Life Cycle Assessment studies are needed to document the true climate impact of algae production and applications.
2. Expand the scope of this study both geographically beyond the EU (i.e. to include EU overseas countries and territories), to include more relevant species, and to include additional cultivation systems such as open ponds, and heterotrophic (or mixotrophic) production systems.
3. More focus on the down-stream processing and inclusion of end-users in survey.
4. The existing process and price for novel food certification is prohibitive for start-ups and new ideas The novel food process is always described as: 3 years and 500.000 Euro. This is prohibitive for start-ups and new ideas. There should be either a leaner process (1 year, 100.000 Euro) or the EU could fund annually 10 novel food studies for algae selected through voting in order to get more products to the market. Currently, there is a "large company bias" since only they can afford the process.
5. Think about putting results in a global context, land, and sea in regard to emissions, sequestration and ecosystem services.
6. Focus on ‘indirect’ climate effects of algae i.e., replacing emissions intensive products such as fertilizers and animal products.
7. Focus on market challenges and marketing of algae products.
8. The technical possibilities for effective and cost-efficient micro- and macroalgae cultivation are now available (albeit far from being exhausted), however, a significant market in EU for the biomass produced in this way is not present. The innovation push is still waiting for the market pull. This is true for all marketing channels (bioplastics, AgroFeed, food).
9. Regarding food, there is (yet) a lack of entrepreneurs who dedicate themselves to the marketing of the products strategies to target one or more customer groups in the corresponding marketing channel (here: food) (consumers, food service, food industry) meaningful market research based on this, sophisticated product developments suitable for the mass market brands that are competitive when other "FutureFood" solutions also compete for these customer groups budget to put

marketing and sales measures in action: acquisition, trade shows, tastings, pitches, CUSTOMER SERVICE (B2B), (national) organizations of marketers (similar to Bioland or CMA for other foods, similar to NorthSea Farmers or Norwegian Seaweed Association on producer side).

2.6.8 Key messages from online survey

The survey included 35 respondents, broadly representing the European algae industry and research environment regarding nationality, size of organisation and position in value chain. Valuable qualitative information was obtained from the survey and included in the study. Limited quantitative knowledge, however, was obtained from the survey, partly due to confidentiality issues.

The respondents identified the major challenges in production, upscaling, post-processing, and market to be mainly related to regulations, technology, costs, and social awareness. In addition, the respondents of the survey suggested a total of 38 additional macro- and microalgae species were suggested for future focus and pointed to the need for addressing in future also the potentials of additional land-based production systems: ponds, raceway ponds and heterotrophic production/fermentation in PBR. Post-harvest processing was also emphasised as an important future focus point to be also to support upscaling of biomass production in a sustainable manner, economically as well as environmentally.

2.7 Interviews with key experts

EU experts on both macroalgae and microalgae were interviewed for this study. The objective was to verify the choices made on selection in algae species and cultivation systems, to give guidance to focus and important points of attention in the study, and to assist in data search by providing guidance to key literature. The experts were also asked to give their viewpoint on algae markets, the role of algae for feed applications and barriers and opportunities in the further development of the algae industry. The interviews were conducted online using the interview guidance that is supplied in Annex 11.6. Those interviewees mentioned in person agreed to have their names and affiliation published. Interview summaries can be found in Annex 11.6.

On the topic of microalgae, microalgae production and R&D are evolving in parallel. From there, the main representatives in the field of microalgae were interviewed. Four well-recognised experts from Portugal, Italy, France, and the Netherlands were interviewed as representatives from the academia and microalgae production for food and nutraceutical applications. This also included a representative for the European Algae Association, which covers both macro and microalgae, but the representative was interviewed with the focus on microalgae.

The interviewees considered many species which included all those considered in the analysis in this report (*Nannochloropsis, Spirulina, Chlorella, Duniella, Haematococcus, Asparagopsis*), but also a variety of other species were considered. Still, none of the interviewees highlighted species not explicitly considered. Interestingly, the use of heterotrophic algae that use organic sources rather than sunlight was mentioned by several interviewees. As this was also suggested in the survey (see Section 2.6), it was considered to add this to the scope of this study. However, it was found that this was beyond the scope and, more importantly, did not fit into the method for analysis since the value chain is too different. For the same reason, mixotrophic species were not considered.

For microalgae cultivation, pond systems and photobioreactors were considered, where the choice is directly related to the species. More vulnerable species require cultivation in closed photobioreactors, whereas the more robust species can be cultivated in open pond systems. Also, indoor equipment was used. Artificial lighting systems were mentioned as being considered, but these are currently yet non-competitive from an energy-efficiency as well as financial viewpoint.

The markets for microalgae food, e.g. vegan food and food ingredients, were generally considered the most important and so far the only economically feasible. There is a lot of competition with Asian manufacturers, so adding knowledge and, thereby, value, such as isdone by extracting functional feed ingredients, was mentioned to be competitive. Downstream processing is important for energy and cost efficiency, where various systems are considered to arrive at an optimised choice. For feed, the use of functional feed ingredients and for feed production for fish hatcheries was considered the most promising, rather than providing bulk protein.

The interviewees mention the chicken-and-egg problem of small production volumes, leading to high algae costs and low market volumes. Scale-up is considered to be essential for cost reduction and market expansion.

Nutrients are generally added as a commercial mix, and nutrient efficiency through efficient recycling is highlighted as a significant advantage of microalgae. This is as opposed to conventional crop, where it was mentioned that typically half of the nutrients are washed out. Using nutrients from industrial waste streams was another option that was highlighted as having significant environmental benefits. CO_2 fixation was not explicitly mentioned, and one producer used potassium carbonate as a carbon source. An advantage of algae cultivation is that these can be grown to produce proteins and vitamins in non-arable land, for example, at industrial sites, polluted ground or abandoned landfills and salt marches. The concept of higher efficiency land use compared to standard crops was mentioned by two interviewees. This would add to the feed produced in Europe and could be used as an additive to conventional feed.

Finally, it was mentioned that in the assessment of algae, specific benefits of algae are often not sufficiently taken into account. These include the mentioned aspect of land use and proper addressing of externalities, which are sometimes addressed in detail for algae cultivation and simplified for the reference technology. This aspect is generally not covered sufficiently when performing assessments such as life cycle assessment studies. The development of standards for algae environmental assessment could contribute to a better quality of these assessments.

The interviews have been used to confirm the choice of species and cultivation systems and were used to confirm that the relevant factors are addressed in the study. As stated above, adding heterotrophic or mixotrophic species has been considered but was discarded. The use of nutrients from waste sources is too diverse to be taken into account and hard to match to the food and feed end uses. The data collection during an interview proved difficult, but many interviewees provided literature that has been considered in the literature search. Full interview reports and details on the interviewees on microalgae are provided in Annex 11.5.

2.7.1 Summary of expert interviews, macroalgae

As for the microalgae, macroalgae production and R&D are evolving in parallel, and main representatives on the field of macroalgae were interviewed. Six well recognised experts from The Faroe Islands, Sweden, Denmark, and the Netherlands were interviewed as representatives from the academia and macroalgae production industry for food, feed, materials, and nutraceutical applications, as well as for production of cultivation technology and seeding materials. A representative from the European Algae Association, which covers both macro- and microalgae, was interviewed with the main focus on microalgae (see previous section).

Many species were considered by the interviewees, where the species were selected for their specific applications. Species included all those considered in the analysis in this report*: Saccharina latissima, Alaria esculenta, Ulva, Palmaria palmata, Gracilaria and Asparagopsis*. A few other kelp species were also considered, including Macrocystis porifera.

For cultivation of macroalgae both marine rope systems and closed and semi-closed landbased cultivation systems were considered, where the choice of system is most often directly related to the species. More delicate, slow growing species require cultivation in closed land-based systems, whereas the more robust species can be cultivated on ropes in open sea. Few species can be cultivated in both types of systems, such as *Ulva* and *Asparagopsis*. For the closed land-based systems, artificial lighting systems were part of the cultivation technology, with companies dedicated to developing energy-efficient and commercially viable systems (PureAlgae, 2022).

The markets for macroalgae the food, e.g. plant protein substitutes, feed (with focus on methane reducing cattle feed) and cosmetics/nutraceutical markets were generally considered the most important market, with the food market so far, the only economically feasible. Downstream processing in the form of freeze-drying, oven-drying, air-drying and lactic acid fermentation/ensiling was considered and energy-efficient procedures making use of excess heat were being developed.

In marine systems, nutrients are not added – and on the contrary, the seaweed production takes up and removes nutrients from the coastal environment, hereby contributing to mitigating eutrophication. In land-based systems, nutrients are generally added as a mineral fertiliser in commercial mix for small-scale R&D production. Using nutrients from industrial waste streams was the target for future production in all systems for both environmental and economic benefits.

As for microalgae, it was mentioned that in the assessment of algae, specific benefits algae are often not sufficiently taken into account. These include the mentioned aspect of land use, and proper addressing of externalities where these are sometimes addressed in detail for the algae cultivation and simplified for the reference technology. This aspect is generally not covered sufficiently when performing assessments such as life cycle assessment studies. Development of standards for algae environmental assessment could contribute to a better quality of these assessments.

The challenges mentioned by the interviewees to a large extent confirmed the outcome of the on-line survey (technology (mechanisation), costs (investments), regulations), but also contributed with new challenges, the most important being the need for knowledge exchange and education/training of future algae farmers/producers, i.e. as a specialised aquaculture education, as well as for selective breeding. Regarding regulations, the issues of organic certification of macroalgae biomass, cultivation of non-indigenous species and bottlenecks in obtaining permits for coastal cultivation sites were the major issues. Market challenges were described as an issue for scaling up to meet demands along with critical mineral content (iodine and arsenic). Several of the macroalgae interviewees expressed their concerns on the issues of seaweed cultivation as a solution for climate change mitigation, calling for more knowledge on carbon uptake, potential carbon sequestration potential and more robust standards based on life cycle assessments of the full production and utilisation of the algae.

The interviews have been used to confirm the choice of species, cultivation systems and challenges, and were used to confirm that the relevant factors are addressed in the study. Collection of data during an interview proved difficult, but many of the interviewees provided literature that has been considered in the literature search. Also, yet unpublished data was provided indicating that production yields have been improving over the last years. Full interview reports and details on the interviewees are available in Annex 11.1.

2.7.2 Interviews with experts from China

The on-line survey was translated from English to Chinese (Annex 11.4) and was sent by email to the top 10 algae producers in China. We received no input, and on that basis, we did not selected experts for interviews.

2.8 Information feeding into the relational database

The information in the relational database from task 1 was:

- Definition and characterisation of species and cultivation systems
- Full composition of algae (based on published literature):
  - Basic composition (% of DM).
  - C,N,P, Ash, Crude protein (CP), Total (crude) lipid, Carbohydrates.
  - Carbohydrate composition: Cellulose, Starch, Alginate, Laminarin, Fucoidan, Ulvan, Agar, Floridian starch, others [free text].
  - Lipid composition (% of Fatty Acids), Omega 3 FA, EPA.
  - Essential aminoacids [%DM].
  - Essential aminoacids [%AA], Lys, Met, His, etc.
  - Macrominerals [ppm DM] Ca, Mg, Fe, Na, K, Cl.
  - Critical minerals [ppm DM] I, Cd, Pb, As, As-in, Hg.
  - High value components: Carotene Lutein Astaxanthin Violaxanthin Phyco- bili- protein Polyphenols Antioxidant activity.
- Yield of algae cultivation in terms of productivity per ha net and gross, and per linear meter of seeded line.

Table 10 provides an overview of the knowledge base. Cells are empty when data are not available, they are yellow when data are available but based on strong assumptions and they contain a "✓" when data are available.

Table 10 Overview of available data in the relational database resulting from Section 2

	Production systems characteristics	Production data		Algae composition						
	Production system, algae type, algae species, phylum, production method, salt/fresh water, open/closed	Productivity data in various units of measurements (per ha, per m, net, gross)	CO_2 uptake	Basic composition	Carbohydrate composition	Lipid composition	Essential and semi essential amino acids	Macrominerals	Critical microminerals	High value molecules
Ulva in photobioreactor	✓	✓		✓	✓	✓	✓	✓	✓	✓
Ulva in rope system	✓	✓		✓	✓	✓	✓	✓	✓	✓
Asparagopsis in photobioreactors	✓	✓		✓	✓		✓	✓	✓	✓
Asparagopsis in rope system	✓	✓		✓	✓		✓	✓	✓	✓
Saccaharina in rope system	✓	✓		✓	✓	✓	✓	✓	✓	✓
Alaria in rope system	✓	✓		✓	✓		✓	✓	✓	✓
Palmaria in rope system	✓	✓		✓	✓	✓	✓	✓	✓	✓

Haematococcus in photobioreactor	✓	✓	🟨	✓		✓	✓			✓
Nannochloropsis in photobioreactor	✓	✓	🟨	✓		✓	✓			✓
Chlorella in photobioreactor	✓	🟨	🟨	✓		✓	✓			
Spirulina in rope systems	✓	✓	🟨	✓		✓				✓

2.9 Discussion

This section provided calculations of nutritional yields of selected species of algae in relevant production systems, and collated costs, GHG emissions, challenges, and constraints to cultivation/large-scale development from surveys and expert interviews, to support consecutive tasks.

A key message from Task 1 is that with present cultivation systems and yields, microalgae production systems can deliver a higher nutritional yield (tonnes of crude protein per area per year) as compared to macroalgae. Within macroalgae production systems, the land-based production of *Ulva* and *Asparagopsis* delivers in range with low yielding microalgae systems, and kelp production at sea has the lowest nutritional yield. As uptake of CO_2 and nutrients is proportional with production capacity, microalgae systems also deliver a higher emission capture and utilisation capacity.

Since data on production yields and composition are scarce for certain species in combination with specific cultivation systems, and further, that values are highly variable between data sources – the results are subject to some uncertainty. In addition, survey and interviews indicated that production numbers available in the literature may not be representative for recent improvements in technology, scale of production and hence production yields. This limits to some degree the credibility of the results. We have however, remained true to the decision of only including published values in the relational database and thus in the results of the study, in order for the results to be as objective as possible. More thorough literature reviews and data mining could potentially have reduced the variability of the data and should be included in future work. Still, this would have required further resources, and the approach of the three scenarios – conservative, base, and optimistic will indicate the range of variation.

The different algae production systems, however, have the potential to complement each other. They offer a selection of possibilities to fit any given area of land or sea, with the given possibilities for CO_2 enrichment or nutrient addition via point sources delivering emission capture and utilisation and thereby supporting the circular bioeconomy. This diversity and complementarity in production systems is a stronghold and should be further explored.

Key messages from surveys and expert interviews highlight the challenges faced in present production of algae in Europe. There is a need for 1) technology development, 2) investments for R&D and scaling up, 3) bringing EU and national food and feed regulations up to date with regards to algae being a unique and diverse group of organisms, not comparable to animals, plants, or fungi.

Future work could address the limitation of the present study by including more literature search and data mining to reduce variability of data, including more species and production systems, and taking into consideration also CO_2 uptake of cultivation systems in marine areas, acknowledging the indirect uptake of CO_2 via the atmosphere.

3 EXAMINATION OF COSTS AND GREENHOUSE GAS EMISSIONS FROM PRODUCTION SYSTEMS

3.1 Introduction

The objective is to develop sound estimates of costs and GHG emissions for different types of algae cultivation systems identified in section 2.2, and to benchmark these costs and GHG emissions with those of alternative sources of vegetable protein including soya. The information was extracted from the literature and synthetized, and feeds into the relational database presented in section 7.

3.2 Algae cultivation costs

3.2.1 Microalgae cultivation costs

3.2.1.1 Methodology

This section presents cost price estimations for the four selected microalgae production systems presented in section 2.2, namely 1) *Spirulina* in photobioreactors or raceway ponds; 2) *Chlorella* sp. in photobioreactors; 3) *Haematococcus pluvialis* in photobioreactors and 4) *Nannochloropsis* sp. in photobioreactors (see Table 11).

Table 11 Microalgae production systems

Production system ID	Algae species	Fresh/salt	Cultivation system	Land-based / marine	Open/closed
1	Spirulina	Fresh	Photobioreactor Raceway ponds	Land-based	Closed
2	Chlorella sp.	Fresh	Photobioreactor	Land-based	Closed
3	Haematococcus pluvialis	Fresh	Photobioreactor	Land-based	Closed
4	Nannochloropsis sp.	Salt	Photobioreactor	Land-based	Closed

Data on dry microalgae production costs[19] were collected from literature review. Nine references were selected based on the following criteria: availability of detailed economic data and scientific publication (see Table 12). Of the nine selected studies, some report on multiple production scenarios reflecting differences in production systems, for example scenarios for different production surfaces that can result in economies of scale. When scenarios were directly relevant for the purpose of this study, they were included as separate entries in the analyses.

In total, 12 production scenarios[20] representing the four different microalgae production systems[21] were selected (see Table 12). As studies differ in research design and

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[19] In order to study the influence of drying cost on the production cost, the results of microalgae production cost include the drying step.

[20] Production scenario: scenario for a production system based on assumptions about photobioreactor setup, surface, and location (see Table 12)

[21] Production system: combination of technology and algae species selected (see Table 11).

reporting, the data were adapted to account for these differences[22]. Data on production method, location, scale, productivity, carbon uptake, costs, revenues, and economic assumptions were extracted for production scenarios and recorded in an excel sheet. Cost data includes capital expenditures and operational expenditures. Capital expenditures (CAPEX) cover significant purchases of fixed assets that are intended to be used over the long term. Capital expenditures consist of buildings, reactor construction (photobioreactor units, glass tubes, binders), equipment (pumping, mixing, heating, cooling, degassing, harvesting, centrifuging, drying, lighting), process control and infrastructure. Operating expenses (OPEX) are the day-to-day expenses to maintain operational activity. Example of OPEX of photobioreactors include electricity, labour, raw materials, maintenance, overhead, carbon, other consumables, water, fertilizers, and pesticides. All cost data are expressed in 2021 values[23].

Table 12 Production scenarios included in the analysis of microalgae production costs

Production scenario	**Production system (see Table 11**			**Location**	**Scale**	**Reference**
	Production technique	**Algae species**	**Production system ID**			
1	Tubular Photobioreactor	Nannochloropsis sp.	4	South of Portugal	1 ha	Vázquez-Romero et al, 2022
2	Tubular Photobioreactor				10 ha	
3	Tubular photobioreactor			Germany	1.2 ha	Schade and Meier, 2021
4	Flat panels		4	New Mexico, US	1 ha	Banerjee & Ramaswamy,2018
5	Tubular photobioreactor	Chlorella sp.	2	US	1 ha	Pavlik et al, 2017
6	Tubular photobioreactor and Photovoltaic			US	1 ha	
7	Tubular photobioreactors and LED			Iceland	1 ha	Fu et al, 2022

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[22] When total costs were reported, cost prices in €/kg were obtained by dividing total costs by the production of dry biomass in kg. Data were also corrected for differences in size of production facilities by dividing production and cost data by the total production surface. All values reported in foreign currencies were translated to euros based on OECD exchange rates for the reported year. Source: https://data.oecd.org/conversion/exchange-rates.htm.

[23] Cost estimates were corrected for inflation based on consumer price indexes from the Worldbank.

8	Photobioreactors and a raceway pond	Haematococcus pluvialis	3	China	1	Li et al, 2011
9	Photobioreactors and a raceway pond	Haematococcus pluvialis	3	Livadeia, Greece	1	Panis & Rosales Carreon, 2016
10	Photobioreactors and a raceway pond	Haematococcus pluvialis	3	Amsterdam, Netherlands	1	Panis & Rosales Carreon, 2016
11	Pond	Spirulina	1	US	7	Downes & Hu, 2013
12	Bioreactors	Spirulina	1	US	10	Costa et al, 2019

3.2.1.2 Results

Figure 18 presents the average, maximum and minimum cost price per microalgae production system presented in Table 11:

- Nannochloropsis sp. in photobioreactors, production scenario 1-4.
- Chlorella sp. in photobioreactors, production scenario 5-7.
- Haematococcus pluvialis in photobioreactors, production scenario 8-10.
- Spirulina in photobioreactors or open pond, production scenario 11 and 12.

The figure also presents the overall average across production systems, which is EUR 27.05/kg dry weight.

The ranges for *Nannochloropsis* sp. and *Chlorella* sp. are in the same order of magnitude, the low value for *Nannochloropsis* being explained mainly by a high productivity level in the scenario number 4 (more than 80 000 kg/ha)[24]. As *Haematococcus* is mainly used for high value product (Astaxanthin), costs of production are the highest and the range is not too large because the results rely only on 2 different articles[25]. The low costs of *Spirulina* are in line with what is presented in several articles (Delrue et al, 2017 and Nappa et al, 2020), which might be explained by the fact that Spirulina is the most common cultivated microalgae species[26] and have a relatively high productivity in open ponds.

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[24] The authors attributed the differences in algae price between their study and other existing analyses to “differences in algae productivity potential for the locations as well as other process parameters and design specifications” (Banerjee and Ramaswamy, 2018).

[25] It is also due to the fact that in a reference (Panis & Rosales Carreon, 2016) it was not possible to extract the share of CAPEX due to the cultivation phase, then we decided to assume that it is equal to the CAPEX presented in another paper analysing Haematococcus (Li et al, 2011) - ID-8. Then, only OPEX are different among references for Haematococcus.

[26] The production volumes of Spirulina at the European scale approximate 142 tons (dry weight) in total (Araujo et al, 2022).

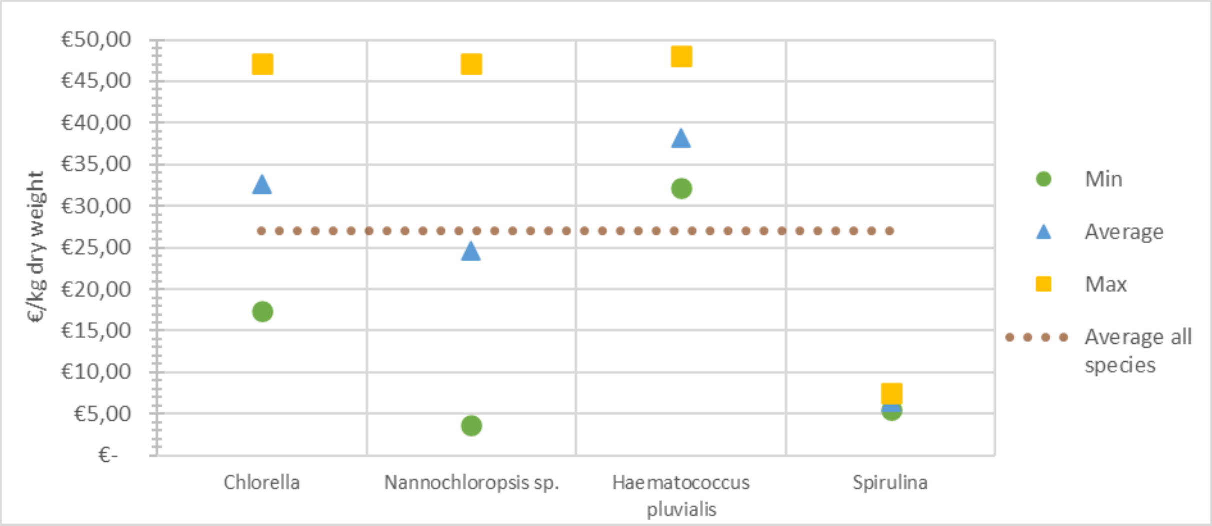

Figure 18 Microalgae production cost per production system

A close look at the disaggregation of cost prices explains the differences in reported cost-prices. On average CAPEX account for 44% of the total cost price and OPEX account for 56% of the cost price of microalgae production. Figure 19 shows the ranges of reported CAPEX and OPEX for microalgae production.

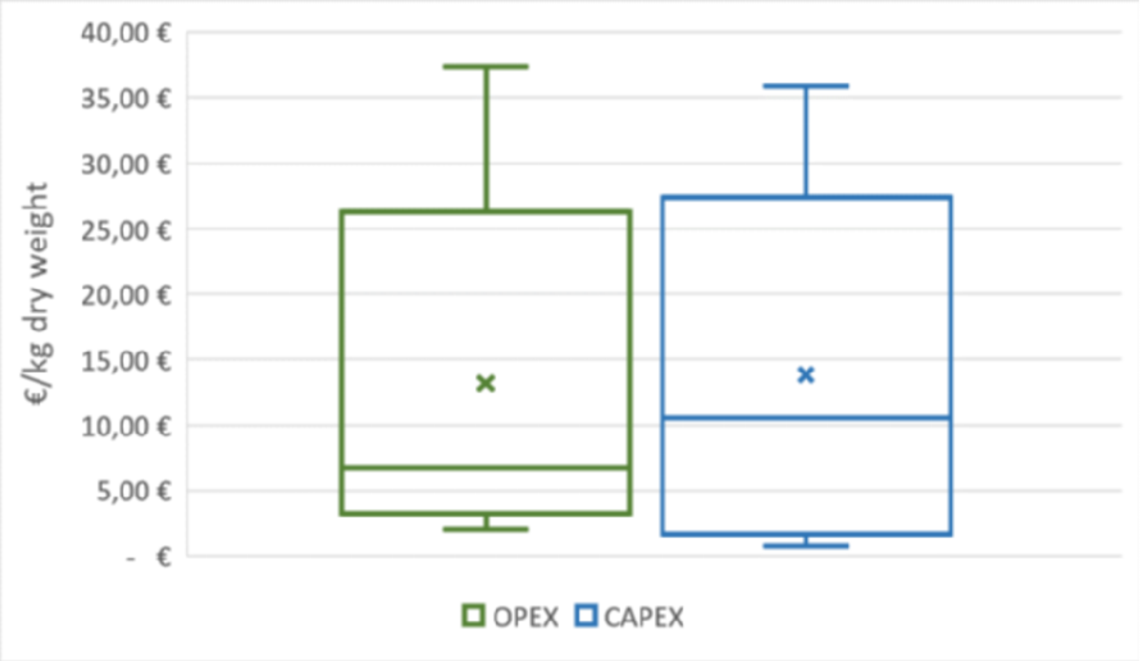

Figure 19 Distribution of reported CAPEX and OPEX for microalgae production

The large range in CAPEX can be explained by:

- System configuration and bioreactor setup: for example, light supply through LED or electricity supply using photovoltaic panels require additional investments.
- Biomass productivity: algae growth depends on climate conditions (temperature, light) that are location dependent.
- Harvesting method (centrifugation requires more investment than ultrafiltration).
- Depreciation assumptions: which affect the yearly costs reported in financial statements.
- Scale of facility: large facilities benefit from economies of scale.

While the large range in OPEX can be explained by:

- Input requirements linked to system configuration and bioreactor setup: for example, LED-based photobioreactors, photobioreactors with photovoltaic panels and photobioreactors relying on geothermal energy have different electricity requirements.
- Input prices: energy prices and labour cost vary across countries.

OPEX cost categories are detailed in Figure 20, showing that on average, electricity, and labour account for most operational costs[27]. However, few studies have included water, fertilizer, and pesticide costs, suggesting that these costs are relatively small.

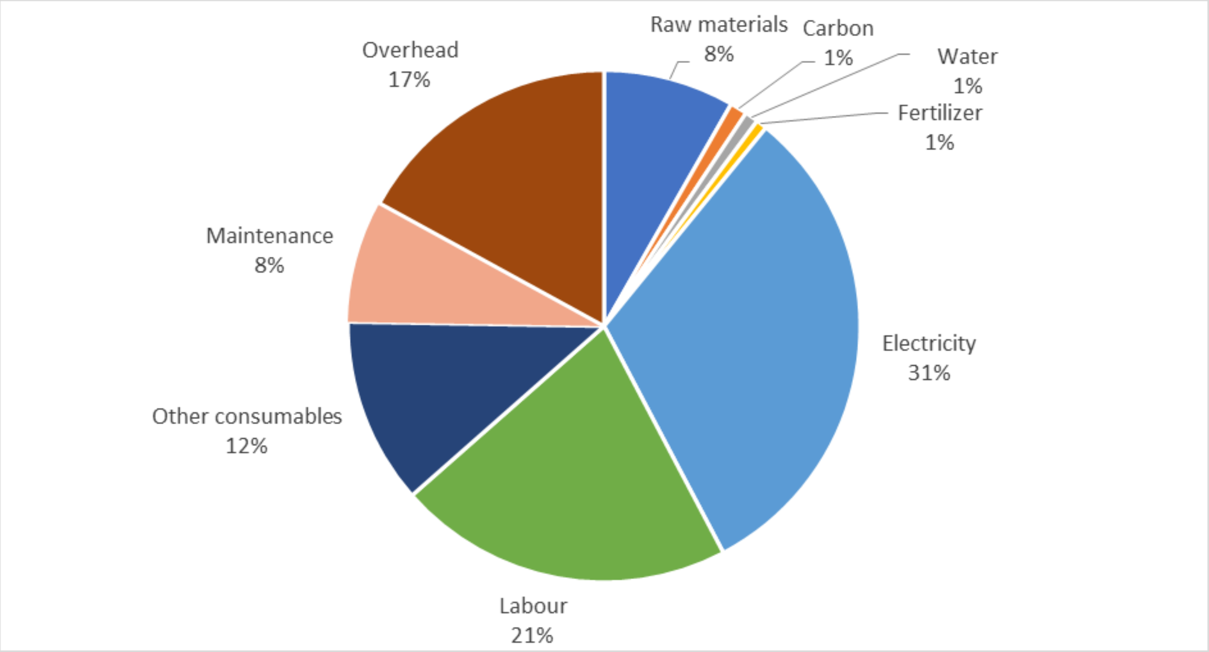

Figure 20 OPEX cost categories

3.2.1.3 Critical analysis: the role of electricity prices

Electricity cost is the main component of total operational cost of producing microalgae (31%, see Figure 20). The average electricity cost reported in the reviewed literature is EUR 0.09/kWh [0.05;0.14]. Electricity costs represents an important part of total OPEX cost because different production steps require energy (see Table 13). Three articles (Norsker et al, 2011; Panis and Rosales Carreon, 2016 and Li et al, 2011) reported that power consumption is mainly due to the cultivation and drying phase.

Differences in reported values are large and can be mainly explained by the use of different production techniques (e.g. centrifuges, ultrafiltration) and drying techniques (spray drying or freeze drying). The spray drying process consumes more energy (36.45 kWh/kg DW) than freeze-drying (22.29 kWh/kg DW) and higher energy consumption is required with centrifugation than with ultrafiltration (Vazquez-Romero et al, 2022).

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[27] This is also confirmed by other authors (Ullmann & Grimm, 2021) who reported that energy and labour are the most important cost factors for microalgae production.

Table 13 Energy used during the production process of microalgae

Steps of the cultivation process	Components requiring energy	% of energy cost due to this step
Inoculation and pre-treatments	Medium preparation power	~1%
Cultivation	Power for low pressure air; Power for compressed air; Power for pond paddling; Mixing/circulation; Power for flue gases supply; Power for O2 removal; Power for water pumping; Power for cooling	[82;95]%
Harvest	Centrifuge power; Power for disk-stack centrifugation	[1;6]%
Drying	Blower/paddle wheel power; Power for cell pulverization; Electrical input to LED lights; Electrical input to centrifuge; Heat needed to dry algal biomass; Power spray drying	[5;99]%[28]

The ongoing energy crisis has resulted in increasing electricity prices. High energy costs will affect operational production costs and consequently the financial viability of microalgae production. Assuming current electricity prices and assuming all other factors being equal, total operational costs would increase by 16% and energy costs would represent 41% of the total OPEX cost[29]. The analysis of electricity prices is provided in Annex 11.9.

3.2.2 Macroalgae cultivation costs

For the costing of algae cultivation systems, two methods could be applied, that is, bottom-up and top-down methods. In bottom-up methods, the algae cultivation costs are derived from a technological design for a defined scenario from which capital costs (CAPEX) and operational costs (OPEX) are derived from the equipment and operations dimensioning. Such a study requires detailed information and a well-defined scenario, from which later sensitivity studies could be applied to quantify uncertainties. This approach has not been selected for this study because of the lack of data to define the scenario and the dimension of the operations.

The other method applied for this study is to use literature sources. By selecting literature in which the scenario is defined and worked out in detail, confidence is added to the data generated. The uncertainties can be quantified to a certain extent using various literature sources.

3.2.2.1 Methodology

The literature survey was done through keyword search and references within relevant papers, completed with suggestions from interviewees. Studies were restricted to those with bottom-up cost assessments. Studies quoting market values, expert quotes and the like were not used. The literature study on macroalgae cultivation revealed that the literature on marine and land-based cultivation is relatively scarce. Also, the technology in the European context is relatively new, meaning that literature has yet to converge to a commonly accepted approach. None of the data provided actual costs; all were

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[28] This wide range is explained by the different techniques used which require more or less electricity.

[29] With the recent increase in energy prices, the average electricity price would reach EUR 0.15 /kWh [0.07;0.37] in 2022 depending on country.

projected cost studies. Cost data were extracted from papers and converted to the required units. Costs are listed on a dry-weight basis for the year 2021. The dry weight percentage from literature was used; when not available, 10% of solid content was assumed. Historical cost data were converted using the Chemical Plant Cost Index (CEPCI, 2021). The currency conversions assumed were 1.1 USD/EUR rate and 0.13 DDK/EUR. The base scenario took the average costs of the literature cost data; the optimistic and conservative took the lowest and highest price. When available, from the total costs, a breakdown was made into capital-related costs (CAPEX) and Operational costs (OPEX). An additional "Base including estimate" scenario was added in which missing cost data were estimated based on a combination of data. For this, the most studied species *Saccharina lat.* was taken as the basis.

Variations for algae cultivation costs were found to be very large. Several factors could play a role here. These factors include differences in cultivation technology, assessment methodology and cost assumptions, the scale of operations, productivity, location etc. As a result, the study result cannot be considered to give an equal-base comparison between different algae species or between macroalgae and microalgae. It works with the best available data for the specific scenario considered.

3.2.2.2 Macroalgae cultivation - marine

Three marine scenarios are considered in this report. Results for the cost analysis listed in the literature were found to focus mostly on *Saccharina latissima*, with only a single study on *Ulva sp.* and no data for *Palmaria palmata*. Results are depicted in Figure 21. The two datasets by (Groenendijk et al., 2016) refer to a base scenario and an optimistic scenario with significant cost reduction and multiple harvests/year. The two datasets by Bak, Mols-Mortensen, & Gregersen (2018) refer to single and multiple harvests per year. The datasets were expanded with the "base including estimate" for this species where costs were based on *Saccharina*, using a linear correction based on the productivity per meter of cultivation line. The resulting price is (EUR 165/kg) for the base, including the estimate scenario, which is very high due to the much lower growth rate found for *Palmaria*.

It is seen that the variation in cost data for *S. latissima* is high. The production capacity in ktonne/yr of dry-weight algae for the references differs significantly, though no direct relation was found between capacity and costs.

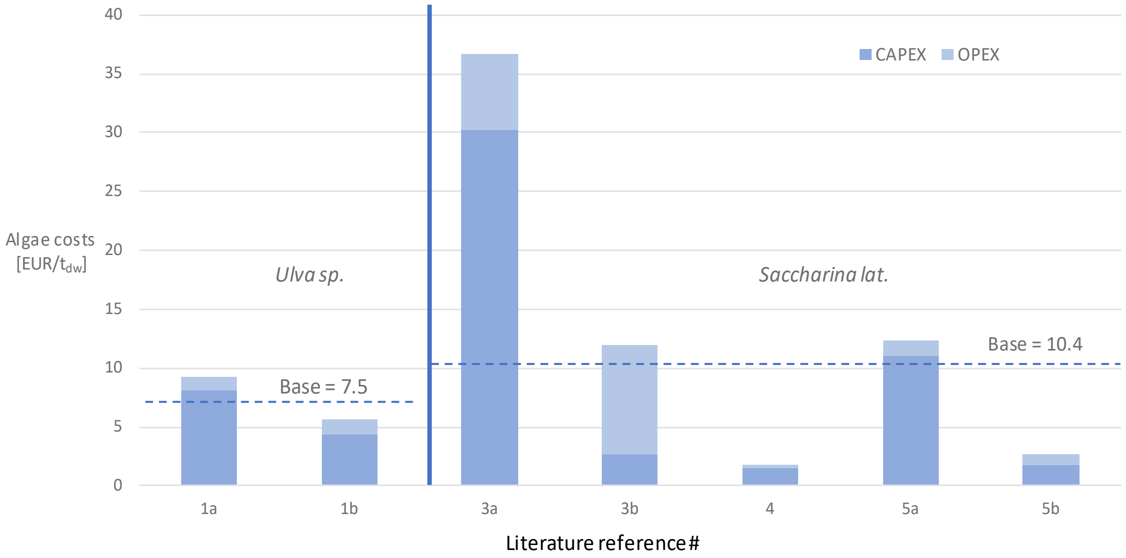

Figure 21 Cost for macroalgae cultivation in marine environment. Total cost including breakdown in CAPEX and OPEX for various literature references. Multiple scenarios in a single reference indicated with a and b.

3.2.2.3 Macroalgae cultivation - land-based

Land-based seaweed cultivation is less considered than marine cultivation. It does, however, have some interesting aspects. It has much better control of cultivation conditions (Hafting et al., 2012). Nutrients can be recycled, or even more interestingly, nutrient-rich industrial effluent streams can be used that combine mitigation of these emissions with seaweed production allowing for ecosystem services (Sode et al., 2013; Nielsen et al., 2012 and Neori et al., 2003).

Costs are strongly influenced by productivity, as discussed earlier in this report. Several factors contribute to the variations found. Firstly, there is a difference in location, growth conditions, cultivation system and nutrient levels. The productivity of seaweed cultivation is also reported for a specific growth period, often daily. Only some authors consider the impact of the yearly growth cycle to determine the annual yield. For sources that did not include such an assessment, as an optimistic approach, a six-month growth period was assumed to obtain the yearly yield, whereas, in practice, this might be different. It is also noted that the data comes from from a different base comparison study when comparing the scenarios for systems and species. As a result, the productivities and, therefore, costs listed cannot be used to benchmark between systems, but instead illustrative for the range encountered in literature.

Cost data for seaweed cultivation is scarcely reported in the open literature. Data was found for *Ulva* in raceway ponds from 1984, and costs have been translated into 2021 costs for this work using the Chemical Plant Cost Index (CEPCI, 2021). The authors report very low algae costs because of very low investment costs (EUR 90 000/ha) and operating costs. More recent data was found for a very small-scale tank system (Ladner, Su, Wolfe, & Oliver, 2018). The small scale considered, resulted in very high algae product costs. Finally, (Nikolaisen, Daugbjerg Jensen, & Svane Bech, 2011) published data for an open pond system. The base scenario has been estimated as the average of costs but is highly uncertain due to the extensive range of data.

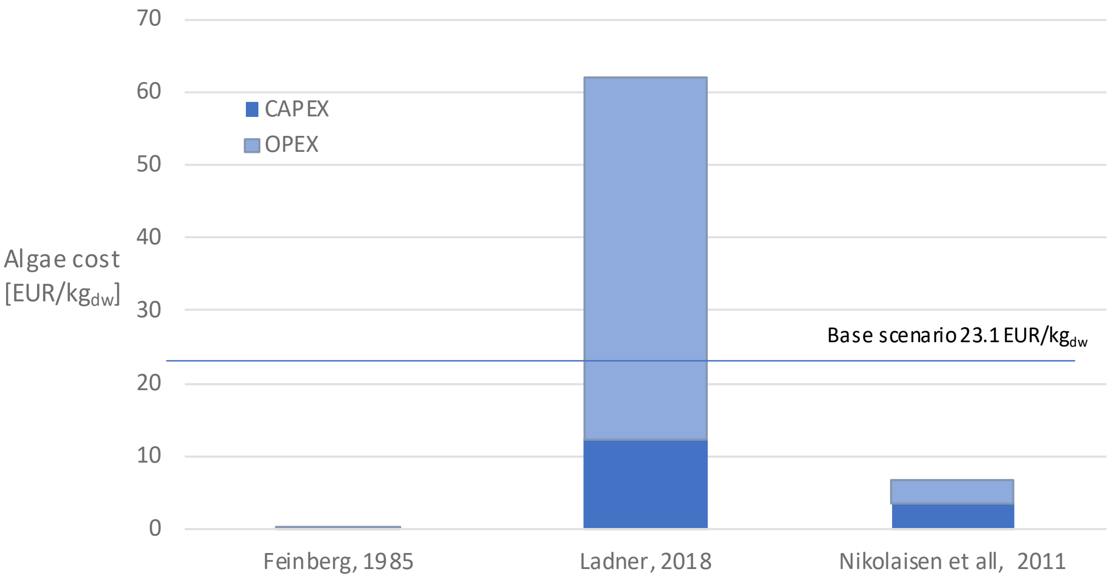

Figure 22 Cost of land-based cultivation of Ulva sp., Range, and breakdown in CAPEX and OPEX

Data for the cultivation of the other macroalgae that were defined in the scenarios for land-based cultivation, *Asparagopsis sp.* and the optionally considered species *Alaria esculenta*, were not available in literature. Given that no data was available for productivities of these species, it was also not possible to extrapolate from productivity data to get estimated costs.

3.2.3 Drying costs

Algae have large water content and need either to be used directly after harvesting or to be stabilized to preserve their quality (Del Olmo et al, 2020 and Enriquez et al, 1993). In the literature search performed it was found that there is not sufficient literature to discriminate between the different algae species. Therefore, the study only discriminates between macroalgae and microalgae. This section will discuss drying as a preservation method with costs, and impacts. Uncertainties in drying cost and impacts are in the feed material's final desired moisture content, effect of salts on the heat of evaporation, dryer type and efficiency, and the energy source and costs thereof.

3.2.3.1 Methods for macroalgae drying

For seaweed, the deterioration is already significant after 24 hours. Stabilization needs to be done shortly after harvesting and various methods, including drying, freeze-drying, freezing, and ensiling, are considered. For the current report, only drying will be considered. Ensiling is a common method of preservation for biological matter that using an anaerobic (natural) fermentation process to lower the acidity level. Though ensiling might be a suitable method for seaweed preservation, it is known to affect the composition of the seaweed, for which the effect on the properties as a feed is not known (Campbell et al., 2020). It must be mentioned that the changes in composition are not necessarily negative since some seaweed co-fermentation processes similar to ensiling are used to produce functional feed for pigs (FermentationExperts, 2022). Also, the current logistics of feed supply to livestock all work with dry substances and the impact of changing these logistics might be substantial and difficult to quantify. Freezing of seaweed has been suggested (Emblemsvåg et al., 2020) but is not considered for the same reason.

Several drying methods are considered in the literature for macroalgae, including sun drying, solar-assisted drying, microwave drying, and fossil-fuel based drying using a variety of dryer types. Sun drying is the most common method for seaweed drying, which is however primarily done in warm climates (Milledge & Harvey, 2016). For the European context this, however, is only possible during summertime in south-European member states only and is therefore not considered.

Macroalgae typically have a high-water content of 85-90%, which is much higher than that of conventional feeds (e.g. grain maize is 14–31%). To stabilize the algae, water contents between 10% and 30% of the dried seaweed are mentioned in various literature. Drying temperatures need to be low to avoid degradation of bioactive components and proteins that are important for the use in feed applications (Silva, Abreu, Silva, & Cardoso, 2019; Djaeni & Sari; 2015).

Literature on macroalgae drying is scarce or is a part of more integrated assessments of a specific valorization chain from which the drying impact cannot be isolated. Literature sources mention the cost and/or impact of algae drying using fossil sources. Trond and Hinge mention costs EUR 478/ton_{dw} for *Saccharina latissima* (Trond, 2014). The data by Nikolaisen for drying *Ulva lactuva* in an industrial dryer translates into costs of EUR 2.20/kg_{dw} (Nikolaisen et al., 2011). The energy impact is significant for both sources with a CO_2 emission of 915 and 1072 $\text{kgCO}_2/\text{ton}_{\text{dw}}$.

The specific GHG emissions depend on the allocation to the drying process. In the limit scenario, it can be assumed that the drying is fully done using renewable power, and no emissions are allocated to the drying process. Since there is no literature on emission-free drying, the additional costs have arbitrarily been set at 50% above the cost of natural gas drying for the *base including estimate scenario.* The CO_2 emissions for emission free drying have been simplified to a zero value in the database, assuming that any externalities are negligible.

To reduce the impact of drying, several methods could be considered. Firstly, there is the use of solar drying, which has been discussed earlier to be of limited potential. Drying by use of geothermal energy is an interesting option (Hallsson, 1992) that is used in Iceland (Ragnarsson, 2003), but dependent on the local availability of geothermal heat. Drying using electric heat can be fully renewable electricity and can be done using microwave technology, as evaluated by (Hakim, Handoyo, & Prasetya, 2020) though at large scale heat pumps could be an attractive option. Dewatering of macroalgae before drying, generally done by some method of pressing, is considered to lower the water content and thereby reduce the drying costs (Milledge & Harvey, 2016). Inevitably however, this comes with a loss of biomass (Gallagher, Turner, Adams, Dyer, & Theodorou, 2017) and though considered by some authors, it was not explicitly considered.

3.2.3.2 Methods for microalgae drying

The cultivation of microalgae is an integrated process in which dewatering and drying are an integral part of macroalgae production. Cultivation yields an algal dispersion ranging from 0.05–0.075% dry matter for open pond systems to 0.3–0.4% for closed systems. After screening, a variety of harvesting methods can be used to supply algae to the drying step. These include coagulation/flocculation, bio-flocculation, gravity sedimentation, flotation, and electrical methods, followed by various types of filtrations or centrifugation. The water content before drying is closely related to the upstream dewatering step (Fasaei, Bitter, Slegers, & van Boxtel, 2018). The moisture content has a significant impact on the drying cost. Typically, the water content of the resulting wet paste in the dryer is 35-75%, which is reduced to 10% after drying (Hosseinizand, Lim, Webb, & Sokhansanj, 2017). The paper concludes that the drying cost is largely affected by the initial water content and can vary over a factor 3 within the range considered. The final dried algae costs are expected to vary less because of the increased costs for dewatering to lower water contents.

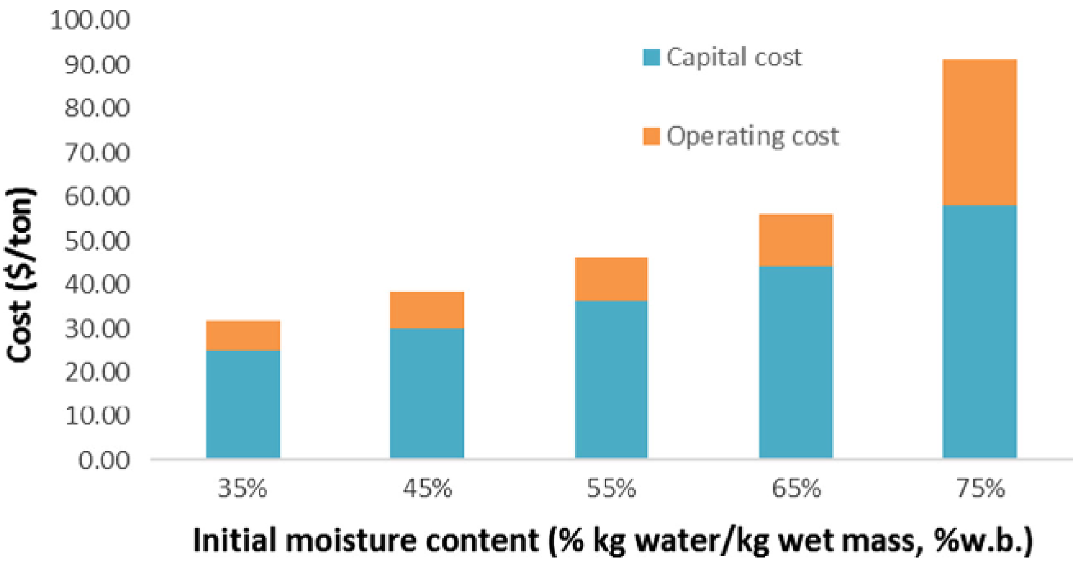

Figure 23 Drying costs of microalgae for belt drying, impact of initial moisture content, figure taken from (Hosseinizand et al., 2017)

Though in principle a large variety of drying methods are possible for microalgae, generally drum drying, or spray drying are considered. In drum drying the algae are spread as a thin layer on a hot rotating drum. As a result of the hot surface, protein denaturation may occur. Spray drying involves dispersion of the microalgae into small particles into a hot air stream. Only a single literature source discusses the costs of microalgae drying separately. The largest energy demand is for the drying step, the standard system having 5.1 kWh/kg algae.

3.2.3.3 Literature survey results

An overview of the drying costs and impact of algae drying is depicted in Figure 24. Data available was limited to a few sources: Nikolaisen et. al. 2011, Aziz, 2012, Fasaei and Bitter, 2018, Houseini and Lim, 2017). The base scenario has been taken as the average value from the literature values. It is seen that the drying costs for macroalgae in literature are higher than for microalgae. For costs, there is a significant difference between the source for both macroalgae and microalgae. Likely this is since the data originates from studies that use very different starting points. The results also cannot be considered an equal base comparison between macroalgae and microalgae. Again, the difference between starting points in literature is here an important factor. CO_2 impact has been derived from literature energy demand listed in the papers, assuming natural gas as the energy source and applying an emission factor of 0.201 and kg CO_2/kWh for power and 56.40 kg/GJ for natural gas. The results in GHG emissions show a lower variation between literature sources than the results on costs.

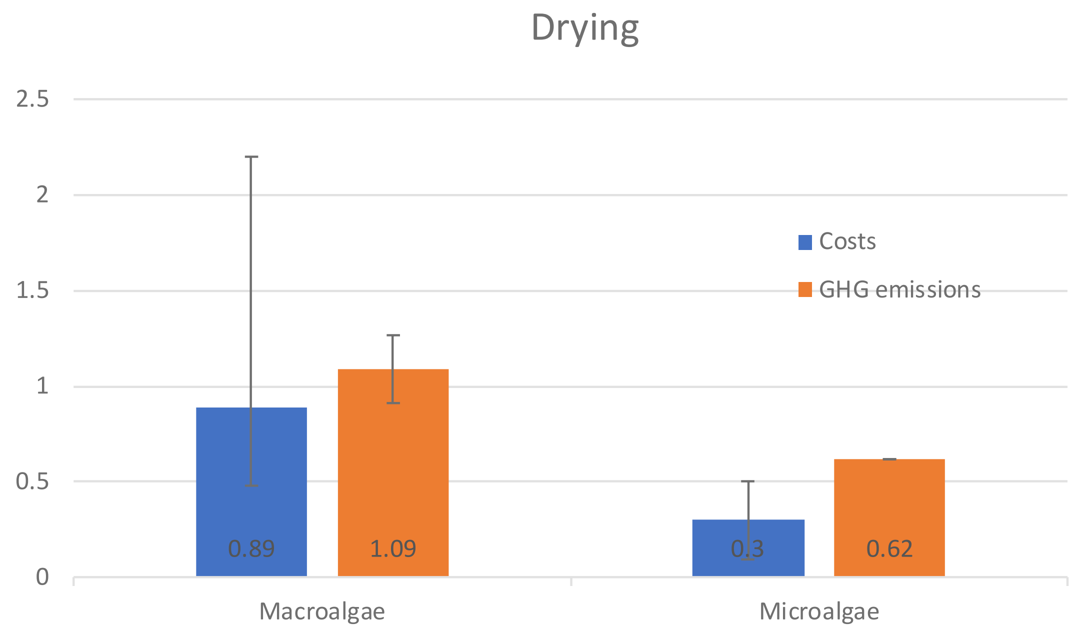

Figure 24 Drying costs and GHG impact, results from literature survey.

3.3 Greenhouse gas emissions

3.3.1 Methods

We present a framework for GHG flow accounting, analogous to the GHG protocol Corporate Accounting Standard (CAS) (Bhatia et al., 2011) but differs in the inclusion of the captured and avoided emissions (green entries in Figure 25). Similar to the CAS, scope I includes the emissions from onsite processes and energy-related emissions from onsite fuel consumption. Scope II covers the energy-related emissions associated to the production and delivery of the electricity, steam, heating, and cooling used for on-site operations. Scope III includes emissions originating from emissions from upstream production and delivery of input to onsite system and downstream treatment processes emissions.

In addition to Scope I-III, we present a Scope IV quantifying avoided emissions resulting from product service systems and we introduce emission capture and utilisation at Scope I (Seghetta et al, 2016a, b; Thomas and Gröndahl, 2020; Thomsen & Zhang, 2020 and Zhang et al, 2022). A visualisation of Scope I to IV emissions and emission capture and utilisation are provided in Figure 25.

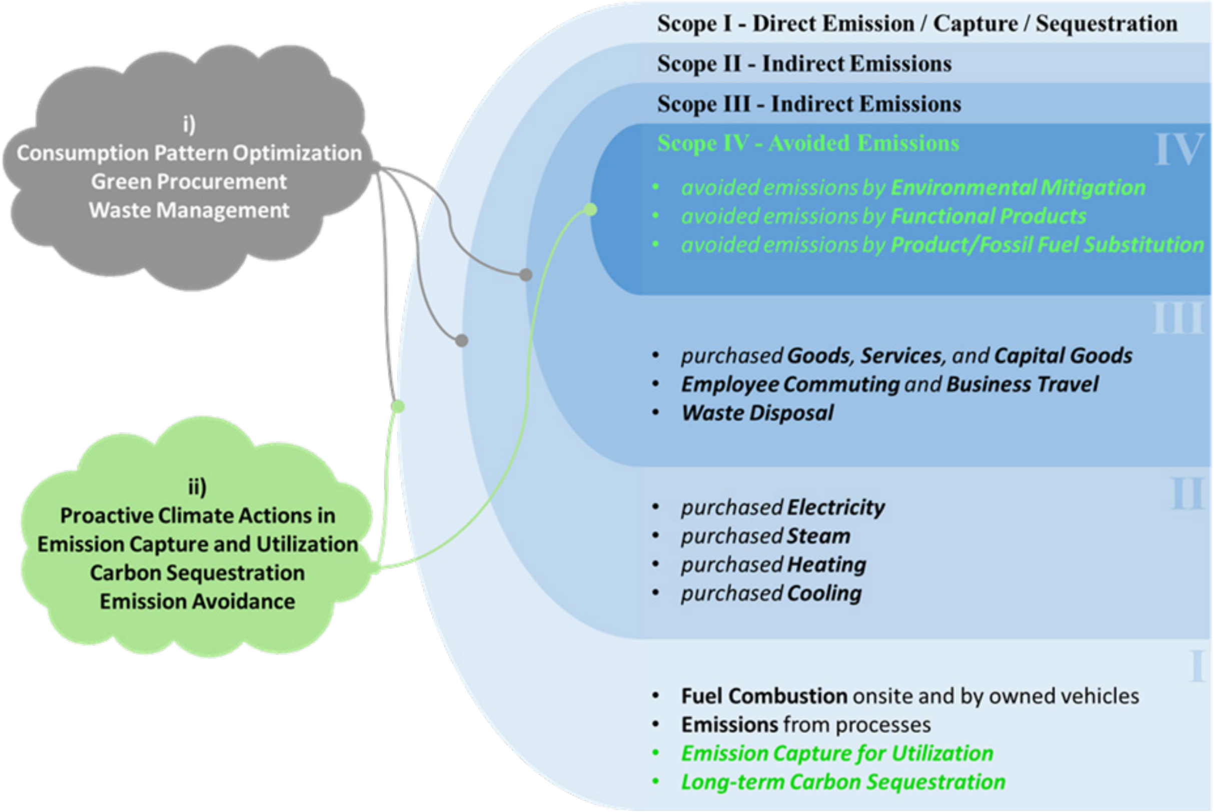

Figure 25 Proposed carbon footprint accounting framework with an extended scope. Green entries are the added GHG flows that are not included in the GHG Protocol Corporate Accounting Standard (Zhang, 2021)

3.3.1.1 Scope I to III

At scope I, the green entries represent carbon capture by land-based or offshore algae-cultivation, resulting from assimilation of dissolved inorganic carbon through photosynthesis, mostly as dissolved carbon dioxide (CO_2) but also as bicarbonate (HCO_3^-) (Zhang et al, 2022 and Hasselstrom & Thomas, 2022). CO_2 emission capture may occur from excess atmospheric and dissolved CO_2 in natural open waters, as well as in land-based cultivation systems. CO_2 emission capture may be calculated as:

$$E_{carbon\ capture,CO2} = m_{C,biomass} \cdot \frac{M_{CO2}}{M_C} \qquad \text{(Eq. 1)}$$

With,

- $E_{carbon\ capture,\ CO2}$ represents carbon negative emissions (emission capture) during the growth contributing to decarbonisation of the climate system and measured in units of kg CO_2 /ton dw algae biomass.
- $m_{C,\ biomass}$ is the amount C-CO_2 assimilated in the algae biomass during the growth phase, hence CO_2 transformed into algae biomass kg C-CO_2 /kg dw algae biomass.
- M_{CO2} /M_C is the mass ratio i.e. 44/12 applied to convert the carbon captured in the algae biomass into units of kg CO_2.

Literature data on scope I-III emissions are presented in the relational database, Table T22_cult_Impact. We did not include long-term carbon sequestration (>100 years) in the relational database, as reliable data are scarce/non-existing and standards/calculation methods being debated (Hurd et al., 2022).

3.3.1.2 Scope IV

Green entries at scope IV accounts for avoided emissions resulting from i) mitigation of environmental degradation, ii) functional products, i.e. bioactive algae-based feed components inhibiting enteric fermentation, iii) avoided emissions resulting from substitution of fossil-based products.

i) Mitigation of environmental degradation:

Mitigation of environmental degradation including climate change may occur through emission capture, utilisation, and sequestration at all steps of a value chain as well as within all scopes.

In the case of algal assimilation of excess nutrients in marine waters may result in water quality restoration through reduced eutrophication level (scope 4). Sources of nutrients could be from agricultural runoff, as well as effluents from wastewater and other industrial point sources. More important is that nitrogen effluents to surface waters, as associated with indirect N_2O emissions (IPCC, 2019), may be avoided upon nitrogen assimilation in the cultivated algae biomass. Avoided indirect N_2O emissions from natural waters are calculated as:

$$E_{avoided\ N2O} = A_N \cdot EF_{N2O} \cdot \frac{M_{N2O}}{2 \cdot M_N} \cdot GWP_{N2O} \qquad \text{(Eq. 2)}$$

With,

- A_N is the nitrogen amount assimilated in the algae biomass, hence avoided N load in surface waters measured in kg N /ton dw algae biomass; the N content as provided in % dm in Table "T13_algae composition" divided by 100.
- EF_{N2O} is the IPCC default emission factor of 0.005 kg N_2O-N per kg N; turned into avoided emission captured in land-based cultivation systems before or after leaching or release of nitrogen from manmade, mainly agricultural, activities to surface waters (IPCC, 2006).
- M_{N2O} /M_{N2} is the mass ratio i.e. 44/28 applied to convert the fraction of avoided N emissions into units of kg N_2O.
- GWP_{N2O} is the global warming potential of 298 for N_2O applied to transform the avoided N_2O emission i.e. $E_{avoided\ N2O}$, into units of kg CO_2e.

It should be mentioned that IPCC recommends a N_2O emission factor of 0.019 kg N_2O-N per kg N for nutrient impacted water and hence the estimated avoided emissions calculated according to equation 2 may be underestimated (IPCC, 2006, Table 6.8A). On the other hand, studies have shown N_2O production from *Ulva lactuca* cultivated in highly nutrient impacted waters (Albert et al., 2013).

Mitigating eutrophication levels of surface waters may be obtained through emission capture of nutrient in industrial process water prior to their release into collective sewer systems and treatment at municipal wastewater treatment plants (Maurya et al., 2022). Scalable plug and play technologies designed to capture land-based aqueous nutrient side-streams and CO_2 point source emissions (e.g. the Danish technology providers Algiecel and PureAlgae) may deliver non-financial profits. Turning nutrients in process water into algae biomass, i.e. Emission Capture and Utilisation, upstream to municipal wastewater treatment plants will furthermore lead to a reduction in direct N_2O emissions from biological treatment (Nielsen et al, 2022). Avoided N_2O emissions calculated according to equation 2 are provided in the relational database, Table T27 Scope 4_N2O.

ii) Functional feed supplement

The produced algae biomass may find several uses, which may result in reductions in the system level net CO_2 emissions; i.e. upon system expansion to include the use phase of the products (Zhang, 2021 and Zhu et al., 2021). In this project, we identified *Asparagopsis taxiformis* as a functional feed supplement with the ability to reduce enteric fermentation of livestock production (Section 6 and Supplementary Table 6.3). The methane reducing effect of bioactive feed supplement in units of avoided methane emission per mass unit of product:

$$E_{CH4\,red} = \left(1 - \frac{F_{CH4,inhib}}{100}\right) \cdot \left(\frac{F_{enteric\,ferm} \cdot E_{conv}}{GWP_{CH4}}\right) \qquad \text{(Eq. 3)}$$

With,

- $F_{CH4,\,inhib}$ represents a reduced methane emission from livestock feed with specified algae-based feed supplement. For *Asparagopsis taxiformis* we find methane reduction efficiency of -30% for dairy cattle and -60% for growing cattle (Section 6). For comparison, other studies have found value ranging from 70-98% within inclusion rates varying between 0.2 to 0.5% (Kindly et al 2020; Roque et al. 2021).
- $F_{enteric\ ferm}$ is the fraction of the CO_2e footprint originating from enteric fermentation set equal to 0.5 (Buretti et al., 2017).
- E_{conv} is the CO_2 footprint of the livestock product, i.e. milk or beef, measured in units of kg CO_{2e}/kg product and provided in the relational database T53_Reference Diet.
- GWP_{CH4} is the global warming potential of 25 for methane applied to transform the avoided emission from enteric fermentation to be subtracted from the carbon footprint of the reference diet-based livestock product.

Absolute measure of the CO_2e emission reduction upon inclusion of algae feed supplements with anti-methanogenic effect is calculated:

$$E_{climate\,prod} = F_{enteric\,ferm} \cdot E_{conv} + (E_{CH4\,red} \cdot GWP_{CH4}) \qquad \text{(Eq. 4)}$$

With,

- $F_{enteric\ ferm}$ is the fraction of the CO_2e footprint originating from enteric fermentation set equal to 0.5 (Buretti et al., 2017).
- $E_{climate\ prod}$ is the carbon footprint of the climate friendly beef or milk provided in units of kg CO_2e/kg product.
- E_{conv} is the carbon footprint of the conventional beef or milk provided in units of kg CO_2e/kg product.
- $E_{CH4\ red}$ quantifies the reduced enteric methane emission calculated according to equation 3.

iii) Avoided emissions resulting from substitution of fossil-based products

Algae may be used as an alternative bulk feed ingredient, substituting conventional, emission intensive, feed ingredients such as soy (Vijn et al, 2020). The potential avoided CO_2e emission per kg conventional feed substituted by algae feed may be calculated according to equation 5:

$$E_{CO2e} = \frac{E_{conv}}{FCR} - E_{algae\,feed} \qquad \text{(Eq. 5)}$$

With,

- E_{conv} is the carbon footprint of the conventional feed provided in kg CO_2e/kg product.
- FCR is the feed conversion ratio measured in units of kg dw feed/kg product.
- Ealgae feed may be expressed as the net carbon footprint of the algae feed (scope I-IV). provided in units kg CO_2e /kg dw algae feed.

The substitution rate is not 1:1, but instead defined by the recommended and maximum recommend inclusion rates as described in Section 6. Equation 5 provides an intensive measure of the change in carbon footprint per mass unit conventional feed substituted with bulk algae feed. An extensive measure of the GHG emission reduction obtained at specified bulk algae feed inclusion rates is calculated according to equation 6:

$$E_{CO2e} = (1 - IR) \cdot \frac{E_{conv}}{FCR} + \left(IR \cdot E_{algae\ feed}\right) \qquad \text{(Eq. 6)}$$

With,

- ECO_2e is the CO_2e emission obtained per dw kg of the new feed composition provided in the relational database table T59_Diet composition GHG.
- IR is the inclusion rate corresponding to the amount of conventional feed substituted by algae feed provided in the relational database table T54_Algae Diet.
- Econv is the carbon footprint of the conventional feed provided in the relational database T53_Reference Diet in units of kg CO_2e/kg product.
- FCR is the feed conversion ratio are provided in the relational database T53_Reference Diet in units of kg dw conventional feed/kg product produced.
- Ealgae feed is the net carbon footprint of the algae-based feed provided in units of kg CO_2e / kg algae feed.

The carbon footprint of the diet including algae in amount corresponding to the recommended and maximum inclusion rates are provided in the relational database, Table T54. More conservative estimates may be obtained by excluding the carbon capture (scope 1) and avoided N_2O emissions (Scope 4) when quantifying the CO_2e emissions of the algae-based feed, while including the energy-related emissions from drying (scope II) (Section 6, Table 30). Most optimistic estimates are obtained by including emission capture in scope I (CO2) and IV (N2O), while assuming emissions free drying of the algae feed. The most pronounced GHG reducing impact are obtained for milk and beef products upon including the anti-methanogenic effect of Asparagopsis taxiformis in scope IV (Section 6, Table 30).

3.3.2 Data sources

Data sources include only scientific peer reviewed publications. No LCA studies were found for:

- Ulva cultivated on in land-based raceway ponds or photobioreactor systems.
- Asparagopsis cultivated in marine rope systems.
- *Alaria* cultivated in marine rope systems.
- *Gracilaria* cultivated in marine rope systems.
- *Palmaria palmata* cultivated in marine rope systems.
- *Dunaliella* cultivated in raceway ponds.

For the remaining algae production systems, literature data sources are provided in the below table.

Table 14 Identified relevant publication used as data sources for GHG emissions in the relational database

Species and Production systems	Literature sources
***Ulva* sp - Rope System** **Ulva_ROP**	Holdt and Kraan 2011; Gillgren & Winquist, 2022
***Asparagopsis* sp - Phobioreactor systems** **Asp_PBR**	Nilsson and Martin, 2022
***Saccharina latissima* – marine rope systems** **Sach_ROP**	Zhang et al., 2022; Thomas et al., 2021; Koesling et al., 2021; Van Oirschot et al., 2021
***Gracilaria* sp. - marine rope systems** **Grac_ROP**	Anand et al., 2018
Haematococcus pluvialis **Haem_PBR**	Onorato & Rösch, 2020
***Nannochloropsis* sp.** **Nann_PBR**	Pérez-López et al., 2017
***Chlorella* sp. - Photobioreactor systems** **Chlo_PBR**	D'Imporzano et al., 2018; Smetana et al., 2017
***Spirulina* sp.- Raceway ponds** **Spir_RP**	Smetana et al., 2017; Tzachor et al., 2022
***Dunaliella* – Photobioreactor system** **Dun_PBR**	Espada et al., 2019

3.3.3 Results

In general, we observe that the total carbon footprint, i.e. excluding CO_2 assimilation in the biomass, is higher for microalgae systems, ranging from 21 to 1087 kg CO_2/kg dw, as compared to macroalgae systems for which the offshore base value ranges from 1.5 to 16 kg CO_2/kg dw algae biomass.

For *Ulva sp* offshore production on marine rope systems, modelled at demonstration and industrial scale, data on the total carbon footprint range from 616 to 2710 with an average of 1498 kg CO_2e/ ton dry weight. Gillgren & Winquist (2022) mention emission capture, but do not include emission capture when calculating the carbon footprint. The functional unit is reported as ton of fresh weight, which is translated into DW using, respectively, a default value of 10% dry matter of fresh weight provided in the relational database and an optimistic value of 44% (Holdt and Kraan, 2011). A net carbon footprint (scope I-III including carbon capture) may be calculated by adding the amount of assimilated CO_2 in the algae biomass to the total carbon footprint (scope I-III excluding carbon capture). The carbon capture i.e. assimilated CO_2, in the algae biomass may be calculated from the carbon content in the algae biomass reported on the relational database in sheet T13_algaecomp.

For *Asparagopsis* sp cultivated in photobioreactor systems, a total carbon footprint ranging from the most optimistic value of 4600 to a conservative value of 46200 and an average (base case) value of 16350 kg CO_2e/ton dry weight. The study includes infrastructure components, raw material, and energy inputs (scope I-III). A sensitivity analysis on thermal energy sources, water recycling and growth rates, while also applying different allocation methods. The inoculum tank represented a hotspot constituting 64% of the total GHG in the baseline scenario of which 75% was associated to the salt input alone. 33% of the total GHG emissions was attributed to the biomass production tanks including pumps, filters, heat exchangers, blowers, LEDs and drier (Nilsson & Martin, 2022).

For *Saccharina latissima,* offshore production, the net carbon footprint varied from −739 to 3131 kg CO_2e/ton dw algae with a base value 535 kg CO_2e/ton dw algae. The total CO_2 footprint range from 398 to 45845 kg CO_2/ton dw, with a base value of 7626 kg CO_2e/ton dw algae (Koesling et al, 2021; Thomas et al, 2021; van Oirschot et al., 2017 and Zhang et al. 2022). For technological mature cultivation systems, net negative CO_2 footprint are observed. The latter documenting the opportunity for the cultivation systems to deliver non-financial profits from climate change mitigation services (Thomsen et al., 2022 and Zhang et al., 2022).

For *Gracilaria* a single study was found from Indonesia, reporting a total footprint of 41 kg CO_2e/ton DW seaweed. For the microalgae *Chlorella, Spirulina* and *Dunaliella*, the base value for the total carbon footprint is in the range of 11-21 kg CO_2/ kg DW. For *Haematococcus pluvialis*, the base value for the total carbon footprint is 114 kg CO_2 / kg dw, for *Nannochloropsis* the base value is a bit higher, i.e. 1086 kg CO_2/kg DW.

3.3.4 Critical analysis

The total carbon footprint across all systems and algae types are large, ranging of 41-2.7 millions of kg CO_2e /ton dw algae. The literature review showed that the individual studies have defined different system boundaries, and the varying level of detail of the reported data makes it difficult to separate contributions to the total and net carbon footprint according to scopes. As such, it was in most cases impossible to separate upstream material input related emissions (scope III) from the energy-related emissions associated to the energy supplied for operation of the land-based production systems (Scope II). Likewise, only some studies include the nutrient and CO_2 emission capture in scope I.

Productivity and dry matter content of the harvested algae biomass are highly influential factors for the net carbon footprint of the production systems whether they be land-based or offshore cultivation systems. No attempts for data gap filling were performed in the database. As explained, it would have been easy to include emission capture at scope I in all CO_2 footprint calculations reported.

For the scope IV, we did not include the avoided direct N_2O emissions at wastewater treatment plants (Nielsen et al, 2022), which would add further to the environmental restoration and climate change mitigating effects of using aqueous side-streams as growth media for nutrient capturing turning emissions into revenue streams. The only macroalgae with this effect calculated is Asparagopsis and results are provided in Supplementary Table 6.3.

The quality of the gaseous as well as aqueous growth media are key determining factors for optimal growth. Among industrial wastewaters, wastewater from food, agro- and aqua-based industries are good for high-quality algae biomass production, because they typically have low content of heavy metals and has good amounts of growth-supporting macronutrients such as nitrogen and phosphorus, which leads to high algae biomass yield (Zhu et al., 2022). For offshore production systems as for any wild seafood, the contamination level reflects the environmental background contamination level and variation in assimilation efficiency of individual algae species (e.g. Gojkovic et al., 2022).

3.3.5 Assumptions

For the scope IV, we calculated the CO_2e footprint of the new diet based on non-specific feed composition data. This assumption makes the environmental benefits from algae cultivation conservative as we did not substitute worst case feed components such as soya-based feed ingredients.

3.4 Alternative sources of vegetable proteins

3.4.1 Production costs

According to the UK Agriculture and Horticulture Development Board, typical spot prices in the period May 2021 to September 2022 for UK grain and protein prices range from EUR 151/ton to EUR 613/ton, with an average of EUR 131, EUR 250, EUR 151 and EUR 343/ton of feed wheat, feed barley, soybean meal and rapeseed meal (AHDB, 2022).

3.4.2 GHG emissions

The CO_2 footprint of feed depends on which ingredient they contain. Feed composition data may be found in the scientific literature as well as from feed industry associations such as, e.g., the Danish Agriculture & Food Council Sector for Pigs, and national statistics (Statstikbanken.dk). Soy protein is an example of an emission intensive feed ingredient in European, and hence the contribution of soy feed ingredients is part of the scope III emission contribution to the convention animal-based product footprint as provided in Table 15.

The CO_2 footprint of feed ingredients in livestock production vary according to the origin as well as processing technology and product type. The CO_2 footprint of soy-based feed may vary between 468 and 6 090 kg CO_2e/ton dw feed (Mogensen et al., 2018). 71% of Danish soya imports come from conventional producers, whereas 20% of soya is certified through RTRS (Round Table on Responsible Soy) credits[30]. The remaining 9% of imports meet European feed industry procurement guidelines for soya (Bosselmann, 2020). In total Denmark import is around 1.7 million tons of soybean meal every year (Callesen et al. 2020); 774 436 tons soy from Brazil, 527 931 tons from Paraguay and 77 667 tons from Argentina (Bossen et al., 2020). EU imports around 5 323 360 tons and 2 627 637 tons from respectively Cerrado and Amazon, 1 581 024 tonnes from Paraguay and 276 043 tonnes from Argentina (IDH, 2020).

An illustrative example of the demand for soy-based feed in the aquaculture sector, is described in a study (Aas et al., 2019) showing demand for soy protein concentrate corresponding to 19.0% or 309 711 tons of the feed composition of Norwegian salmon feed in 2016. Rapeseed and camelina oil accounted for 19.8% or 322 580 tonnes (Aas et al., 2019).

The environmental performance of livestock, poultry and fish production systems at the EU scale is represented by a literature review of the CO_2 footprint of final products from different production systems from intensive conventional production systems to extensive and organic production systems (Abín et al., 2018; Caseey & Holden, 2006; Desjardins et al., 2012; Djekic et al, 2020; Flysjö, 2012; Halberg et al., 2010; Liu et al., 2016;

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[30] https://responsiblesoy.org/

Mazzetto et al., 2021 and Nguyen et al., 2011). The GHG emission was estimated based on conventional unspecified animal-derived food products as shown in Table 15.

Table 15 CO_2 footprint of representative animal-derived food products, [kg CO_2e/kg product]

Product	Base	Optimistic	Conservative
Chicken meat	2,48	2,13	3,30
Eggs	2,08	1,14	3,50
Salmon	5,23	3,39	7,01
Pig meat	3,13	2,83	3,50
Milk	1,18	0,90	1,53
Beef meat	10,60	8,00	13,00

As the feed composition can vary according to market prices, member state (MS) and farm level, we used the final product carbon footprint as a measure of environmental performance of the animal-derived food production systems that are based on conventional feed demands reflected in the feed conversion ratios provided in Section 6.4. The potential algae-production in Europe is in the range of 146 mill. to 406 mill. ton dw/yr (see Section 5). Adopting a super conservative assumption of 10% of the dry weight algae biomass being protein (Relational Database, Table 13), a production of 15-41 ton of crude protein/year would enable a substitution of the total European import of soy-based feed protein of around 10 mill tons (Aas et al., 2019) from the rest of the world. This is the technical potential resulting from the mapping. Also, limiting factors for inclusion rates of the different types of macro- and microalgae is a barrier for using the full potential as described in Section 6.

3.5 Comparison and benchmarking

In the literature survey it was concluded that especially data regarding the cost of macroalgae cultivation is scarce and that literature values vary greatly for both macroalgae and microalgae. Also, elements such as location, plant capacity, and assessment approach make it virtually impossible to directly compare results between species, between macro-microalgae or between technologies. If more and better information would be available here, this would lead to a greater confidence in the results. The average algae biomass price of 31 €/kg of dry weight algae biomass is a factor 90 to 236 above the price level of conventional feed (World Bank, 2023), which makes algae-based feed non-competitive with existing feed market prices.

3.6 Information feeding into the relational database

The information fed in into the relational database from this task is:

- Cultivation costs data, including breakdown in CAPEX and OPEX for microalgae, and land and marine macroalgae.
- Costs and GHG impact of algae drying.
- Carbon uptake from open and closed land-based algae cultivation in terms of relative amount of CO_2 fixated related to the amount fed from a point source.
- GHG impact of algae cultivation addressing separately the scope 1.1, 1.2, scope 3 and scope 4 emissions. It also feeds in the information to assess scope 4 emission effects in the database.

Table 16 provides an overview of the knowledge base. Cells are empty when data are not available, they are yellow when data are available but based on strong assumptions and they contain a "✓" when data are available.

3.7 Discussion

The analysis of microalgae costs revealed a major issue, namely the dependence of production systems on raw materials and inputs prices (mainly labour and energy prices). It shows that with an average increase of more than 60% in energy costs, OPEX cost would increase by 10%, which illustrates the need to find solutions and innovations in production systems. Solutions can be found through two channels; (a) on the cost side by limiting energy costs thanks to investments in photovoltaic or other renewable source of energy for example and (b) on the revenue side by taking more advantages of the environmental impact causes by microalgae production by monetizing ecosystem services provided by microalgae cultivation (water treatment, CO_2 capture…). Then, further research should focus on the identification of solutions to lower the costs of microalgae production. As the research progresses and the results of the technical-economic analysis are published, the previous analyses can evolve, and their robustness may be strengthened.

In the literature survey it was concluded that especially quantitative data on the cost of macroalgae cultivation are scarce and that literature value vary greatly. Also, the elements as location, plant capacity, assessment approach make it impossible to directly compare results between species, between macro- and microalgae or between technologies. The results of the study do however give input to selecting the starting points for a bottom-up study in which these could be compared on an equal-base comparison. Macroalgae cultivation costs were found to be high in comparison with conventional feed products. Most algae costs are between EUR 6 and EUR 35/ton_{dw}, which is much more than the conventional feed costs that are significantly below EUR 1/$ton_{dw.}$ Cost reductions will be key in increasing the potential for algae in feed applications, while making use of specific functionalities of algae will remain important for added value.

In land-based algae cultivation, CO_2 (or bicarbonate) is supplied to enhance growth, which can also serve as a means of capturing CO_2. Only part of the CO_2 supplied is fixated into algae, where the value for closed systems (base scenario 60%) is higher than for open systems (base scenario 30%). The effect of light periods for photosynthesis (i.e. length of day/night) and seasonality, also in relation to latitude, might be underestimated in these values and is advised for further study. Algae drying was added to the study in a later stage and is shown to have a significant contribution to cost prices.

Algae GHG emissions may become negative for production systems where the sum of emission capture (scope I), avoided emissions for substitution of emission intensive feed ingredient (scope IV) and in case of methane reducing bioactive feed supplements in livestock production (scope IV) exceeds the sum of material (scope III) and energy-related emissions (scope II). Onshore algae production systems have higher material and energy-related CO_2 emission compared to offshore seaweed cultivation systems. Future potential nutrient and carbon credit systems may contribute to improved business cases in algae production when making use of industrial side-streams for CO_2 and fertiliser/nutrient additions. Regarding the carbon credits however, substantial knowledge gaps still exist and require both research on the carbon cycle and mass balances of the individual production systems, as well as thorough Life Cycle Analyses of the entire production processes.

Table 16 Overview of available data in the relational database resulting from Section 3

	Cultivation cost					**Drying cost and impact**					**Cultivation impact**				
	Capacity in reference	Specific and total investments	CAPEX	OPEX	Total cost price	Drying cost (drying natural gas)	Drying cost (emissions free drying)	Drying GHG emissions drying natural gas	Drying GHG emissions free drying	GHG emissions for respectively scope 1.1, 1.2, 2, 3	Total carbon footprint	Net carbon footprint	Drying GHG from T21	Total carbon footprint including drying	Net carbon footprint including drying
Ulva in photobioreactor						✓		✓	✓						
Ulva in rope system			✓	✓	✓	✓		✓	✓		✓				
Asparagopsis in photobioreactors						✓		✓	✓		✓		✓	✓	
Asparagopsis in rope system						✓		✓	✓						
Saccharina in rope system	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	
Alaria in rope system						✓		✓	✓						
Palmaria in rope system						✓		✓	✓						
Haematococcus in photobioreactor			✓	✓	✓	✓		✓	✓		✓		✓	✓	
Nannochloropsis in photobioreactor			✓	✓	✓	✓		✓	✓		✓		✓	✓	
Chlorella in photobioreactor			✓	✓	✓	✓		✓	✓		✓		✓	✓	
Spirulina in rope systems			✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	

4 ASSESSMENT OF BREAK-EVEN CARBON PRICES

4.1 Introduction

Microalgae have the potential to recycle CO_2 emissions from industry flue gases and thereby contribute to climate change mitigation. The economic value of CO_2 mitigation can be estimated assuming that the CO_2 mitigation from algae production might be credited by selling carbon emission rights on markets. These additional revenues potentially have an impact on the profitability of microalgae production. The break-even carbon prices assessment allows the analysis of the effect of carbon prices on the economics of algae feed production and answers the question: "Has algae feed the potential to become economically viable with additional revenues from CO_2 credit sales?" The specific objectives are to:

- Assess carbon prices that break-even algae cultivation costs with potential revenues coming from (a) the sale of algae biomass and (b) the amount of greenhouse gases from flue gases used in production.
- Investigate how realistic break-even carbon prices are as compared to the past, current, and future dynamics of the carbon price on the market in Europe.
- Illustrate possible adaptations in the calculation method to better reflect the challenges faced by microalgae producers.

For the analysis of break-even carbon prices, it is assumed that the carbon that will be captured during the cultivation phase will not be released in a later phase of the product's life cycle.

4.2 Approach

A break-even analysis is a financial calculation that weighs total production costs against revenues and determines the revenues that are required to cover all costs. The break-even carbon price analysis focuses on 4 closed microalgae production systems[31] that use flue gases (see Table 11): 1) *Nannochloropsis* in photobioreactors, 2) *Chlorella* in photobioreactors, 3) *Spirulina* in photobioreactors and 4) *Haematoccocus* in photobioreactors.

There are two potential sources of revenues from the production of microalgae with flue gases: 1) algae feed sales, and 2) sales of carbon credits. The break-even analysis focuses specifically on the potential revenue from carbon credits and aims to determine the break-even carbon price. The break-even carbon price represents the carbon price required to offset algae feed production costs besides revenues from the sale of algae biomass (see Figure 26).

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[31] The selection of algae production systems included in the break-even analysis is based on the longlist of production systems presented in Section 2.2. Such an analysis relies on the calculation of a carbon price based on the amount of carbon used in a production system. Therefore, only closed production systems that rely on flue gases for CO_2 can be included in the analysis.

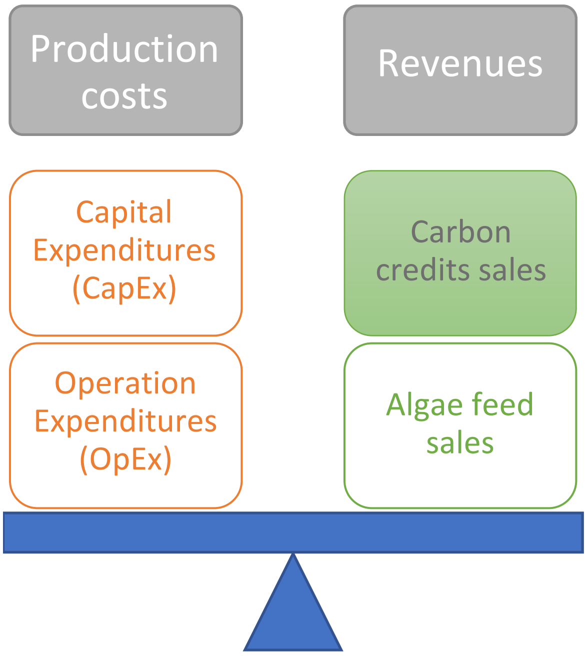

Figure 26 Break-even analysis of carbon credit sales for micro-algae production

The break-even carbon price is the difference between algae production costs and revenues from biomass sales divided by the quantity of carbon that is captured. The amount of carbon captured by algae growth is equal to the quantity of carbon rights that can be sold on the carbon market. The break-even carbon price of production scenario T can be calculated as follows:

$$P_c^T = \frac{C_f^T - P_f}{Q_c} \qquad \text{(Eq. 6)}$$

where, C_f is the cost price of algae feed production for production scenario T in EUR/kg DW, P_f is the sales price of algae feed in EUR/kg DW, and Q_c is the quantity of carbon required to produce 1 kg of algae.

4.3 Data collection

The calculation of break-even carbon prices uses a set of parameters and Table 17 provides an overview of variables and input parameters. Data on production costs, algae feed prices and carbon uptake were collected from the review of available literature.

Table 17 Variables and parameters to calculate break-even carbon price

Description	Abbreviation	Unit	Parameter/variable	Source
Break-even carbon price	P_C	EUR/kgCO$_2$	Variable	
Cost price of algae production	C_f	EUR/kg of dry weight biomass	Parameter	Literature review, see previous Section 3.2.1
Price of algae feed	P_f	EUR/kg of dry weight biomass	Parameter	Literature review, see next Section 4.3.1
Carbon uptake	Q_C	Kg of CO$_2$ / kg of dry weight biomass	Parameter	Literature review, see next Section 4.3.2
Production scenario	T	[1, 2]	Parameter	See Table 12

4.3.1 Price of algae feed

The main source of revenue from microalgae production is the sale of dry algae biomass (see Figure 26). It is assumed that dry algae biomass can be directly used as animal feed and that no further post-processing is required. Three articles (Vázquez-Romero et al, 2022; Schade and Meier, 2021 and Pavlik et al, 2017) conducted a detailed technical-economic analysis and reported sales prices for different types of seaweed products (biomass, frozen paste, dry microalgae biomass). From these studies it can be concluded that, on average, microalgae biomass is sold for EUR 31/kg of dry weight. To reinforce this result, which is based on only 3 references not necessarily using dry biomass prices, an additional article was reviewed (Araújo et al, 2021 – see Table 18). They provided business to business prices ranges [32] based on consultation with algae producers. Differences in prices can be explained by different factors such as the production system, production costs (energy and work force), geographical origin, certification schemes (e.g., organic production). These prices will be used in the break-even carbon price analysis, relying on the minimum and maximum prices to perform a sensitivity analysis.

Table 18 Price range for selected microalgae species produced in photobioreactors

Microalgae species	Min (EUR/kg dw)	Max (EUR/kg dw)
***Chlorella* sp**	25	50
Spirulina	30	70
Nannochloropsis	30	110
Haematococcus[33]	150	300

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[32] Business to Business price is the selling price from one company to another.

[33] Haematococcus is a microalgae species used for the extraction of high value products which may explain these higher prices than those of other species.

4.3.2 Carbon uptake

From the studies included as production scenarios in the analysis of microalgae production cost prices, only two provide estimates of the total amount of carbon required to produce one kilogram of algae biomass (Schade and Meier, 2021 and Pavlik et al, 2017), see Table 19.

Table 19 Reported carbon uptake for production scenarios included in the estimation of cost prices

Production scenario	**Technology**	**Species**	**Carbon uptake in kg CO_2/kg biomass**	**Reference**
3	Tubular photobioreactor	*Nanno-chloropsis*	1.8	Schade & Meier, 2021
4	Tubular photobioreactor and photovoltaic	*Chlorella* sp.	2	Pavlik et al, 2017
5	Tubular photobioreactor			

These values are consistent with literature. Iglina (2022) suggests that 1.8 kg of $CO_2$is absorbed per kg of biomass produced and Norsker et al, (2011) estimates carbon uptake by microalgae species at 1.8 kg CO/kg of dry weight biomass. Therefore, for the calculation of carbon break-even prices, it is assumed that the average carbon uptake of microalgae species is equal to 1.8 kg CO_2/kg of dry weight biomass.

4.4 Estimated break-even carbon prices

In order to identify production scenarios (see Table 12) for which additional revenues from the sales of carbon credits is needed (besides revenues from algae sales) to break-even with microalgae production cost prices were compared with minimum and maximum algae feed prices[34], see Figure 27. The figure shows that:

- Assuming maximum algae sales prices: the maximum selling price is equal or superior to the production cost in all cases[35]. At the maximum sales prices the production of microalgae is economically viable and no additional revenues from the sales of carbon credit are required.
- Assuming minimum algae sales prices: the minimum selling price is not always sufficient to cover production costs, see production scenarios 1, 2, 6 and 7. The production of microalgae is not economically viable if only revenues from algae feed sales are considered. Additional revenues from the sale of carbon rights on carbon market could complement revenues and increase economic viability. Consequently, break-even carbon prices are calculated for these production scenarios.

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[34] Collected from (Araújo et al, 2021), these prices are not prices per production scenario but per type of algae.

[35] In these cases, if break-even carbon prices were calculated, they would be negative.

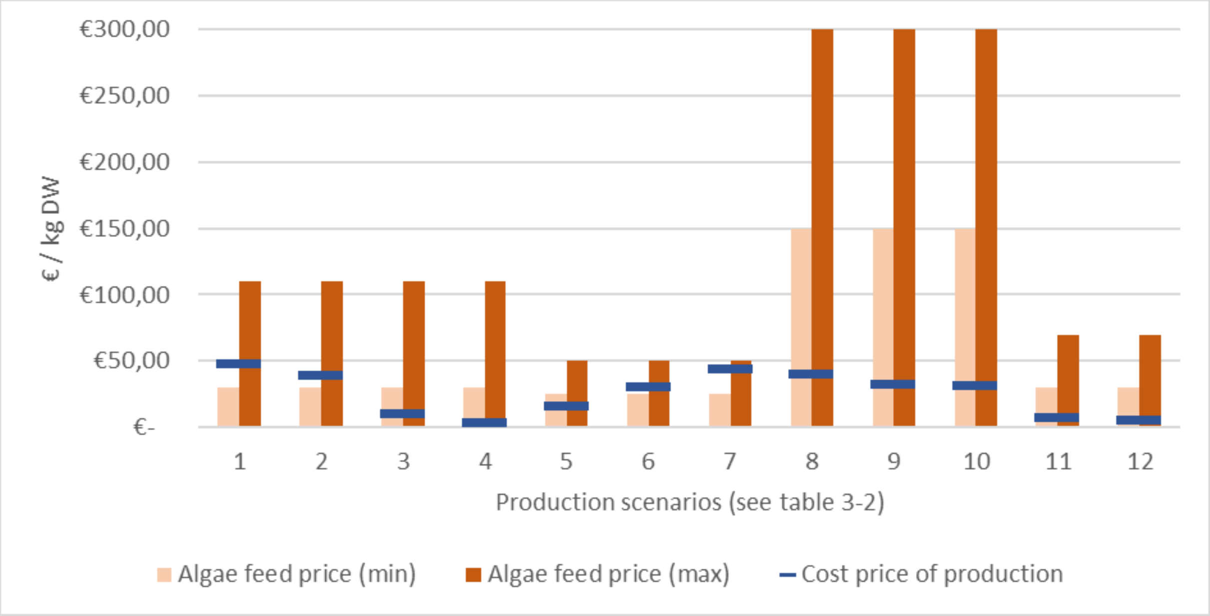

Figure 27 Comparison of production costs (cost prices) with revenues (algae feed prices)

Table 20 presents the estimated break-even carbon prices for the identified production scenarios that need additional revenues to offset production costs. The results show that the average break-even carbon price is equal to EUR 7/kg of CO_2. This is equal to EUR 7 000/ton of CO_2, which is very high compared to the actual carbon market price of EUR 80/ton of CO_2. The high estimated break-even carbon prices can be explained by the low carbon uptake of microalgae, consequently high carbon prices are needed to offset production costs. The estimated break-even carbon prices are not realistic.

To overcome this issue, Section 4.5 suggests computing the break-even algae feed price that makes it possible to offset algae feed production costs besides revenues from the sale of algae proteins given the actual carbon price on the market, and then, compare it to the alternative feed price on the market (soybeans meal).

Table 20 Break-even carbon prices

Production scenario	**Cost price of algae production (EUR/kg DW)**	**Minimum price of feed (EUR/kg)**	**Carbon uptake ($kgCO_2/kgDW$)**	**Break-even carbon prices (EUR/kg CO_2)**
1	47	30	1.8	9.5 (EUR 9500/ton of CO_2)
2	38	30	1.8	4.7 (EUR 4700/ton of CO_2)
6	30	25	1.8	5.3 (EUR 53000/ton of CO_2)
7	44	25	1.8	11.0 (EUR 11 000/ton of CO_2)

4.5 Estimated break-even algae feed prices

4.5.1 Approach

The break-even feed price represents the feed price required to offset algae feed production costs besides revenues from the sale of carbon credits (see Figure 26)[36]. The break-even feed price P_f^T can be calculated as:

$$P_F^T = \frac{C_f^T - (P_C \cdot Q_C)}{Q_P}\frac{C_f^T - (P_C \cdot Q_C)}{Q_P} \qquad \text{(Eq. 7)}$$

Where Cf is the cost price of algae feed production for production scenario T in EUR/kg, Qc is the quantity of carbon required to produce 1 kg of algae, Pc is the carbon price on the market and Qp is the quantity of crude proteins provided by one kilogram of algae, in kg. In the end, P_f^T represents the break-even algae feed price in EUR/kg of crude protein and can be compared to the price of soybeans meal in EUR/kg of crude proteins.

4.5.2 Data collection

The calculation of break-even algae feed prices uses a set of parameters presented in Table 21. Data on production costs and carbon uptake were already collected for the calculation of break-even carbon prices. For the calculation of the break-even feed prices, additional data on carbon prices and the quantity of proteins provided by one kilogram of algae biomass were collected.

Table 21 Variables and parameters for the algae feed break even prices analysis

Description	Abbreviation	Unit	Parameter/variable	Source
Break-even algae feed price	P_F^T	EUR/kg of crude protein	Variable	
Cost price of algae production	C_f	EUR/kg of dry weight biomass	Parameter	Literature review, see Section 3.2.1
Carbon price on the market	Pc	EUR/ton of CO_2	Parameter	Market price, see Section 4.3.1
Carbon uptake	Q_C	Kg of CO_2 / kg of dry weight biomass	Parameter	Literature review, see Section 4.3.2
Quantity of crude proteins	Qp	Kg crude proteins/kg of algae	Parameter	See Section 4.5.2.1
Production scenario	T	[1, 2]	Parameter	See Table 12

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[36] The methodology is the same as for the calculation of break-even carbon prices.

4.5.2.1 Amount of crude proteins

Table 22 presents the average value (also called “base”) of crude proteins that is present in one kilogram of algae. These values were estimated in Section 2.4.3.

Table 22 Amount of crude protein in one kilogram of microalgae

Microalgae species	Average value of crude proteins content in one kilogram of algae
***Chlorella* sp**	0.3 kg of crude protein / kg DM
Spirulina	0.52 kg of crude protein / kg DM
Nannochloropsis	0.285 kg of crude protein / kg DM
Haematococcus	0.21 kg of crude protein / kg DM

4.5.2.2 Carbon prices data

Created in 2005, the EU ETS (European Union Emissions Trading Scheme) is the European market for carbon in which carbon emissions allowances are traded. The meeting of supply and demand for allowances determines the price for carbon[37]. Since 2013 (Phase 3 of the EU ETS), allowances are allocated by auction. Currently, the European Energy Exchange (EEX) is the common auctioning platform. Today, the carbon price is equal to EUR 83.4/ton CO_2.

The evolution of future carbon prices is uncertain and influenced by many factors (demand, supply, policy making). Figure 28 provides a range of carbon prices depending on different scenario such as:

- A baseline scenario based on the observed prices from 2012 to 2021 on the EU ETS market[38] , projected prices from 2022 to 2025[39] and linear projections from 2026 to 2050 based on price trends from 2012 to 2025.
- A minimum scenario setting an objective of EUR 150 in 2050[40]. Based on the observed price in 2022 and linear projections from 2023 to 2050 based on price trends from 2012 to 2025.
- A maximum scenario setting an objective of EUR 200 in 2050. Based on the observed price in 2022 and linear projections from 2023 to 2050 based on price trends from 2012 to 2025.

The observed value on the market in 2022 will be used for the computation of algae feed break even prices i.e. EUR 83.4/ton CO_2 or EUR 0.0834/kg CO_2.

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[37] Nitrous oxide (N2O) emitted in acid production and perfluorocarbons from aluminium production are also covered.

[38] Source: EEX Emissions market /EUA Primary Market Auction. https://www.eex.com/en/market-data/environmental-markets/eua-primary-auction-spotdownload). At the time of the consultation the prices in 2022 were available until 14/03/2022.

[39] https://www.theice.com/products/197/EUA-Futures/data?marketId=6734673&span=3

[40] Objectives of 150 € and 200 € in 2050 where set based on 2 studies: (1) EY Net Zero Centre (2022) Essential, expensive and evolving: The outlook for carbon credits and offsets. An EY Net Zero Centre report, EY, Sydney and (2) ESG research, Carbon Pricing, In Various Forms, Is Likely To Spread In The Move To Net Zero Aug. 9, 2022.

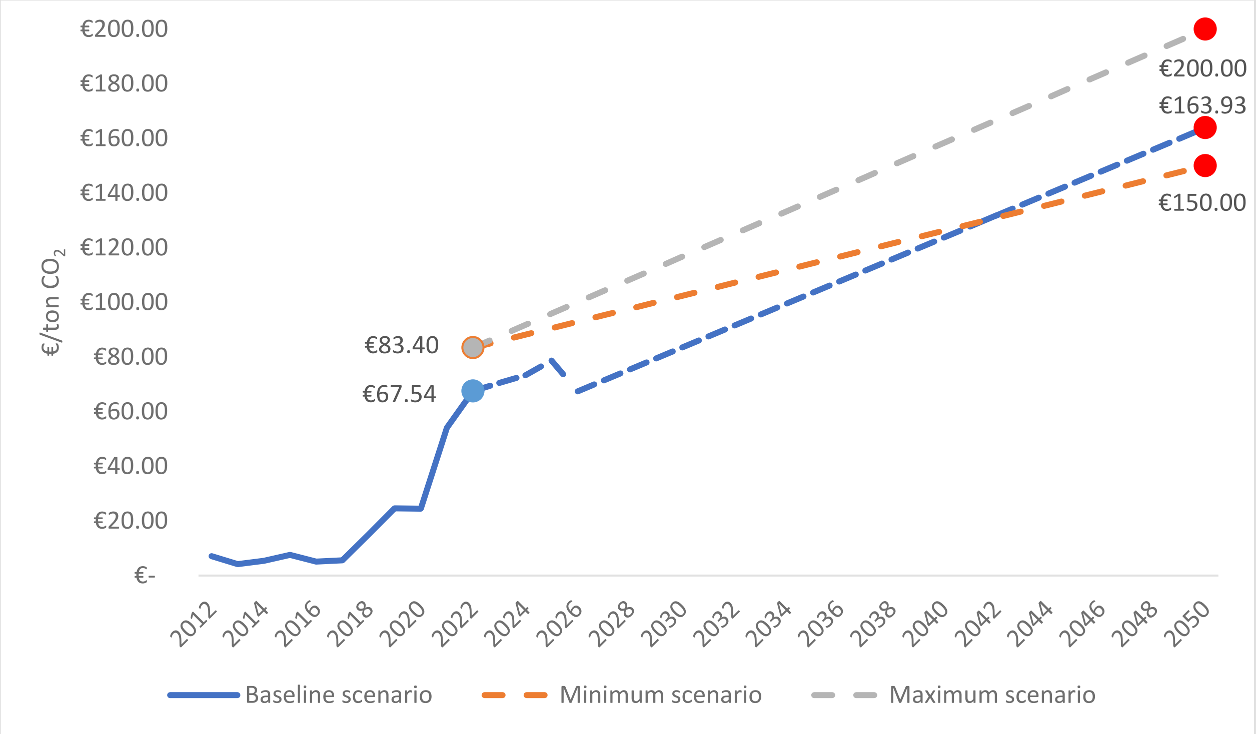

Figure 28 Evolution of the carbon price between 2012 and 2050 (based on projection from 2022 to 2050)

4.5.3 Results

Revenues from carbon is coming from the multiplication of carbon price on the market with the amount of carbon, basically 1.8 kg of carbon times EUR 0.08/kg of CO_2, making revenues from carbon very low. Therefore, we can expect that a high price of algae feed will be required to compensate. Results of the break-even algae feed prices are presented in Table 23. The average break-even algae feed price is EUR 113/kg crude proteins, which is higher than the soybeans meal price which was EUR 0.92/kg of crude proteins in 2021[41]. These results are based on a current carbon price. But even with a carbon price reaching EUR 200/ton CO_2 (Maximum scenario, see Figure 28) the price of algae would not be competitive with the actual price of soybeans meal.

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[41] Based on the "Pink sheet" data from the world bank commodity price data (https://www.worldbank.org/en/research/commodity-markets) translated into euros. The average market price of soybeans meal in 2021 was 0.41 €/kg. Knowing that soybean meal can provide 0.44 to 0.48 kg/kg crude protein, the price of 1kg of crude proteins from soybeans meal is between 0.85 to 0.92 €.

Table 23 Break-even algae feed prices

Production scenario	Cost price of algae production (EUR/kg DW)	Price of carbon (EUR/kgCO_2)	Carbon uptake (kgCO_2/kgDW)	Quantity of crude proteins (kg /kgDW)	Break-even algae feed prices (EUR/kg DW)
1	47.16 €	0.00834	1.8	0.285	164.94 €
2	38.43 €			0.285	134.33 €
3	9.61 €			0.285	33.19 €
4	15.68 €			0.3	51.76 €
5	30.40 €			0.3	100.84 €
6	43.94 €			0.3	145.98 €
7	3.37 €			0.285	11.30 €
8	39.25 €			0.21	186.21 €
9	31.62 €			0.21	149.88 €
10	31.17 €			0.21	147.72 €
11	6.46 €			0.52	12.13 €
12	5.18 €			0.52	9.68 €

4.6 Information feeding into the relational database

Only the results of the break-even carbon prices were included in the relational database. The data used to calculate the break-even carbon prices were inserted into the database (i.e. algae cost price; algae feed market price; CO_2 captured) along with the sources of each information. For algae cost prices, the link was made with the work done in a previous sheet (T21_Cult cost) where the cost of the 12 production scenarios presented in Table 12 were included as well as a base (average), conservative (minimum) and optimistic (maximum) scenario for each algae species.

Algae market prices were directly inserted into the sheet, including for each species only the minimum price as we have demonstrated that it is only relevant to compute break-even carbon price in some cases where the algae feed price is at its minimum (see Section 4.4). Finally, a single value of CO_2 captured was included. This resulted in 24 different scenarios per algae species (each of 12 production scenarios + base, conservative and optimistic scenario for each algae species). The break-even carbon price was calculated for each of the 24 scenarios but only the positive break-even carbon prices were displayed, namely the one presented in Table 20.

Table 24 provides an overview of the knowledge base. Cells are empty when data are not available, they are yellow when data are available but based on strong assumptions and they contain a "✓" when data are available.

Table 24 Overview of available data in the relational database resulting from Section 4

	Cultivator perspective break-even price		
	Algae feed market price	**CO2 captured**	**CO2 break-even price**
Ulva in photobioreactor			
Ulva in rope system			
Asparagopsis in photobioreactors			
Asparagopsis in rope system			
Saccharina in rope system			
Alaria in rope system			
Palmaria in rope system			
Haematococcus in photobioreactor	✓	✓	✓
Nannochloropsis in photobioreactor	✓	✓	✓
Chlorella in photobioreactor	✓	✓	✓
Spirulina in rope systems	✓	✓	✓

5 MAPPING THE GEOGRAPHICAL POTENTIAL FOR LAND-BASED MARINE ALGAE CULTIVATION AND RESULTING CARBON CAPTURE

5.1 Introduction

The objective is to map and estimate the potential for land-based marine algae cultivation and resulting carbon capture and resource use, feeding results into the relational database, and linking digital maps produced with the Atlas of the Seas.

5.2 Approach

The aim is to map the potential of the "Best available technology" and is therefore not subdivided into the scenarios used in the other sections. This activity uses results from the previous sections to determine the requirements for algae production and the feasibility to capture carbon from point sources. We aggregated the data collected in the literature review and from interviews into macro- and microalgae and open and closed production systems respectively which results in four combination possibilities. There is a huge variation in the data from literature. Therefore, we did not work with the data from the optimistic but from the base scenario. From the base scenario, mean values were calculated for the simplified production systems to assure equal weight for the production systems. The key spatial variables were identified as land availability, slope, and CO_2 availability from point sources.

Since there are no large-scale inland algae productions sites using CO_2 sources established, we had to work with assumptions about how far away the algae production sites can be located from the point sources. For the transportation of CO_2 from the point sources to the algae production, it is much more expensive to use pressurized systems. Pressurized CO_2 pipelines do already exist for other purposes. In the USA they are estimated up to 5000 miles and in Europe the OCAP is connecting Amsterdam and Rotterdam at a length in the order of magnitude of 60 km (Brown 2021 and Linde plc, 2022). The feasibility of pipelines for carbon capture and storage in the EU has been investigated (Santen et al, 2011). We therefore assume, that this infrastructure will be available for algae production.

As a consequence of the CO_2 pipelines, we expect not only that larger areas can be supplied with CO_2 but also that it will be possible to transport the CO_2 over distances to the algae production site. Thus, it is no longer necessary to estimate the limiting factor locally and the calculations will be carried out at country level. Other parameters, such as ground water levels, geological conditions and concrete water availability at the location were not included at this scale.

The data scanning at the start of the project revealed that the data at EU level is good compared to the available national data. Therefore, the only extrapolation was done for the amount of CO_2 and number of locations of small CO_2 sources.

5.3 Data collection and Methods

5.3.1 Spatial data

5.3.1.1 CO2 supply from point sources

For the EU wide mapping, the Large industrial complexes and combustion (LICC) (EEA 2022a) were used as CO_2 sources. For the case studies, point sources with amounts of CO_2 emissions could be obtained for France and the Netherlands (Ministère de la Transition écologique 2021, Rijksoverheid 2022). For Denmark, a list with the energy and heat production plants which deliver into the public network without information about the CO_2 emissions was available (Energistyrelsen 2022). For the LICC we assume that CO_2 transportation in future will not be limited by technology. As a simplified approach, we have included a circle with a radius of 10 km for the LICC and 1 km for small point sources as possible locations for algae production respectively.

5.3.1.2 Suitable land use classes

For all EU countries, 44 land cover classes are mapped in Corine Land Cover (CLC, EEA 2020a) at minimum mapping unit of 25 ha or 100 m width. For the case studies, we investigated national data sources which could give a better indication of available land, especially around industrial sites, but no sources with significantly better information were found, so that CLC was used for the case studies as well. Because of the minimum mapping unit, agriculture land includes small roads, houses, and other smaller areas. We therefore set the availability for agricultural land to 90%. For industrial and other suitable urban sites, it is difficult to determine, how much of the area is convertible. We did not find national data with better information. Therefore, we set the value to 5% of the chosen industrial classes in CLC, but this value can be higher, if algae production units can be combined with existing buildings, by e.g. installing them on roofs (Table 25).

Table 25 CLC land use classes and the percentage that is considered convertible to algae production. Wetlands and water bodies are not included in the table

Landuse Code	Landuse Name	Percentage convertible
111	Continuous urban fabric	
112	Discontinuous urban fabric	
121	Industrial or commercial units	5%
122	Road and rail networks and associated land	
123	Port areas	5%
124	Airports	5%
131	Mineral extraction sites	
132	Dump sites	
133	Construction sites	
141	Green urban areas	
142	Sport and leisure facilities	
211	Non-irrigated arable land	90%
212	Permanently irrigated land	90%
213	Rice fields	
221	Vineyards	
222	Fruit trees and berry plantations	
223	Olive groves	
231	Pastures	90%

241	Annual crops associated with permanent crops	
242	Complex cultivation patterns	
243	Land principally occupied by agriculture with significant areas of natural vegetation	
244	Agro-forestry areas	
311 – 333	Natural areas	
334	Burnt areas	
335	Glaciers and perpetual snow	

5.3.1.3 Slope

Data for the slope is available for all EU countries, except for Madeira, the Azores, the western part of the Canary Islands and French oversea areas (EEA 2016). Slopes less than 2% were considered suitable for algae production.

5.3.2 Calculation of the potential

5.3.2.1 Potential based on CO_2 availability

The technical potential is based on CO_2 availability from point sources. The amount of algae that can be produced given a certain amount of CO2 in a point source can be calculated according to:

$$yield\ = CR \cdot CFE \cdot CO2\_em \cdot (CC)^{-1} \cdot \tfrac{C}{CO2}WR \qquad \text{(Eq. 8)}$$

With the yield being the algae produced, CR the capture ratio, CFE the capture fixation efficiency, CO_2_em CO_2 emitted, CC carbon content and $\frac{C}{CO2}WR$ the C to CO_2 weight ratio, which results in:

$$\frac{tonne\ algae_{dw}}{yr} = \left[\frac{CO_2\ supplied}{CO_2\ point\ source}\right]\left[\frac{CO_2 fixated}{CO_2\ supplied}\right]\left[\frac{tonne\ CO_2}{yr}\right]\cdot\left[\frac{kg\ C}{kg\ algae_{dw}}\right]^{-1}\cdot\left[\frac{tonne\ C}{tonne\ CO_2}\right]$$

(Eq. 9)

$$\frac{tonne\ algae_{dw}}{yr} = \left[\frac{CO_2\ supplied}{CO_2\ point\ source}\right]\left[\frac{CO_2 fixated}{CO_2\ supplied}\right]\cdot\left[\frac{kg\ C}{kg\ algae_{dw}}\right]^{-1}\cdot\left[\frac{MW_{CO2}}{MW_{CO2}}\right] \qquad \text{(Eq. 10)}$$

$$\frac{tonne\ algae_{dw}}{yr} = \left[\frac{CO_2\ supplied}{CO_2\ point\ source}\right]\left[\frac{CO_2 fixated}{CO_2\ supplied}\right]\cdot\left[\frac{kg\ C}{kg\ algae_{dw}}\right]^{-1}\cdot\left[\frac{12.01}{44.01}\right] \qquad \text{(Eq. 11)}$$

The capture ratio is the amount of CO_2 captured per amount of CO_2 produced in the point source, and assuming all the CO_2 captured is supplied to a single algae farm this is equal to the ratio between the CO_2 supplied to the algae farm and the amount of CO_2 produced by the point source. The carbon capture ratio depends on the capture technology, but is typically 0.85 with ranges between 0.8 and 1.0 (Metz et al., 2005).

The carbon fixation efficiency [CO_2 fixated/CO_2 supplied] is the ratio between the amount of CO_2 fixated in the algae and the CO_2 supplied. (See the dedicated note). This currently states for the base scenario:

- 0.6 for closed systems.
- 0.3 for open systems.

The data for the carbon content [kg C/kg algae] varies per species as in the database. Typical values that can be taken as a simplified approach are:

- For macroalgae a typical content is 0.30 kg_C/kg_algae dw (range 0.22-0.37).
- For microalgae a typical content is 0.50 kg_C/kg_algae dw (range 0.43-0.53).

This data is based on the ranges available from Phyllis database[42]. Subsequently the CO_2 captured is:

$$CO_2\ captured = CR \cdot CFE \cdot CO2_{em} \qquad \text{(Eq. 12)}$$

With, CR being the capture ratio, CFE the capture fixation efficiency, CO_2_em CO_2.

5.3.2.2 Area based potential

Space requirements for the production systems are collected in the examination of the production systems. As described in the approach, the data was aggregated to four simplified production systems, resulting in:

- For macroalgae in an open system, the average area requirement is 38.7 ton_dw/ha.
- For macroalgae in a closed system, the average area requirement is 14.3 ton_dw/ha.
- For microalgae in an open system, the average area requirement is 137.5 ton_dw/ha.
- For microalgae in a closed system, the average area requirement is 40.6 ton_dw/ha.

For the selected suitable area, the potential was calculated as:

$$Yield = SA \cdot AR \qquad \text{(Eq. 13)}$$

And the CO_2 captured as:

$$CO2\ captured = Yield \cdot CC \cdot \left(\frac{C}{CO2}WR\right)^{-1} \qquad \text{(Eq. 14)}$$

With the yield being the algae produced, SA the suitable area determined in the spatial mapping, AR the area requirements, CC carbon content and $\frac{C}{CO2}WR$ the C to CO_2 weight ratio.

5.3.2.3 Effective potential

In the steps above, we calculated the potential based on the CO_2 availability and the area-based potential separately. Whether the potential based on the CO_2 availability or the area-based potential is higher, can differ for algae production systems and depends on the CO_2/area ratios per country. We therefore defined the effective potential as the potential supported by all necessary conditions. Thus, from the area based and the CO_2 based potential, the minimum values were chosen as effective potential per production type.

5.3.2.4 Best available technology

Similar to the effective potential, the best available technology is characterized by the highest possible algae production or CO2 capture respectively. Based on the effective

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[42] www.phyllis.nl - TNO, 2022.

potential, the production type with the highest yield or CO2 capture per country, is considered best available technology for that country.

5.3.3 Estimation of additional factors

5.3.3.1 Nutrient uptake

We did not consider nutrient uptake as a limiting factor in the mapping of the potential but added the required N uptake to produce the mass of the effective potential. The nutrient uptake was calculated as:

$$N\ uptake = Yield \cdot NC \qquad \text{(Eq. 15)}$$

With N uptake as nitrogen uptake, and NC the Nitrogen content. The Nitrogen content was collected in the examination of the production systems:

- Macroalgae have an average Nitrogen content of 3.32%.
- Microalgae have an average Nitrogen content of 5.36%.

5.3.3.2 Water scarcity

For the mapping it is assumed, that the water will be recycled. Data on water consumption was acquired as part of the breakeven point calculation and varies between 0.53 m^3/kg DW/ha for bioreactors and 149.12 m^3/kg DW/ha for photobioreactors and a raceway pond. Nogueira Junior et al. (2018) estimated the requirements to 1564 l/kg algae in ponds and 372 l/kg algae- in photobioreactors. Water was not included in the mapping as limiting factor but added as additional information. The Water Exploitation Index plus (WEI+) during the summer 2015 was aggregated on country level and used as an indicator for countries with limited water resources (EEA 2022b).

5.3.4 Approach for extrapolation from the case studies

For the case studies, point sources with amounts of CO_2 emissions could be obtained for France and the Netherlands (Ministère de la Transition écologique 2021, Rijksoverheid 2022). For Denmark, a list with the energy and heat production plants which deliver into the public network without CO_2 emissions was available (Energistyrelsen 2022). The Danish data includes the capacity, but not all stationary point sources with emission values. Thus, only the French and Dutch values were used to develop the extrapolation factors. The Danish data was used to calculate the area available for algae production in Denmark.

We used the amount of CO_2 and the area around the CO_2 sources from the two case studies with complete input to calculate the ratio between the complete dataset and LICC. This ratio was applied to extrapolate from the CO_2 emissions based on the LICC data and the convertible area around the LICC positions for the EU-wide mapping (Table 26).

CO_2. production values for France and the Netherlands vary highly. France had in 2021 the highest share of nuclear power worldwide with 69% and the Netherlands produced only a small amount of their energy (3.1%) from nuclear power (Wikipedia 2022). With the current share of combustion for energy production, the use of nuclear power leads typically to less CO_2 emissions from big powerplants and thereby to a higher ratio between small CO_2 sources and LICC. The ratio is influenced by other factors, such as the amount of big CO_2 emitting industries. Comparing the CO_2 intensity of electricity generation in the EU, France lies 74% below and the Netherlands is 24 % above the EU wide average in 2017 (EEA 2020b). We do not have other data sources to estimate the ratio of small stationary sources in relation to the LICC and have therefore used the average to represent the powermix in Europe to some degree. By including France, the small sources are probably slightly overestimated.

Table 26 Extrapolation factor derived from LICC and national data

Country code	CO_2 from LICC [kg/yr]	CO_2 case data [kg/yr]	CO_2 ratio	Buffer area around all sources	Buffer area around small sources	Area ratio
FR	7.7E+10	1.8E+11	2.399167	40518.9193	2550.973	0.062958
NL	8.24E+10	8.9E+10	1.076828	10428.39438	2428.451	0.232869
Average	1.59E+11	2.7E+11	1.715437	50947.31368	4979.424	0.097737

5.4 Results at EU-level

Based on the LICC as input data with a factor from the 2 case studies, we estimated the CO_2 emissions from point sources to be 2251 mill. Ton CO_2/year and the potentially convertible area to algae production as 106,960 km2 (Figure 29, annex 11.8, Table 43). The relation between CO_2 emissions and convertible area per country varies strongly. The two case studies that were used to develop the extrapolation factors are close to the average for all countries. The country with the lowest CO_2 emissions from point sources in relation to convertible area is Denmark (DK) and the two countries with the highest lowest CO_2 emissions from point sources in relation to convertible area are Malta (MT) and Portugal (PT) (Figure 29). These three countries are either for all production systems limited by the available CO_2 (DK) or by the convertible area (MT and PT). For the other countries the limiting factor can vary for the different production systems (Annex 11.8, Table 43).

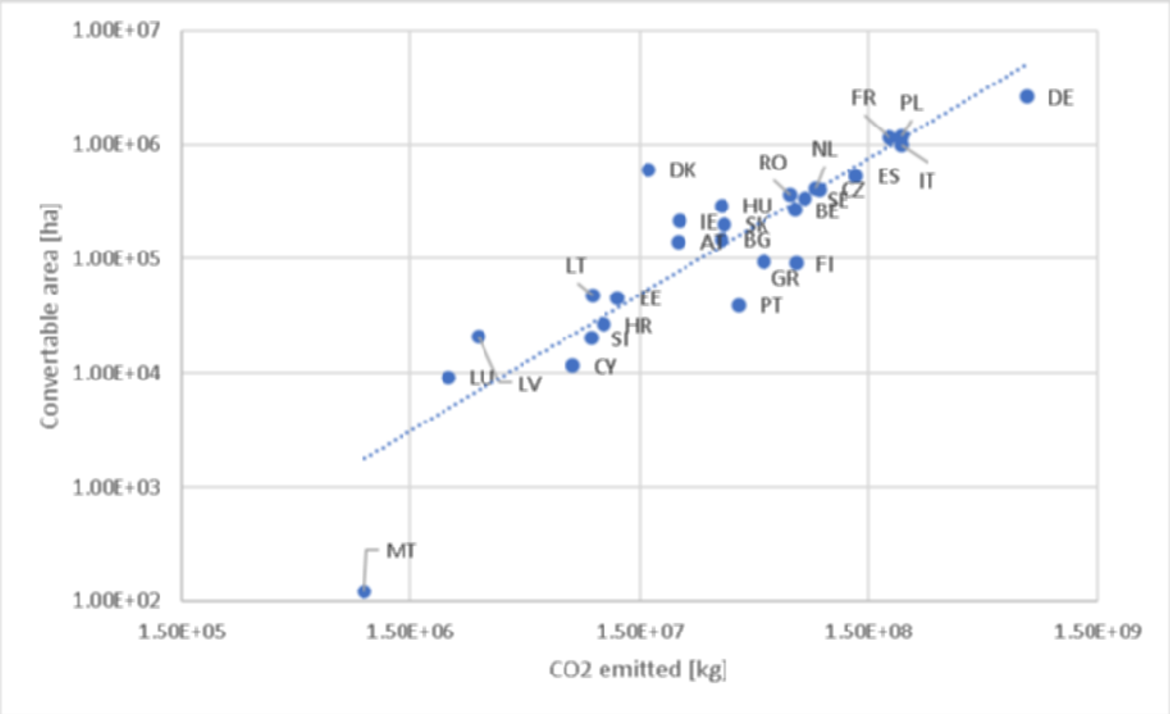
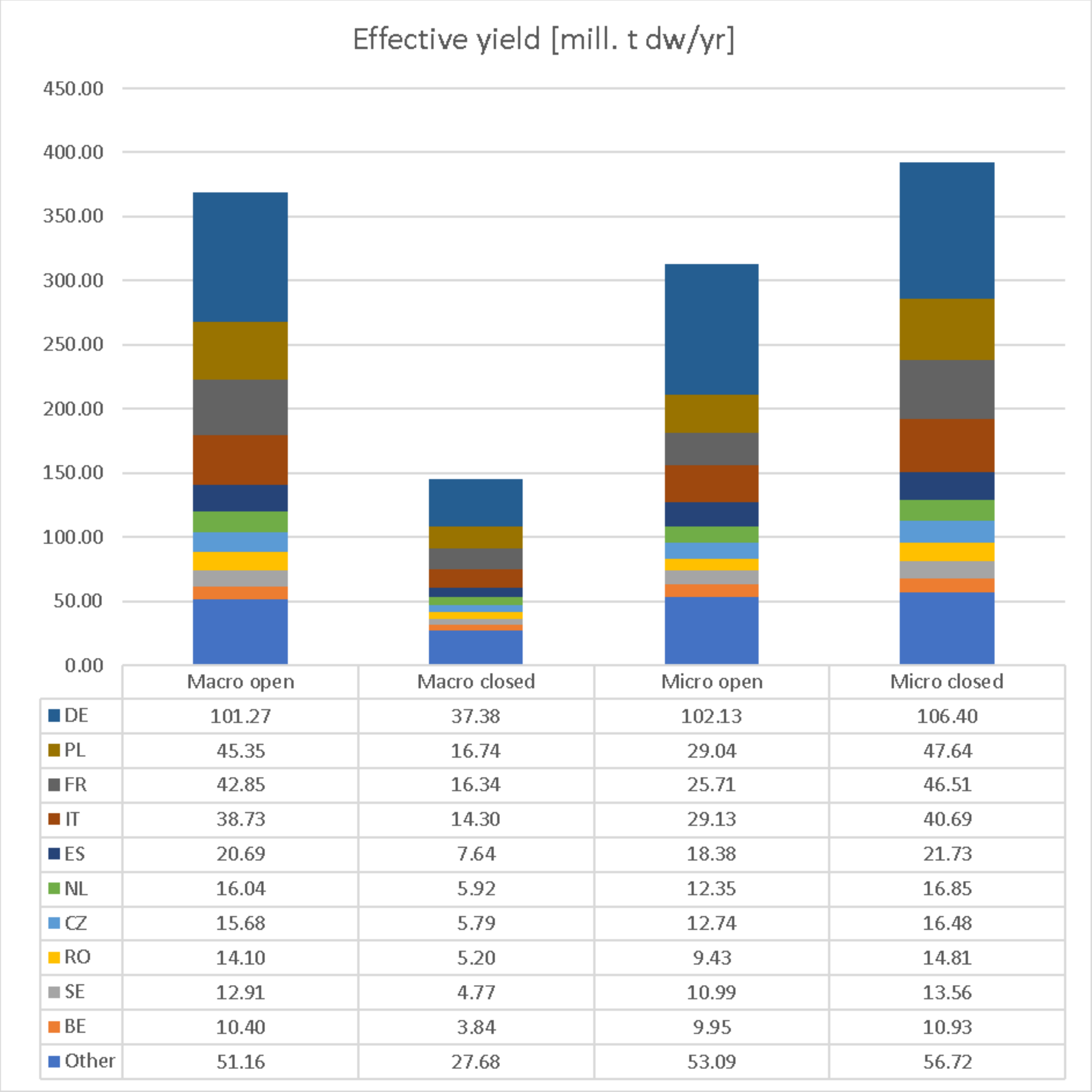


Figure 29 Relation between CO_2 emitted from stationary point sources and convertible area per country

5.4.1 Potential feed production

At EU level when only choosing one system, the yield values range from 146 mill. to 392 mill. ton dw/yr (Figure 30, Annex 11.8, Table 45). The limiting factor is predominantly the available area. For those countries with more CO_2 available in relation to the area, the microalgae systems are more effective, for the highest CO_2 to area ratio the microalgae in closed systems. For 19 countries the system that provides the highest yields and CO_2 capture is microalgae production in a closed system. For the other countries microalgae production in open systems is the most effective system except for Denmark, where macroalgae production in a closed system is optimal. (Annex 11.8, Table 43) The results for the most effective system per country are shown in Figure 31.



	Macro open	Macro closed	Micro open	Micro closed
■ DE	101.27	37.38	102.13	106.40
■ PL	45.35	16.74	29.04	47.64
■ FR	42.85	16.34	25.71	46.51
■ IT	38.73	14.30	29.13	40.69
■ ES	20.69	7.64	18.38	21.73
■ NL	16.04	5.92	12.35	16.85
■ CZ	15.68	5.79	12.74	16.48
■ RO	14.10	5.20	9.43	14.81
■ SE	12.91	4.77	10.99	13.56
■ BE	10.40	3.84	9.95	10.93
■ Other	51.16	27.68	53.09	56.72

Figure 30 Effective potential for feed production [mill. t dw/yr] from the four simplified production systems. Only the 10 countries with the biggest potential are shown separately, the other countries are aggregated, and the values can be found in Annex 11.8, Table 43

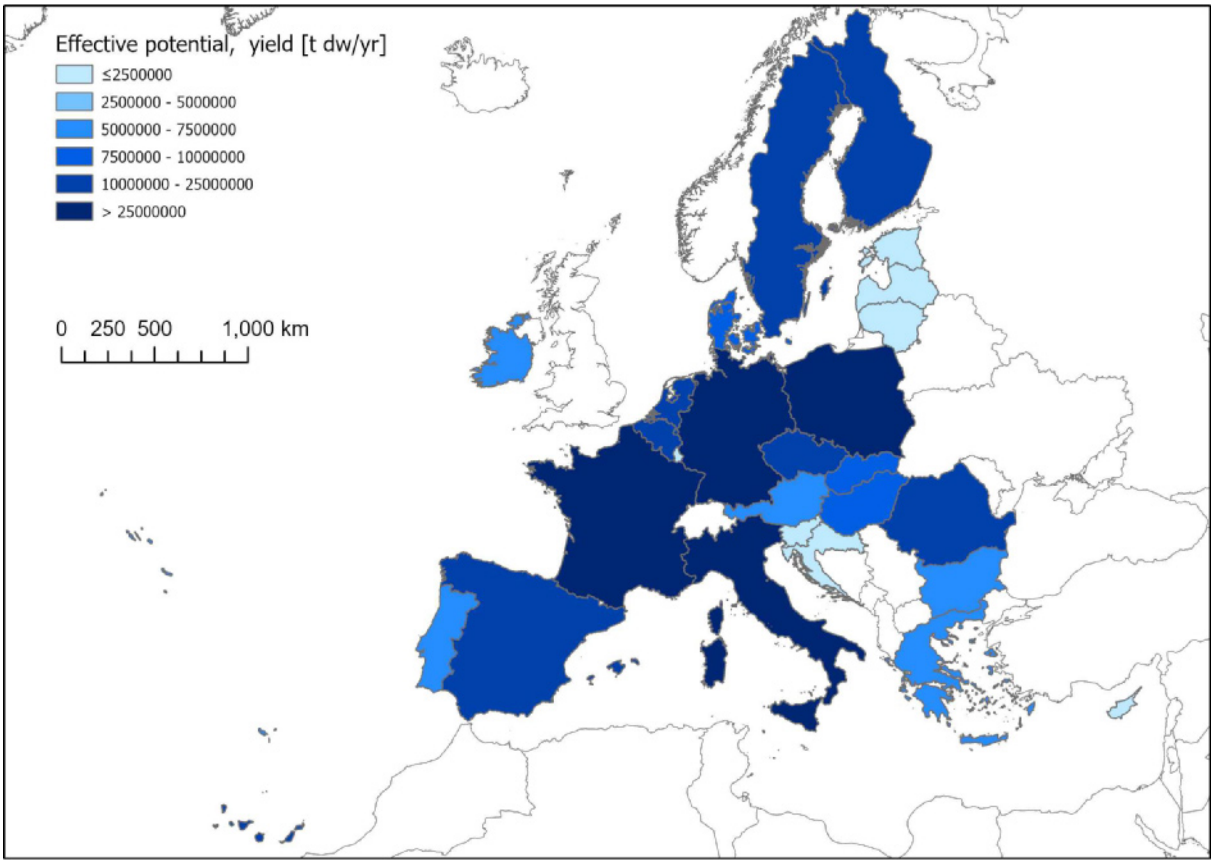
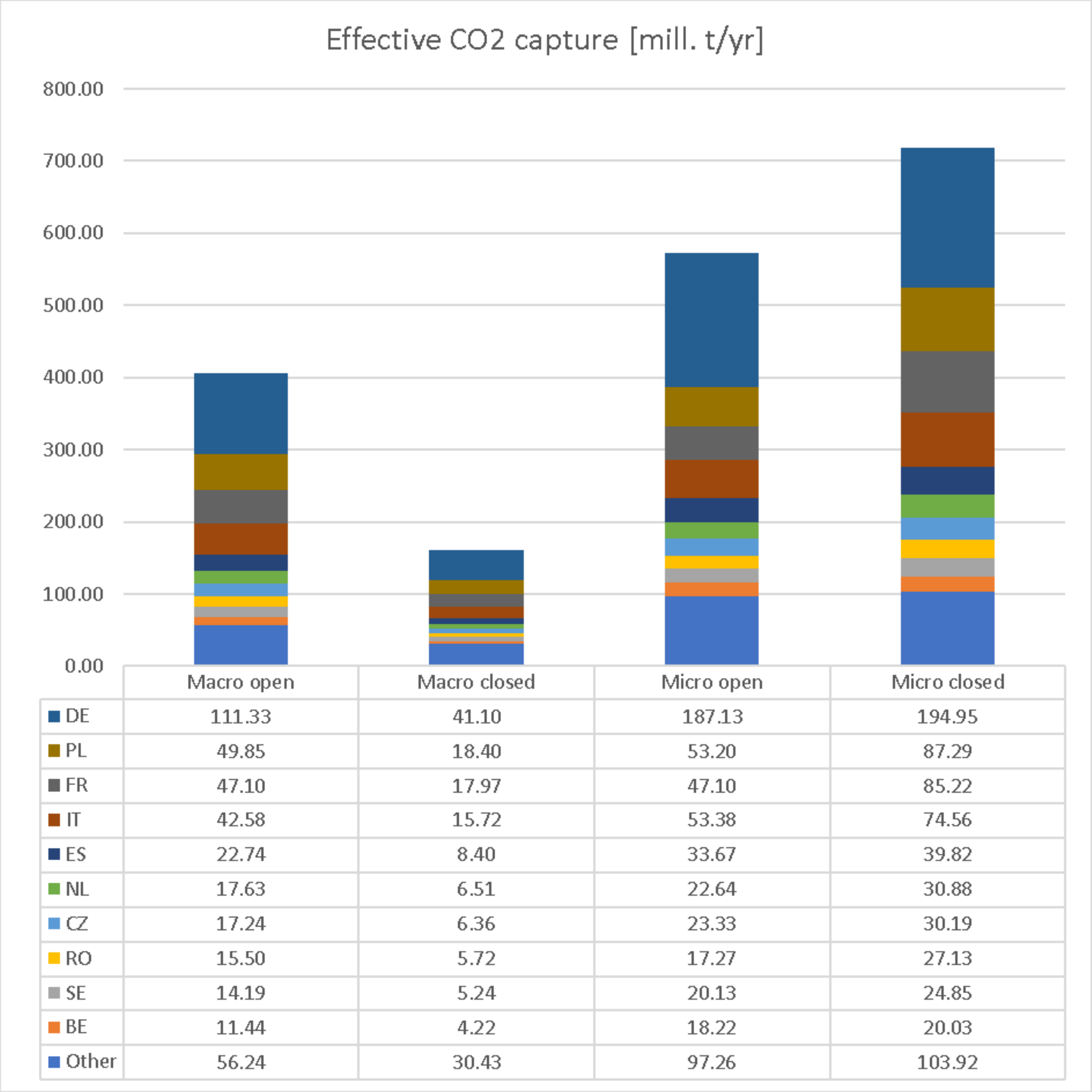


Figure 31 Effective potential for feed production per country

5.4.2 Potential CO_2 Capture

The total amount CO_2 captured for the four production systems, ranges from 160 mill. To 719 mill. T CO_2/yr at EU level (Figure 32, Annex 11.8, Table 44). The results for the most effective system per country are shown in Figure 33.



	Macro open	Macro closed	Micro open	Micro closed
■ DE	111.33	41.10	187.13	194.95
■ PL	49.85	18.40	53.20	87.29
■ FR	47.10	17.97	47.10	85.22
■ IT	42.58	15.72	53.38	74.56
■ ES	22.74	8.40	33.67	39.82
■ NL	17.63	6.51	22.64	30.88
■ CZ	17.24	6.36	23.33	30.19
■ RO	15.50	5.72	17.27	27.13
■ SE	14.19	5.24	20.13	24.85
■ BE	11.44	4.22	18.22	20.03
■ Other	56.24	30.43	97.26	103.92

Figure 32 Effective CO_2 capture [mill. t/yr] for the four production systems. Only the 10 countries with the biggest potential are shown separately, the other countries are aggregated, and the values can be found in Annex 11.8, Table 44

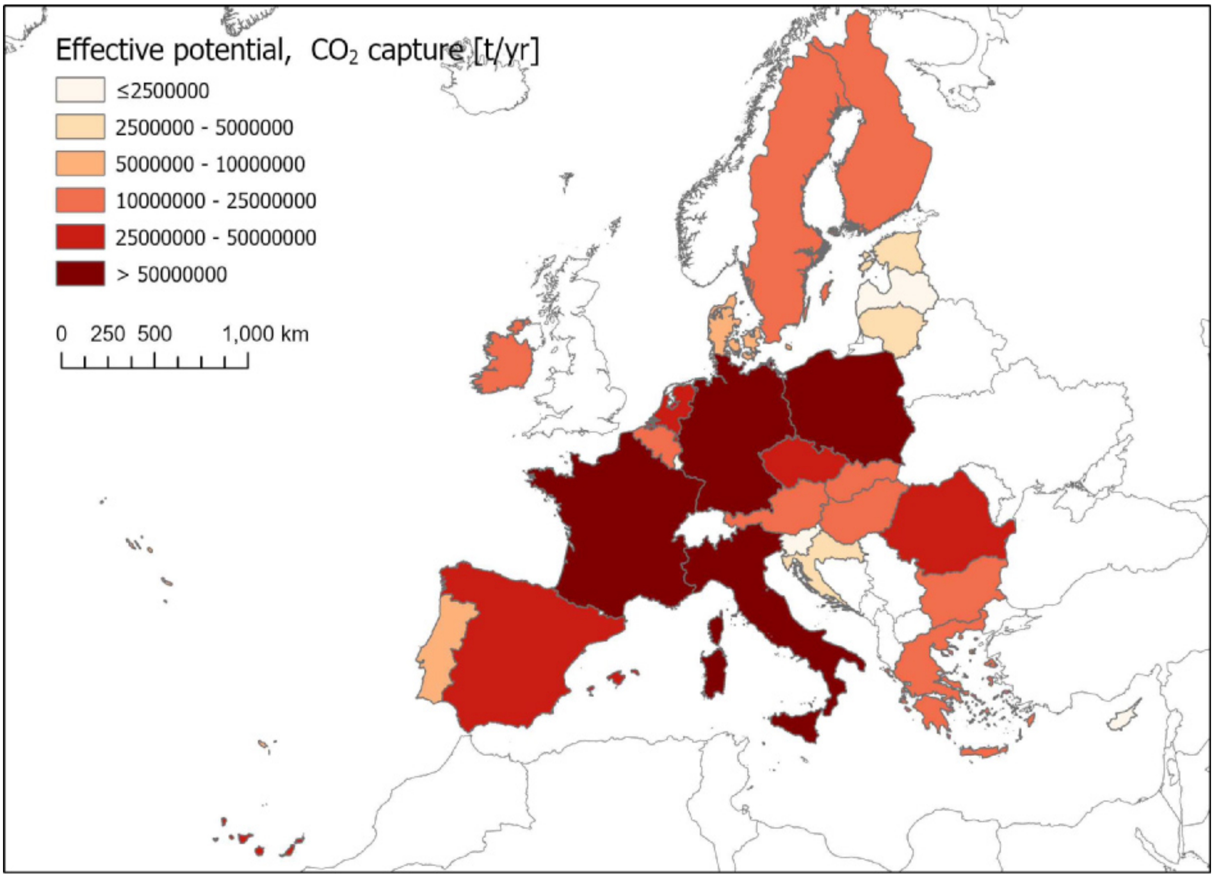
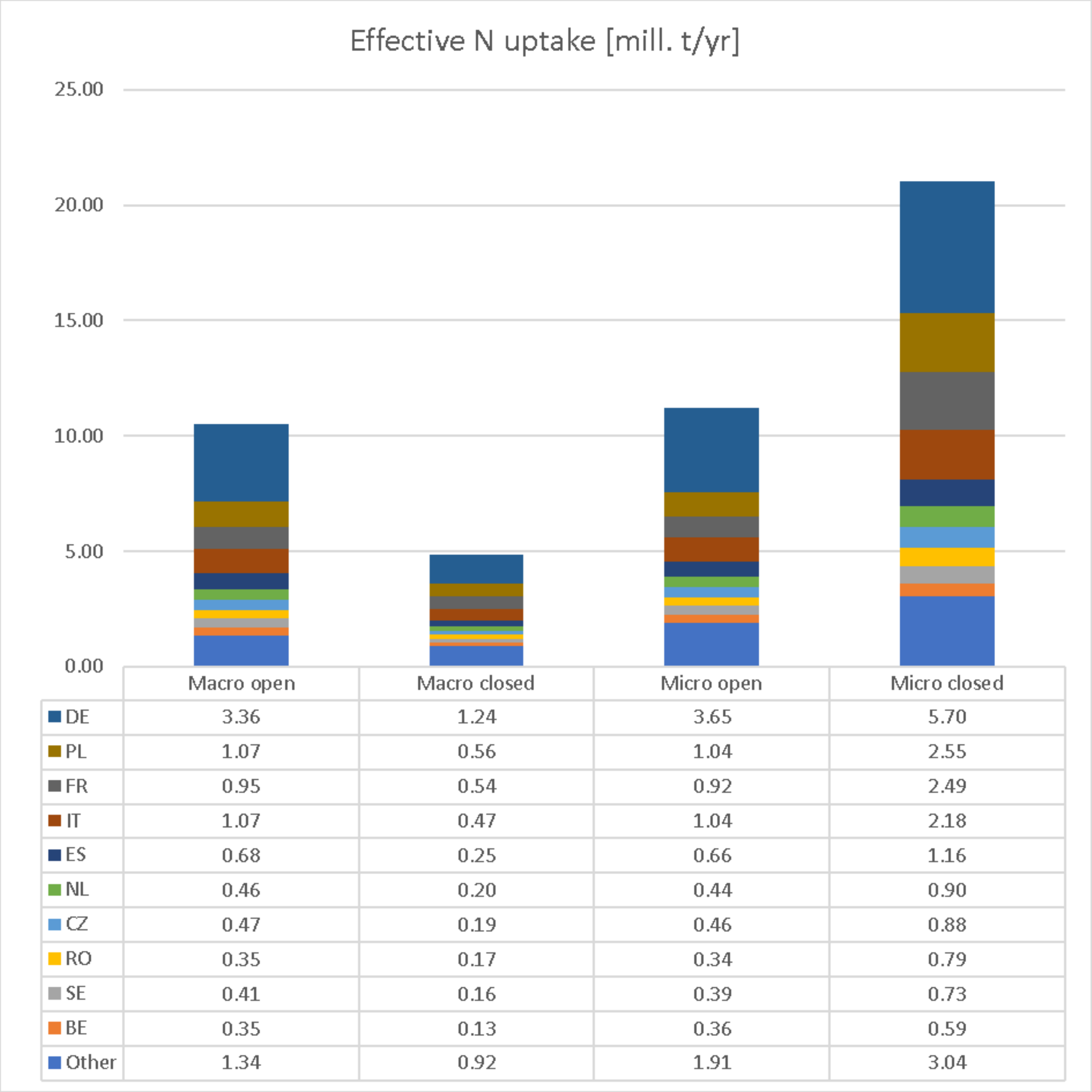


Figure 33 Effective potential for CO_2 capture per country

5.4.3 Potential nutrient uptake and water limitations

The total amount nitrogen uptake for the four production systems, ranges from 4.83 mill.to 21.0 mill. Ton N/yr at EU level (Figure 34, Annex 11.8, Table 45). The results for the most effective system per country are shown in Figure 35. The Water Exploitation Index plus (WEI+) aggregated per country delivers information about the possible water supply limitations. It is expected that countries with already high-water exploitation during summer can experience limitations for algae production in open systems (Annex 11.8, Table 45).



	Macro open	Macro closed	Micro open	Micro closed
DE	3.36	1.24	3.65	5.70
PL	1.07	0.56	1.04	2.55
FR	0.95	0.54	0.92	2.49
IT	1.07	0.47	1.04	2.18
ES	0.68	0.25	0.66	1.16
NL	0.46	0.20	0.44	0.90
CZ	0.47	0.19	0.46	0.88
RO	0.35	0.17	0.34	0.79
SE	0.41	0.16	0.39	0.73
BE	0.35	0.13	0.36	0.59
Other	1.34	0.92	1.91	3.04

Figure 34 Effective potential for nitrogen uptake [mill. t/yr] from the four simplified production systems. Only the 10 countries with the biggest potential are shown separately, the other countries are aggregated, and the values can be found in Annex 11.8, Table 45)

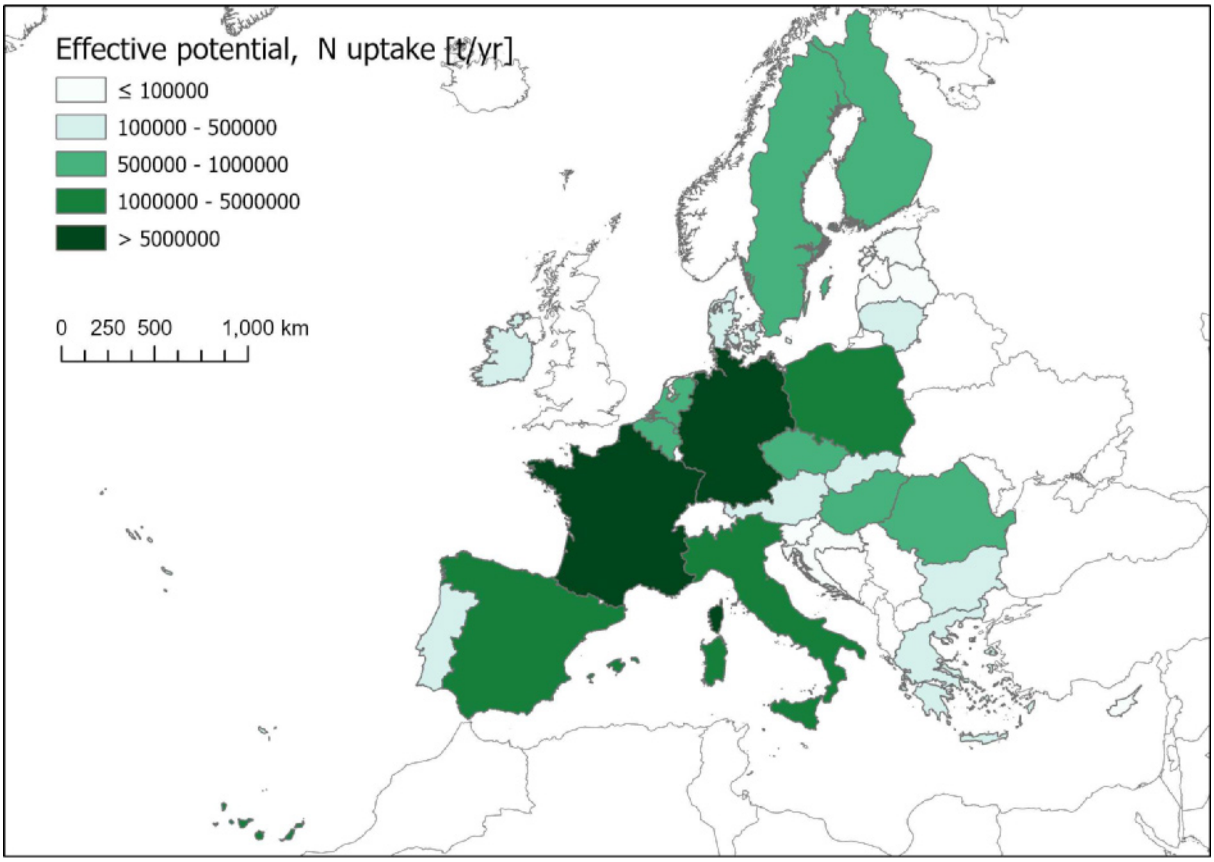


Figure 35 Effective potential for N uptake per country

5.4.4 Uncertainties and limitations

The mapping results are a rough estimate for the potential for land-based algae production with CO_2 supply from emissions. It is based on a limited set of parameters and assumptions that must be fulfilled. Simplified requirements, along with carbon and nitrogen content mean that the expected range for the full set of possible production systems is higher. With the current setting the most effective potential for feed production and CO_2 capture was achieved by the same system, but not for nitrogen uptake. With more variation in the parameters, the most effective solution can also vary between feed production and CO_2 capture. We did not investigate other components of the algae composition and the demand for these components from livestock production. Water supply and nutrient availability were not considered as limiting factors for the calculation.

The chosen search distance around the CO_2 sources requires that CO_2 pipelines will be available. Otherwise, not only would the available area decrease significantly, but it would also be necessary to have a sufficient amount of convertible area around the single CO_2 sources. Agricultural land is the dominating land type contributing to the convertible land. The chosen conversion rate for agricultural land is high. Due to other factors, the area available for algae production might be lower and differ for the different production systems. Geological conditions and groundwater levels can influence the possibility for construction of buildings or pond systems and planning laws can prohibit conversion.

The variation of growth factors throughout Europe were not considered. The data did not allow to adjust the mapping parameters dependent on light availability or the length of the growing season. The calculation of the CO_2 capture in the mapping is purely considering the uptake of CO_2 from the point source. The GHG emission estimation concludes that the total CO_2 footprint is high and has a wide range. The studies that the estimation is based on, did not always consider CO_2 capture. For the selection of the land use and carbon capture method, we therefore suggest considering the total CO_2 footprint including CO_2 capture in comparison to the replaced uses and alternative CO_2 capture methods. Due to the conclusion that the break-even point of algae production for feed production, including the sale of carbon credits, is not competitive at the moment, it is not possible to estimate where the algae production would be financially feasible.

5.4.5 What are the key challenges and constraints to cultivation/large scale development?

The challenges and constraints for scaling up cultivation of algae in EU are many and diverse. Commonly referred to examples include regulatory barriers, complexity of the administrative procedures and regulations, the still low consumer awareness, the small market size, the sustainability of the production chain and the lack of credits for the environmental services provided by algae production (Araujo et al, 2021). In this study, stakeholders in the part of the algae value chain related to production/cultivation, point to different challenges for the different species and production systems.

General challenges however, are; 1) high costs of both establishing (CAPEX) and running (OPEX) an algae production facility, which gives a reduced competitive market advantage for European producers in competition with countries from the global south, where cost of labour is lower, 2) Regulatory barriers are also mentioned in relation to obtaining the necessary permits for cultivation, for the potential for cultivation of non-indigenous, and inconsistency in the frameworks for organic certification of the produced algae between marine and land-based systems, 3) Technology readiness level of both cultivation systems and seed production, 4) the lack of/need for standardised knowledge exchange and educated and trained 'algae cultivation specialists' with a back-ground in science as well as practice, and 5) the need for a robust value chain with security for all parts of the value chain, both production and utilisation of the algae biomass.

5.5 Information feeding into the relational database and into the Atlas of the Seas

The results of the mapping feed into the database and are structured as described in Table 27. The data is reflecting the steps of calculating the potential limited by CO_2 supply, available area and the effective potential which includes nitrogen uptake.

Table 27 Data contained in the database. Macro and micro are used as shortened form for macro- and microalgae and open and closed describe the grouping of the production systems

Column header	Description
Country code	Country code
CO_2 emitted [t/yr]	Amount of CO_2 from point sources
Yield from makro open CO_2based [t dw/yr]	Feed production based on available CO_2
Yield macro closed CO_2based [t dw/yr]	
Yield micro open CO_2based [t dw/yr]	
Yield micro closed CO_2 based [t dw/yr]	
CO_2 capture open CO_2 based [t/yr]	CO2 captured based on available CO_2

CO_2 capture closed CO_2 based [t/yr]	
ha_agr_ind_convertable	Area available for conversion to algae production
Yield macro open [t dw/yr]	Feed production based on available area
Yield macro closed areabased [t dw/yr]	
Yield micro open areabased [t dw/yr]	
Yield micro closed areabased [t dw/yr]	
CO_2 capture macro open areabased [t/yr]	CO_2 captured based on available area
CO_2 capt macro closed areabased [t/yr]	
CO_2 capture micro open areabased [t/yr]	
CO_2 capt micro closed areabased [t/yr]	
Number of systems that are CO_2 limited	Number of systems per country that are CO_2 limited
Effective yield macro open [t dw/yr]	Effective potential for feed production and CO_2 capture which is supported by both limiting factors
Effective yield macro closed [t dw/yr]	
Effective yield micro open [t dw/yr]	
Effective yield micro closed [t dw/yr]	
Effective CO_2 capture macro open [t/yr]	
Effective CO_2 capt macro closed [t/yr]	
Effective CO_2 capture micro open [t/yr]	
Effective CO_2 capt micro closed [t/yr]	
Most effective system	Most effective system
N uptake macro open [t/yr]	N uptake by the chosen effective potential
N uptake macro closed [t/yr]	
N uptake micro open [t/yr]	
N uptake micro closed [t/yr]	
Water Exploitation Index summer [%]	
Most effective yield all systems	

Most effective CO_2 capture all systems	The effective potential across all production systems for yield, CO_2 capture and N uptake.
Most effective N uptake all systems	

Table 28 provides an overview of the knowledge base. Cells are empty when data are not available, they are yellow when data are available but based on strong assumptions and they contain a "✓" when data are available. Table 29 provides an overview of the geographic data that is ready for upload to the European Atlas of the Seas (europa.eu).

Table 28 Overview of available data in the relational database resulting from Section 5

	All EU countries
CO_2 extrapolated	✓
Available area	✓
Yield for the simplified production systems	✓
Effective yield for the simplified production systems and total per country	✓
CO_2 captured for the simplified production systems	✓
Effective CO_2 captured for the simplified production systems and total per country	✓
N-update for the simplified production systems	✓
Effective N-uptake for the simplified production systems and total per country	✓

Table 29 Overview of available data that can be uploaded to the European Atlas of the Seas

	All EU countries
Effective potential for feed production per country	✓
Effective potential for CO_2 capture per country	✓
Effective potential for N uptake per country	✓

5.6 Discussion

We calculated the potential for algae production based on CO_2 from point sources country wise for macroalgae and microalgae in open and closed systems respectively. This resulted at EU level with the same production system EU wide, in a potential yield from algae production from 146 mill.to 406 mill. ton dw/yr, while the potential amount of CO_2 captured ranges from 160 mill. to 719 mill. Ton CO_2/yr. The possible nitrogen uptake from this production would vary between 4.89 mill.to 30.8 mill. ton N/yr at EU level. With the selected settings, it depends on the available CO_2 to available land ratio and the chosen production system, if the limiting factor for production is the CO_2 emitted or the available area. The available area depends heavily on the assumption, that algae production can be connected to the sources via CO_2 pipelines.

The best technical solution is depends in detail on the combination of other factors and the specific goals for production. It is expected that production costs and demand will have a great influence and will lead to a mixture of systems.

For the mapping on EU scale, it would be possible to consider the total CO_2 footprint and to conduct a similar estimate for the marine production systems. Additionally, we suggest selecting smaller test cases for more detailed analysis, where the factors that are mentioned as uncertainties and limitations above are considered.

We have prepared three maps with the effective potentials per country which are ready to be included in the European Atlas of the Seas. Evaluating the current contents of the European Atlas of the Seas, it was observed that the Atlas is restricted to factual information. The results of the mapping study in this report, however, presents the results in an exploratory scenario study under highly uncertain assumptions. The authors feel that including the geographic data with the effective potentials per country is not within the philosophy of the atlas of the seas and it would be better, to publish them in close connection to the report. The upload to the European Atlas of the Seas is technically possible though and the layers have been included with the deliverables of this study for this and other purposes.

6 POTENTIAL ANIMAL FEED REQUIREMENTS AND METHANE EMISSION REDUCTIONS THAT COULD BE MET BY ALGAE

6.1 Introduction

The objectives of this section are to:

- Establish the animal species-dependent potential for inclusion of algae in animal diets.
- Evaluate the potential to employ anti-methanogenic algae as a strategy to target enteric methane emission from ruminant livestock.
- Identify (where relevant) needs for appropriate technologies (e.g. post-harvest, breeding) to optimize nutritional value of algae.

To achieve these objectives, first the key nutritional requirements of selected categories of intensively reared food-producing animals are presented in Section 6.2. Information on livestock, poultry and fish production systems at the member state and EU scale, the total annual production of milk, beef, pork, eggs, chicken meat and salmon fillet in the EU, and feed conversion rates (kg of diet dry matter (DM) consumed per kg of produce) typical for intensive production systems for the selected categories of food-producing animals are given in the section 6.3.

The following section (6.4) provides a discussion of the nutritional properties of the selected species of algae when included in diets for the different categories of food-producing animals and the potential methane mitigating properties of algae in ruminants. Potential barriers for dietary inclusion of algae are identified, and a recommended maximal dietary inclusion rate (RMDIR) was proposed for each algae species when fed to each of the different animal categories considering animal productivity and health aspects. Furthermore, section 6.4 estimates the total quantity of feed DM consumed for production of each of the animal-derived foods, and estimates are provided for the market potential for algae when fed at the RMDIR in each of the animal production systems.

Finally, Section 6.6 presents the data included in the Relational database and the calculations of (based on data compiled in other tasks): feed conversion rates (g of diet DM per kg of animal food produce), recommended maximal dietary inclusion rate (RMDIR = maximal % algae DM in total diet DM) for each alga species (provided the species is not combined with other species in the diet) for each of the selected animal species, annual demand for algae DM production to be able to feed at the RMDIR, estimated quantities (tons DM per year) of spared conventional feed DM at the RMDIR for algae, estimated quantity (tons DM per year) of spared conventional feed protein at the RMDIR for algae, estimated total annual reduction in enteric methane emission from ruminants (%) at the RMDIR for the algae species with anti-methanogenic properties.

Overall, the discussions in Section 6.2, Section 6.3, and Section 6.4 are based on data derived from a compiled Supplementary Table 6-1, which provides information on nutritional requirements of selected categories of intensively reared livestock, poultry and fish used for production of animal-derived foods, as well as scientific evidence, to the extent it is available, regarding nutritional properties of the individual algae species for the selected categories of food-producing animals. In addition, factors which may limit the dietary inclusion of algae in diets for these categories of animals are also identified. Lastly, estimated proportions of animal diets (% of diet DM) that could be met by algae and estimated achievable reductions in enteric methane emission (%) by addition of algae with anti-methanogenic properties to diets for ruminants are presented and included in the relational database.

It must be pointed out that valid information on nutritional properties of many of the selected algae species, when fed to the selected categories of food-producing animals, is very scarce and often non-existent, as evident from Supplementary Table 6-1. When information was scarce or non-existent for a target animal species, data could sometimes be retrieved from other similar animal species. The estimates for achievable RMDIR's for different categories of animals without compromising animal productivity or health is hence associated with great insecurity, and this is an area, where a substantial research effort is needed in the future. In general, low digestibility and/or high contents of certain critical minerals were identified as significant biological barriers for dietary inclusion for certain macroalgae species, and this is an area where significant research and development is also needed to overcome such barriers by application of cost-efficient technologies, e.g. post-harvest processing and algae breeding for nutritional value.

6.2 Assessment of nutritional requirements of livestock, poultry and fish

6.2.1 Selection of animal species

The purpose of this assessment was to provide information about:

- The nutritional requirements of the following categories of food-producing animals in intensive production systems: lactating dairy cows, fattening calves, fattening pigs, egg-laying hens, broilers, and growers of Atlantic salmon.
- Existing upper limits for dietary contents of critical components (e.g., minerals) according to EU regulations that potentially could restrict the use of algae as feed for the selected food-producing animals.

This information will be used in section 6.4 to identify needs for post-harvest technologies to improve nutritional quality and overcome limitations for inclusion in animal diets.

6.2.2 Approach

It was decided in this task to focus on the most important food producing animals from a commercial perspective in intensive production systems, namely lactating dairy cows, fattening bulls, fattening pigs, egg-laying hens, broilers, and growers of Atlantic salmon. These categories reflect different animal species and types of produce as well as differences in terms of requirements for nutritional properties of the diet. In the Supplementary Table 6-1, requirements for dietary provision of energy and individual nutrients for those species have been listed, as well as upper limits for contents of certain critical minerals from an animal health perspective.

The livestock sectors in different European countries have developed various distinct systems to calculate nutritional requirements and express dietary recommendations for optimal performance of food-producing animals, and the similarities and variations in the terms used to express nutrient requirements have been exemplified by compilation of recommendations used in the three EU member states Denmark, Netherlands, and France. Some systems are used in several different countries within the EU, sometimes in slightly modified versions. The National Research Council (NRC) of the USA (NRC, 2021) publishes minimal nutrient requirements of cattle, pigs, and poultry (to avoid development of deficiency symptoms) and upper limits for minerals and vitamins (to avoid toxicity). The NRC values are updated more or less frequently and provide a basis for dietary recommendations for particular minerals and vitamins in many countries. It is worth noting that dietary recommendations were not available from all the three member states in the same level of detail. In the case of cattle, the NorFor (Volden, 2011), CVB (CVB, 2021) and NRC provided recommendation for energy, protein, minerals, and vitamins, whereas the French INRA model (Agabriel, 2007) provided data for energy, protein, Ca and P. For pigs, dietary recommendations were quite similar apart from France, where nutrient requirement tables were not available. For poultry, the large breeding companies selling different breeds of chicken also provide dietary recommendations, which are the most accurate for the specific genetic make-up of the birds. The CVB model is also widely used for poultry. Atlantic salmon is the most important marine fish farmed in Europe, but nutritional requirements are less well-defined compared to the other animal species. The reported values by FAO (FAO, 2022) for Atlantic salmon growers will be used as well as values from the NRC.

6.2.3 Data considered

The different systems used in different countries to describe nutritional value of a feed require information about two main parameters: 1) the chemical composition and 2) the digestibility (and for ruminants: rumen degradability) and metabolization of energy and protein. Energy content can be expressed in different ways, but in all the species it is either expressed as metabolizable energy (ME), which accounts for energy losses in faeces, urine and methane, or net energy (NE) which accounts for also heat loss associated with ingestion and metabolism of the feed components. ME thus represent the absorbed amount of energy available for metabolism in the body, and NE represents the amount of energy that can be directly recovered in produce (maintenance heat production, energy deposited in tissues, milk, eggs). Protein quality for monogastric animals depends on the profile of absorbable amino acids, and protein recommendations consider the ratios between standardized ileal (i.e., small intestinal) digested (SID) amounts of each of the amino acids as compared to an ideal protein, and the SID for each amino acid is expressed relative to SID Lys.

For cattle, requirements for individual amino acids are not typically reported because of the symbiotic cow-rumen microbiota relationship developed during evolution, where rumen microorganisms are able to synthesize the essential amino acids (EAA), provided rumen degradable sources of N and carbon are available. This makes ruminant animals quite independent of amino acid composition in the diet.

Chemical analysis can provide information about the gross content of nutrients in a feed, but they do not provide information on how well the animal will be able to digest, absorb and metabolize these nutrients. It is therefore imperative to have information about the digestibility of individual nutrients in a feed, since knowledge about DM and chemical composition of the DM does not provide sufficient information about provision of digestible and metabolizable nutrients and energy.

The presence of antinutritional factors is also an important component of nutritional value. For all species, high levels of minerals can lead to toxicity, and the European Commission has defined upper limits for contents of certain critical minerals either in the individual feed (arsenic, As; cadmium, Cd; mercury, Hg; lead, Pb) or in the complete daily feed ration (iodine, I) (see Section 6.4 and Table 32). For pigs, poultry, and fish (especially carnivorous), dietary fiber can be antinutritional as these species are not well-adapted to digest fiber due to limited microbial fermentation in the gut. Other antinutritional factors can be present in feed ingredients, such as mycotoxins, phytate, antitrypsinogenic factors, and glucosinolates.

The dietary recommendations for the selected species of food-producing animals reported in Supplementary Table 6-1 were used to estimate the RMDIR of algae in diets for the different animal species and to identify the main barriers that need to be overcome to increase the use of algae in feeding of food-producing animals.

In Supplementary Table 6-1, nutrient requirements of dairy cattle, fattening calves, fattening pigs, laying hens, broilers and salmon growers are presented according to the models used in different member states, when available, or in the case of poultry recommendations from breeding companies were used. Values for the following requirements have been provided:

- Metabolizable (ME) or net energy (NE).
- Protein or digestible protein.
- Digestible amino acids.
- Digestible fat and essential fatty acids (when available).
- Carbohydrates and fiber (when available).
- Macro and micro minerals (including upper limits).
- Vitamins.

6.2.4 Results

For cattle, NE systems are used to express energy requirements for maintenance, growth and milk production in DK, F and NL, and recommendations for NE are similar across these member states. In modern protein evaluation systems used for cattle in Europe, recommendations are given for the quantity of amino acids absorbed in the small intestine, which is derived from small intestinal digestion of feed protein that was not microbially degraded in the rumen plus digested microbial protein synthesized in the rumen. Microbial synthesis in the rumen is determined by the provision of rumen degradable carbohydrate, provided there is a sufficient supply of nitrogen. Recommendations for a so-called protein balance in the rumen are also given and it is calculated as the difference between protein degradation in the rumen and the microbial synthesis of protein. Fat recommendations are expressed as a maximum value rather than a requirement since microbial fermentation in the rumen is suppressed by high intakes of fatty acids. The NRC requirements (NRC, 2021) for minerals and vitamins provide the basis for recommendations for these nutrients in most systems, and the NRC also provides upper limits for safe intake of minerals from an animal health perspective.

For pigs, energy requirements are also expressed in NE terms. Protein requirements are based on the so-called standardized ileal digestible (SID) values for amino acids, which indicate the absorbed amounts of amino acids from the small intestine corrected for endogenous losses. Recommendations for other amino acids than Lys are expressed relative to the content of SID Lys in the diet. Recommendations for calcium and phosphorus are expressed as standardized total tract digestible (STTD) values, which correct for endogenous losses. In Denmark (SEGES, 2021) requirements for Ca and P also consider whether phytase is added to diets to increase availability. There are no specific recommendations mentioned for carbohydrates or fat for pigs, except for specific essential (polyunsaturated) fatty acids.

In the case of chicken, the dietary recommendations provided by breeder companies are the ones that are typically used because breeding schemes have led to development of strains with specific genetic traits and requirements. Energy requirements for chicken are expressed as ME and amino acids requirements are also considering composition relative to an ideal protein. There are no specific recommendations mentioned for carbohydrates or fat.

For fish, energy requirement is presented as digestible energy (DE). Amino acids requirements from FAO (FAO, 2022) and NRC (NRC, 2011) are presented as a percentage of protein. The main difference here is that salmon have specific requirements for dietary fatty acids higher than in terrestrial species. Carbohydrates and fibre requirements are available from the FAO. Recommendations for minerals and vitamins are listed from the FAO.

6.2.5 Critical analysis

For all species, digestibility and metabolization of organic matter are key factors determining the energy value of a feed. For monogastric animals, the protein value of a feed depends on the amino acid composition, digestibility and hence absorption of the individual EAA in the small intestine, since EAA cannot be synthesized by the animal itself. In the protein evaluation systems used for monogastric animals, contents of individual EAA are expressed relative to that of Lys and recommendations are given relative to composition of a defined ideal protein with optimal amino acid composition.

Any EAA that is supplied in sub-optimal amounts in the complete diet may limit protein synthesis and hence productivity of the animal. For ruminant animals, EAA composition in the diet is normally not considered, but rather total amino acid absorption from supply of feed protein that was not degraded in the rumen plus digested microbial protein passing into the small intestine. Rumen degradability is the main factor determining overall digestibility of feed carbohydrates and protein, and hence both energy and protein values of the feed. When it comes to introducing novel feed resources like algae, contents of critical minerals need to be considered, since exceeding maximum levels will exclude them as feeds.

The two most important factors that presently may restrict the inclusion of algae into animal feeds (apart from cost and availability) are thus: 1) high contents of critical minerals intrinsic to the algae species, and 2) low digestibility of organic matter including protein. Issues regarding palatability of feeds can normally be solved by addition of feeds that disguise the taste e.g., molasses.

6.3 Characterizing livestock, poultry and fish production in Europe

6.3.1 Approach

The total annual production of milk, beef, pork, eggs, chicken meat and fish in each partner member state and at the EU were extracted from EUROSTAT. Feed conversion rates (kg diet DM consumed per kg produce) for Danish production systems and the selected categories of food-producing animals were adopted from Osei-Owusu et al (2019).

6.3.2 Data considered

The average feed conversion ratios (FCRs) for animal products, provided in unit of [DM feed kg/kg final product] are 2.6 for pork, 1.3 for chicken, 4.75 for beef, 0.79 for milk, 1.35 for salmon and 1.78 for eggs for Denmark (Osei-Owusu et al 2019) and are assumed representative for European level.

6.3.3 Results

The total feed demand was estimated from the FCRs and annual production volumes in Figure 36 and Figure 37. FCR vary according to feed composition, but in this analysis, we assume that the Danish FCR are representative for Europe.

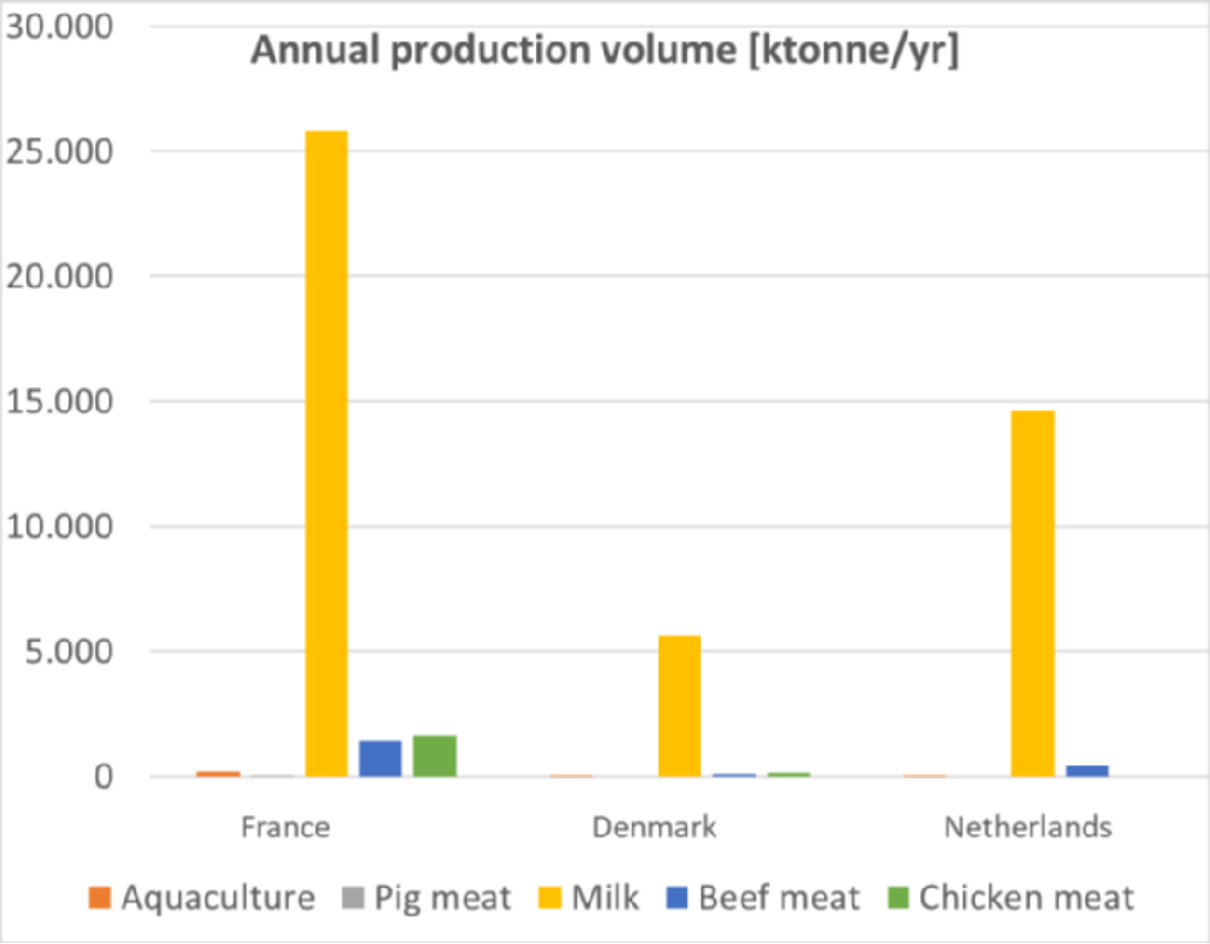


Figure 36 Annual production volumes of animal products in the member states (EUROSTAT, 2022)

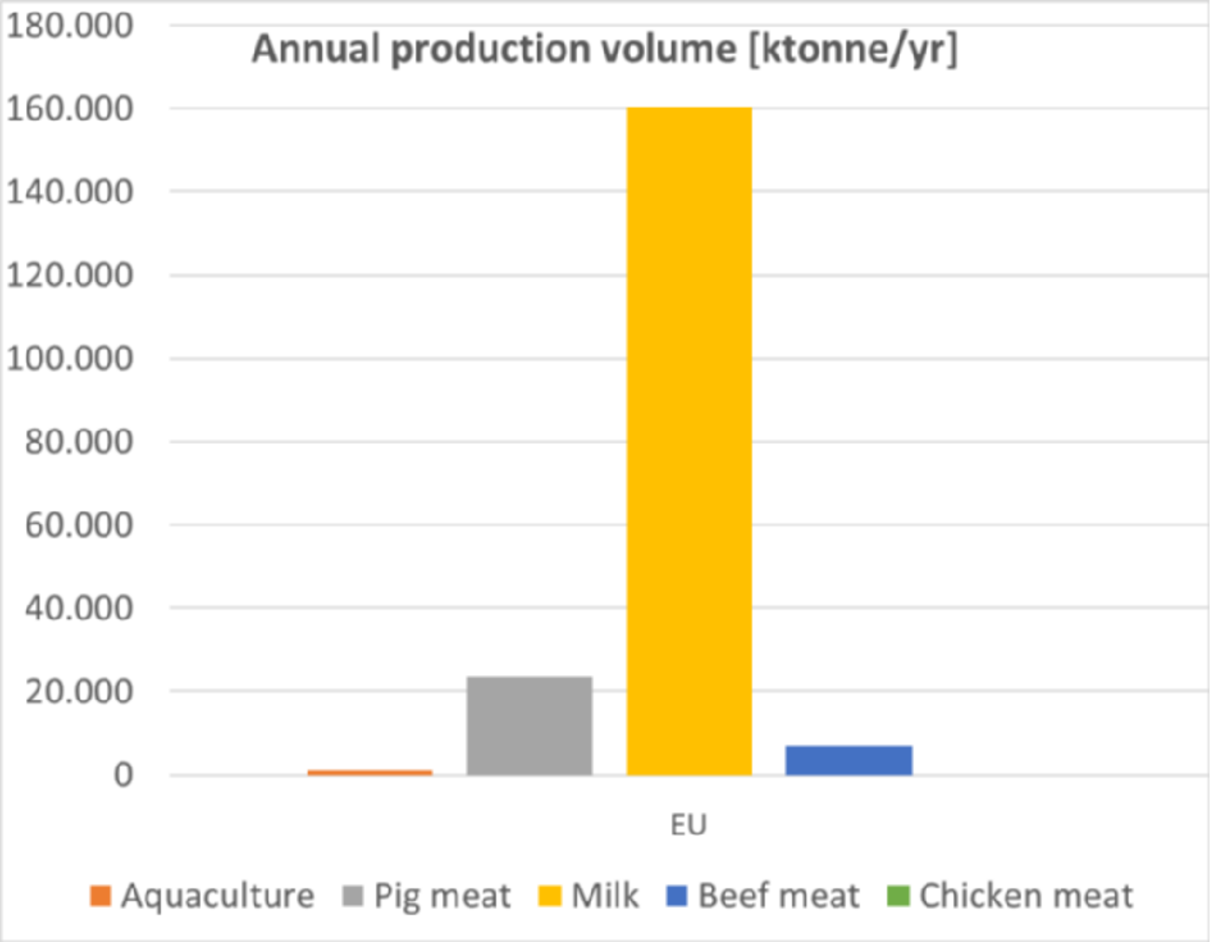


Figure 37 Annual production volumes of animal products in the EU (EUROSTAT, 2022)

The resulting feed demand and associated CO_2 footprint of the conventional diets, calculated by the relational database, result "T56_Reference diet results", is shown in Table 30 below.

Table 30 Carbon footprint of animal-based food product before (conv) and after inclusion of Saccharina latissima as bulk feed at recommended inclusion rates and inclusion of Asparagopsis as a methane inhibiting feed supplement. Data are provided for yearly productions in partner member state and EU calculated from the relational database and Section 3.3

Member state	Product	Production [kt/yr]^1	GHG conv [kt CO_2e/yr]^2	GHG recom IR [kt CO_2e /yr]^3	GHG Asp [kt CO_2e/yr]	GHG change [%]
France	Salmon	191	999	968	n.o.	-3%
Denmark	Salmon	38	198	192	n.o.	-3%
Netherlands	Salmon	39	206	200	n.o.	-3%
EU	Salmon	1070	5597	5422	n.o.	-3%
France	Chicken_meat	1646	4089	4039	n.o.	-1%
Denmark	Chicken_meat	163	406	401	n.o.	-1%
Netherlands	Chicken_meat	n.a.	n.a.	n.a.	n.o.	n.a.

EU	Chicken_meat	n.a.	n.a.	n.a.	n.o.	n.a.
France	Pig_meat	2204	5730	6935	n.o.	21%
Denmark	Pig_meat	1724	4481	5423	n.o.	21%
Netherlands	Pig_meat	1719	4470	5411	n.o.	21%
EU	Pig_meat	23394	60824	73613	n.o.	21%
France	Milk	25835	30485	30441	25913	-15%
Denmark	Milk	5644	6660	6650	5661	-15%
Netherlands	Milk	14608	17237	17212	14652	-15%
EU	Milk	160282	189133	188856	160763	-15%
France	Beef_meat	1424	15098	14833	10568	-32%
Denmark	Beef_meat	122	1295	1273	907	-32%
Netherlands	Beef_meat	430	4554	4474	3188	-32%
EU	Beef_meat	6802	72100	70838	50470	-32%

[1] Production data from Table T52

[2] CO_2e footprint data from Table T53

[3] CO_2e footprint from conventional feed product and FCR are taken from Table TT53, CO_2 footprint for algae diet from Table T13 and inclusion rates for *Gracilaria* (used for alle bulk feed substitution data) are taken from Table T54

[4] Functional feed supplement *Asparagopsis taxiformis* modelled for milk and beef products

The reduction in the CO_2 footprint resulting from substituting conventional feed with algae-based feed are calculated according to equations provided in chapter 3.3. As may be observed from Table 30, exemplified by *Saccharina latissima* as a bulk feed according to defined inclusion rates does not reduce the carbon footprint of the products significantly, while a bioactive ingredient such as Asparagopsis taxiformis reduces the product carbon footprint by 15% to 32%. Further details on the results of the relational database are presented in Section 7.

6.4 Estimated proportion of animal diets that can be met by algae

The main objectives were to:

- Propose a recommended maximal dietary inclusion rate (RMDIR) of each of the selected algae species in diets for the different categories of animals.
- Estimate the enteric methane mitigating potential of each algae species, when fed to cattle at the RMDIR.
- Identify limitations for inclusion of algae in animal diets and discuss needs for technologies (e.g. post-harvest processing, breeding) to overcome such limitations.
- Identify areas where research and development are needed.

6.4.1 Approach and data considered

Except for certain microalgae in the aquaculture industry, cultivated algae have not been used on a commercial scale as a feed ingredient for food-producing animals due to the high cost of algae cultivation and processing, and the limited supply of algae biomass. The information available on nutritional value of algae for the non-marine animal species is, therefore, predominantly from scientific studies, particularly in vitro studies, where the digestibility of algal biomass was estimated. Different in vitro protocols and methodologies have been used in different studies, and results expressed in varying terms, and hence, results are not always directly comparable. Only very few in vivo feeding/production studies were conducted with the selected algae species in the targeted food-producing animals and often under conditions that were not easy to compare (differences with respect to animal age, breed, production level, basal diet, sex). As a result of the scarcity of literature, in vivo data from studies in other animal species, similar to the targeted food-producing animals, were therefore considered, when available.

A Supplementary Table 6.1 was constructed to aid knowledge extraction regarding:

1. Key nutritional properties of algae when fed to the different food-producing animal species.
2. Implications for diet digestibility and animal productivity when algae are included in the diet.
3. Maximal proportion of algae DM evaluated as safe to include in animal diets without compromising feed intake, animal productivity or health.
4. Anti-methanogenic potential of algae when fed to cattle.
5. Algae-related factors that limit the inclusion in animal diets (e.g. critical minerals, digestibility).
6. Potential for increased dietary inclusion, if those limitations were overcome (e.g., by post-harvest processing and/or breeding).

As discussed in Section 6.2, the degradability of OM in the rumen, particularly dietary fibre, is the main determinant of the overall digestibility and hence energetic value of a feed stuff for ruminant livestock. Ruminants do not have a specific requirement for supply of EAA in the diet, since the rumen microbiota can utilize any N source for microbial protein synthesis, including EAA. Therefore, for cattle the retrieved information relating to protein quality traits of algae was focused only on crude protein (CP) digestibility.

In monogastric animals including fish, the main determinant of energetic value of a feed is the digestibility of OM in the small intestine, i.e., OM that can be degraded by enzymes produced by the animal itself. The extent of hind-gut fermentation of dietary fibre is limited (fattening pigs) to virtually non-existent (poultry, salmon) in the selected monogastric animals. Protein quality is determined by the magnitude of absorption in the small intestine of the individual EAA. Hence, in feed stuff tables made for intensively reared pigs, digestibility coefficients for a given feed are given both for overall CP, but also for the individual EAA (Tybirk et al., 2021).

Information on digestibility of individual EAA has not been found for any of the selected algae species, and hence only ratios of the total EAA content relative to total content of Lys could be calculated (see Table 31 derived from Supplementary Table 6.1). This clearly illustrates the extensive knowledge gap regarding nutritional value of most of the selected algae species, for example the contents of critical minerals, digestibility of DM, OM, CP, individual EAA and the impact of dietary inclusion of algae on animal performance when fed to the targeted food-producing animals. Hence, the recommended maximal dietary inclusion rates (RMDIR) proposed in the following sections for each of the selected algae species and targeted food-producing animals are associated with significant uncertainty.

Mineral and vitamin contents in algae DM are normally considerably higher than in terrestrial feeds, especially in marine macroalgae, and there is also a very high variability in mineral contents depending on algae species, growing conditions at the site of harvest as well as harvest season (see relational database, T13_algaecomp).

Macroalgae could potentially be utilized to produce mineral supplements, but in this task the focus is on the main factors of importance for bulk use of algae as feed ingredients, i.e., energetic and protein value. Thus, mineral contents will only be discussed, if contents of certain minerals are deemed critical for dietary inclusion of an algae.

6.4.2 Results for nutritional properties and methane mitigating potentials of algae

Table 31 provides an overview of the CP content and the contents of EAA and semi-EAA relative to Lys, based on the base values collated in Task 2, and the recommendations for contents in the diet of standardized ileal digested (SID) EAA relative to SID Lys are shown for comparison. It should be possible to compare these ratios, assuming that the variability in digestibility for the individual EAA do not vary a lot in a given algae biomass, i.e., SID EAA mainly depends on overall digestibility of the CP.

Table 31 Algal contents of essential and semi-essential amino acids (relative to contents of Lys) as compared to animal requirements (derived from base values given in relational database Table T13_algaecomp)

Algae species	**Crude protein**	**Lys content**	**Algal amino acid content (% of Lys)**									
	% of DM	**% of total AA**	**Met**	**Thr**	**Trp**	**Ile**	**Leu**	**Val**	**Phe**	**His**	**Cys+Met**	**Phe+Tyr**
Macroalgae:												
Alaria esculenta	12.1	5.23	26	78		71	122	108	74	24	53	103
Asparagopsis sp	16.0	4.78	31	115	3	103	152	136	103	26	47	166
Gracilaria sp	20.5	3.01	234	429	37	105	113	67	112	55	303	199
Palmaria palmata	20.4	6.41	31	73		63	103	99	71	25	90	
Saccharina latissima	9.6	5.97	33	89	28	73	123	97	80	26	69	89
Ulva sp.	16.4	4.52	45	112	21	85	143	120	106	28	64	167
Microalgae:												
Chlorella sp.	30.0	13.1	43	77	17	74	151	103	89	37	54	149
Dunaliella	40.0											
Haematococcus pluvialis	17.0	5.69		96		84	191	129	79	100		126
Nannochloropsis sp.	28.5	13.9	36	69	2	73	135	90	80	31		
Spirulina sp.	52.0											
Protein recommendations:		**g SID Lys/kg diet as-fed**	**Amount of SID amino acid relative (%) to SID Lys**									
Slaughter pig (75-100kg)		7.3	29	63	18	53	101	66	60	34	58	95
Broiler (Ross)		5.6	43	67	16	68	110	77	55	27	78	103
Layer hen (Lohmann)		11.8	46	70	23	77	184	80	105	38	86	186
Salmon grower		24.0	29	46	13	46	63	50	38	33	46	75

DM: Dry matter. SID: Standardized ileal digested

Table 32 provides an overview of the contents of certain critical minerals, for which the EU has defined maximum allowed contents in individual feed stuffs (so-called Reject values for arsenic, cadmium, mercury, lead) or maximum allowed contents in the complete diet as a whole (iodine). These values are defined by the European Commission (EC2015/861, EC2019/1869 and EC1275/2013). Furthermore, the critical mineral contents in seaweed products directly sold as dietary supplements or as food for humans has following EU regulations. The Pb and Cd concentration should be <3 mg/kg of algal DM and Hg concentration should be <0.1 mg/kg of algal DM as per EU regulations (Holdt and Kraan et al., 2011). Furthermore, as per French regulations, inorganic As and iodine content should be <3 and <0.5 mg/kg of algal DM respectively (Holdt and Kraan et al., 2011).

Table 32 Contents of critical minerals* potentially limiting inclusion of algae in animal diets compared to EU Commission defined reject values (maximum allowed concentrations in feeds for food-producing animals)

Algae species	I	As	As-in	Cd	Hg	Pb
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Macroalgae:						
Alaria esculenta	437	32.1				0.60
Asparagopsis sp	3370	0.40		0.020	0.020	0.51
Gracilaria sp		8.67		0.89	0.050	2.60
Palmaria palmata	640	9.33		0.15		14.5
Saccharina latissima	2644	37.7	0.65	0.86	0.32	3.56
Ulva sp.	108	6.98	3.10	2.34	0.01	1.96
Microalgae:						
Chlorella sp.						
Dunaliella						
Haematococcus pluvialis						
Nannochloropsis sp.						
Spirulina sp.						
Maximum allowed content per kg algal DM (unless otherwise stated)	**5 mg/kg diet**	**40 mg**	**---**	**1 mg**	**0.1 mg**	**15 mg**

*Base values extracted from relational database Table T13_algaecomp.

As-in: inorganic arsenic. DM: Dry matter.

Table 33, Table 34 and Table 35 provide an overview of the data compiled in Supplementary Table 6-1 regarding digestibility of algal DM, OM and/or CP determined either in vitro or in vivo, and the impact of dietary addition of algae on animal performance and for ruminants also enteric methane emission. For references to the reviewed scientific studies: see Supplementary Table 6-1.

Table 33 Digestibility traits (base values and observed range) for algae species in cattle, and impact of dietary algae inclusion on overall diet digestibility, animal performance, and in ruminants on reduction of enteric methane emission (data compiled from Supplementary Table 6-1)

IN CATTLE:	**Digestibility of algal biomass:**			**Impact upon inclusion of algae in animal diets:**				
				Change in digestibility:		Change in animal performance	CH_4 reduction (%)	In vivo dietary inclusion tested
	In rumen	Whole tract	Season effect	In rumen	Whole tract			
Macroalgae:								
Alaria esculenta	DM: 50 (25-80)% OM: 40 (13-64)%	DM: 52 (50-58)% CP: 45 (40-52)%	Spring > autumn	DM: -6%-units OM: -6-7%-units	ND	ND	0	ND
Asparagopsis sp	DM: 36% OM: 37%			DM: -4-6 %-units OM: -1-7%-units		FI: 0 - -38% MY: 0- -12% DWG: 0 - +26%	Cows: 30 (25-35) Growing: 60 (40-98)	0.1-2.0% in DM/OM
Gracilaria sp	40 (32-48)%			DM: -3 - -4%-units OM: -4 - +5%-units CP: -10%-units		FI: -19%	0 (+/-)	25% as-fed (sheep)
Palmaria palmata	DM: 85 (81-91)% OM: 75 (74-76)% CP: 46%	DM: 85 (83-86)% CP: 78 (77-79)%	No	DM/OM: +1 - 3%-units			(increases)	
Saccharina latissima	DM: 43 (28-69)% OM: 44 (29-70)%	CP: 74%	Summer>autumn >winter	DM: -1 - -7%-units OM: -7 - +5%-units	DM/CP: 0	FI: 0 MY: 0	0 (+/-)	4% in DM
Ulva sp.	DM: 45 (29-57)% OM: 45 (19-73)% CP: 38 (23-54)	DM: 49% CP: 77%	No	DM: 0 - -3%-units OM: -2 - +5%-units CP: -8%-units	OM: -1 - -4%-units CP: -1 - -3%-units	FI: 0 - -20%	0	8.3-25% as-fed (sheep)
Microalgae:								
Chlorella sp.				0	0	FI: 0 MY: 0 Low palatability Feed preference		~2.3-6.8% in DM
Dunaliella	Data not available for cattle							
Haematococcus pluvialis	Data not available for cattle							
Nannochloropsis sp.					0	FI: 0 MY: 0		~5% in DM
Spirulina sp.					0	FI: 0 MY: 0 Low palatability Feed preference		2.6-~5 % in DM

BWG: Body weight gain. CP: Crude protein. DM: Dry matter. FCR: Feed conversion rate. FI: Feed intake. GE: Gross energy. ME: Metabolizable energy. OM: Organic matter.

Table 34 Digestibility traits (base values and observed range) for algae species in pigs and impact of dietary algae inclusion on overall diet digestibility, animal performance, and in ruminants on reduction of enteric methane emission (data compiled from Supplementary Table 6-1)

IN PIGS:	**Digestibility of algal biomass:**		**Change when added to diet:**		
	Whole tract	Ileal	Diet digestibility	Animal performance	Dietary inclusion
Macroalgae:					
Alaria esculenta		CP: 79%			
Asparagopsis sp	Data not available for pigs				
Gracilaria sp		CP: 30%			
Palmaria palmata	OM: 85 (84-86)%	OM: 64 (62-66)% CP: 83% ((10)-			
Saccharina latissima	OM: 78 (75-81)%	OM: 78 (75-81)% CP: 80 (71-89)%			
Ulva sp.	OM: 78 (73-83)%	OM: 59 (51-67)% CP: 74 (69-80)%			
Microalgae:					
Chlorella sp.			DM/OM: 0 CP: 0 Fiber: 0 GE: 0	FI: 0 BWG: 0 FCR: 0	1-5% as-fed
Dunaliella	Data not available for pigs				
Haematococcus pluvialis	Data not available for pigs				
Nannochloropsis sp.	Data not available for pigs				
Spirulina sp.			DM/OM: 0 CP: 0 Fiber: 0 GE: 0	FI: 0 BWG: 0 FCR: 0	1% as-fed

Abbreviations: See Table 33.

Table 35 Digestibility traits (base values and observed range) for algae species in chicken and fish, and impact of dietary algae inclusion on overall diet digestibility, animal performance, and in ruminants on reduction of enteric methane emission (data compiled from Supplementary Table 6-1)

	IN CHICKEN				IN FISH*	
	Algae whole tract digestibility	Change when added to diet:			Change when added to diet:	
		Diet digestibility	Animal performance	Dietary inclusion	Animal performance	Dietary inclusion
Macroalgae:						
Alaria esculenta	Data not available for chicken				BWG: 0 FCR: 0	5% of DM
Asparagopsis sp	Data not available for chicken					
Gracilaria sp	Data not available for chicken				If <9% inclusion: BWG+FCR: 0 If >9% inclusion: BWG: -23 - -40% FCR: +38 - +53%	3-12% as-fed
Palmaria palmata	Data not available for chicken				BWG: 0 FCR: 0	5-15% as-fed (in salmon)
Saccharina latissima	OM: 55 (41-75)% CP: 60 (41-79)%	OM: -11.5% CP: -2.0% Cfat: -10.6%	FI: 7 - 9% BWG: 0% FCR:7 - 13 %	10% as-fed		
Ulva sp.	OM: 47 (41-64)% CP: 55 (41-69)%	<10: 0 >10, ME: -21%	FI: 0 <10, BWG: 0 >10%, BWG: -25% <10, FCR: 0 >10%, FCR: 26%	1-30% as-fed	<10% inclusion: BWG: 0-+50% FCR: 0 - +6% >10 inclusion: BWG: 0 - ? FCR: +26-+62%	5-20% fishmeal replaced
Microalgae:						
Chlorella sp.			FI: 0 BWG: 0-+6.3% FCR: 0	1-10% as-fed		
Dunaliella	Data not available for chicken or salmon					
Haematococcus pluvial	Data not available for chicken or salmon					
Nannochloropsis sp.	Data not available for chicken					3-20% as-fed
Spirulina sp.			FI: -10 - +21% BWG: 14 - 35% FCR: -6 - +15%	0.5-2% as-fed	<10% inclusion: BWG: 0 - +62% FCR: -40 - +12% >10% inclusion: BWG: 0 - +14% FCR: 0 - +24%	3-20% as fed

*Data only derived from salmon if specifically stated. Abbreviations: see Table 33.

6.4.2.1 Macroalgae

Base values for concentrations of critical minerals exceeded rejection values (maximum allowed content in a feedstuff) for cadmium (Cd) in *Ulva sp.* And mercury (Hg) in *Saccharina latissima*, as shown in Table 32, and this excludes them for use as a feed ingredient. Therefore, the RMDIR for these 2 species has therefore been set to 0% for all the animal species (Table 36). *Alaria esculenta, Palmaria palmata* and particularly *Saccharina latissima* and *Asparagopsis taxiformis* had high to extremely high contents of another critical mineral, namely iodine (I). Restrictions on dietary iodine for food-producing animals are, in this case, defined as a maximum concentration in the total daily ration (5 mg/kg diet as-fed with 88% DM = 5.68 mg/kg diet DM). Hence, assuming other feed ingredients in the diet would not contribute with iodine, RMDIR for *Alaria esculenta, Palmaria palmata* and *Asparagopsis taxiformis* could amount to 1.3%, 0.88% and 0.15%, respectively (Table 36).

Within the EU, the tropical *Asparagopsis taxiformis* cannot be cultivated in the wild, but only in on-land systems, where iodine content in the tank water could be controlled. This has been taken into account, when assigning a higher RMDIR for *Asparagopsis taxiformis*, namely 0.5%, to be benefitted from its ability to inhibit methane formation in the forestomaches of ruminant animals (Table 36). For *Gracilaria sp.,* iodine was not available in the data from Task 2, but Cabrita et al. (2016) reported a content of only 46.7 mg iodine/kg DM in *Gracilaria vermiculophyla* with concentrations of the other critical minerals being well under rejection values. It therefore appears that this alga has a substantially lower intrinsic preference for uptake and deposition of iodine than the other 2 red macroalgae species, and the RMDIR for these algae could therefore exclusively be based on its presumed nutritional qualities.

As was shown in Table 33 to Table 35, Palmaria palmata had the highest whole tract digestibility in ruminants and ileal digestibility in pigs of DM/OM and CP, and of a magnitude comparable to other quality feeds for pigs (Rønn et al., 2021). All the other macroalgae species, particularly Asparagopsis taxiformis, had a relatively low (<50%) rumen degradability in cattle, and the overall digestibility of a diet was suppressed when these algae species were included. A similar picture appeared for chicken for the two algae species, where information could be found (Saccharina latissima and Ulva sp.), and performance of the chicken was also reduced on diets with 10% addition of algae in feed-as fed. Unexpectedly, whole tract and ileal digestibilities of the macroalgae appeared to be as high or higher in pigs than in cows, except for Gracilaria sp., and fish also sustained performance with up to 9% (15% for Palmaria palmata) inclusion of algae in their diet (no data was found for Saccharina latissima in fish). Despite the low digestibility, feeding a diet to dairy cows with 4% Saccharina latissima in DM had no negative effect on cow performance (Nielsen MO, personal observation).

Gracilaria sp. And *Palmaria palmata* had the highest content of CP followed by *Ulva* sp. And are relevant to consider as protein feeds. If it is assumed that the digestibility is of fairly similar magnitude for the individual amino acids, then *Gracilaria* sp. Has an amino acid profile (Table 31) that is particular rich in Met, Thr and Cys+Met, and it would meet requirements for all EAA for all the animal species, except Leu for laying hens and Val for poultry in general. The amino acid profile of *Palmaria palmata* fulfils requirements for fattening pigs and salmon growers, except for His and Phe+Tyr, but does not fulfil requirements for poultry for 5 of the EAA. *Ulva* sp. Has a better amino acid profile than *Palmaria palmata* and, except for laying hens, fulfils requirements for most EAA for all the animal species. In salmon nutrition, the very high content of Ω-3 fatty acids and eicosapentaenoic acid (EPA) in *Palmaria palmata* (see relational database Table T13_algaecomp) is also interesting.

In contrast to the other macroalgae species, *Asparagopsis taxiformis* has dramatic anti-methanogenic properties in cattle. Appr. 30% reduction in methane has been achieved in dairy cows by addition of 0.5% in diet DM, whereas 40-98% methane reduction could be achieved in steers without depression of feed intake or animal performance (see Supplementary Table 6.1 and Table 36). On the other hand, *Asparagopsis taxiformis* cannot be assigned any significant feed value, due to its inhibitory actions on digestive processes, risk of rumen wall damage, suppression of feed intake and milk production. The lack of nutritional value makes it irrelevant as a feed for monogastric animals.

Table 36 Recommended maximal dietary inclusion rate (RMDIR) for macroalgae for food-producing animals, potential for enteric methane mitigation from dietary addition of macroalgae for cattle, and EU market potential for macroalgae as feed or feed additive (for explanation of calculations: see section 6.6)

Milk:

Annual production in EU (x1,000 tons; of which F/NL/DK: 16.4%/9.3%/3.5%):	**160,282**
Feed conversion rate (kg diet DM/kg produce):	**0.79**
CP contens in diets (% of diet DM):**	**17.0**

Algae species	**A esculenta**	**A taxiformis**	**G vermiculophyla**	**P palmata**	**S latissima**	**Ulva**
Recommended maximal dietary inclusion rate (% of diet DM)*	1.3%	0.50%	5%	0.88%	0%	0%
Maximal dietary inclusion rate if critical mineral issue solved	5% (I)	0.5% (I)	5%	10% (I)	5% (Hg+I)	5% (Cd)
Market potental of algae as feed in EU (x1000 tons DM/yr)	1,646	633	6,331	1,114	0	0
Spared conventional feed (x1000 tons DM/yr)	1,646	0	6,331	1,114	0	0
CP content in algal DM (%)	12.1	16.1	20.5	20.4	9.6	16.4
CP in algae : CP in feed conversion ration	0.75	0.00	0.75	1.00	0.50	0.75
Spared conventional feed CP (x1000 tons per year)	149	0	973	227	0	0
Enteric methane mitigation upon addition to basal ration	0%	30%	0%	0%	0	0%

Beef:

Annual production in EU (x1,000 tons; of which F/NL/DK: 20.9%/6.3%/1.8%):	**6,802**
Feed conversion rate (kg diet DM/kg produce):	**4.75**
CP contens in diets (% of diet DM):**	**15.5**

Algae species	**A esculenta**	**A taxiformis**	**G vermiculophyla**	**P palmata**	**S latissima**	**Ulva sp**
Recommended maximal dietary inclusion rate (% of diet DM)*	1.3%	0.5%	7%	0.88%	0%	0%
Maximal dietary inclusion rate if critical mineral issue solved	5% (I)	0.5% (I)	7%	10% (I)	5% (Hg+I)	5% (Cd)
Market potental of algae as feed in EU (x1000 tons DM/yr)	420	162	2,262	284	0	0
Spared conventional feed (x1000 tons DM/yr)	420	162	2,262	284	0	0
CP content in algal DM (%)	12.1	16.1	20.5	20.4	9.6	16.4
CP in algae : CP in feed conversion ration	0.75	0	0.75	1.00	0.50	0.75
Spared conventional feed CP (x1000 tons per year)	49	0	263	44	0	0
Enteric methane mitigation upon addition to basal ration	0%	60%	0%	0%	0%	0%

Pork:

Annual production in EU (x1,000 tons; of which F/NL/DK: 9.4%/7.3%/7.4%):	**23,394**
Feed conversion rate (kg diet DM/kg produce):	**2.60**
CP contens in diets (% of diet DM):**	**16.3**

Algae species	**A esculenta**	**A taxiformis**	**G vermiculophyla**	**P palmata**	**S latissima**	**Ulva sp**
Recommended maximal dietary inclusion rate (% of diet DM)*	1.3%	0%	2%	0.88%	0%	0%
Maximal dietary inclusion rate if critical mineral issue solved	2% (I)	0%	2%	10% (I)	5% (Hg+I)	5% (Cd)
Market potental of algae as feed in EU (x1000 tons DM/yr)	791	0	1,216	535	0	0
Spared conventional feed (mio. tons DM/yr)	791	0	1,216	535	0	0
CP content in algal DM (%)	12.1	16.1	20.5	20.4	9.6	16.4
CP in algae : CP in feed conversion ration	0.50	0	0.50	0.75	0.25	0.50
Spared conventional feed CP (mio. tons per year)	48	0	125	82	0	0

Eggs:

Annual production in EU (x1,000 tons; of which: F/NL/DK: 14%/10%/1%):	**7,060**
Feed conversion rate (kg diet DM/kg produce):	**1.78**
CP contens in diets (% of diet DM):**	**18.4**

Algae species	**A esculenta**	**A taxiformis**	**G vermiculophyla**	**P palmata**	**S latissima**	**Ulva sp**
Recommended maximal dietary inclusion rate (% of diet DM)*	1.30%	0%	2%	0.88%	0%	0%
Maximal dietary inclusion rate if critical mineral issue solved	2% (I)	0%	5%	10% (I)	2% (Hg+I)	2% (Cd)
Market potental of algae as feed in EU (x1000 tons DM/yr)	163	0	251	111	0	0
Spared conventional feed (mio. tons DM/yr)	163	0	251	111	0	0
CP content in algal DM (%)	12.1	16.1	21	20	9.6	16.4
CP in algae : CP in feed conversion ration	0.50	0	0.50	0.75	0.25	0.50
Spared conventional feed CP (mio. tons per year)	0	0	26	17	0	0

Chicken meat:

Annual production in EU ex NL (x1,000 tons; of which F/DK: 13.4%/1.3%):	**12,300**
Feed conversion rate (kg diet DM/kg produce):	**1.30**
CP contens in diets (% of diet DM):**	**22.2**

Algae species	**A esculenta**	**A taxiformis**	**G vermiculophyla**	**P palmata**	**S latissima**	**Ulva sp**
Recommended maximal dietary inclusion rate (% of diet DM)*	1.3%	0%	2%	0.88%	0%	0%
Maximal dietary inclusion rate if critical mineral issue solved	5% (I)	0%	5%	10% (I)	5% (Hg+I)	5% (Cd)
Market potental of algae as feed in EU (x1000 tons DM/yr)	208	0	320	141	0	0
Spared conventional feed (mio. tons DM/yr)	208	0	320	141	0	0
CP content in algal DM (%)	12.1	16.1	21	20	9.6	16.4
CP in algae : CP in feed conversion ration	0.50	0	0.50	0.75	0.25	0.50
Spared conventional feed CP (mio. tons per year)	0	0	33	22	0	0

Salmon filet:

Annual production in EU (x1,000 tons; of which: F/NL/DK: 17.9%/3.7%/3.5%):	**1,070**
Feed conversion rate (kg diet DM/kg produce):	**1.35**
CP contens in diets (% of diet DM):**	**35.6**

Algae species	**A esculenta**	**A taxiformis**	**G vermiculophyla**	**P palmata**	**S latissima**	**Ulva sp**
Recommended maximal dietary inclusion rate (% of diet DM)*	1.3%	0%	10%	0.88%	0%	0%
Maximal dietary inclusion rate if critical mineral issue solved	5% (I)	0%	10%	10% (I)	5% (Hg+I)	10% (Cd)
Market potental of algae as feed in EU (x1000 tons DM/yr)	19	0	144	13	0	0
Spared conventional feed (mio. tons DM/yr)	19	0	144	13	0.00	0
CP content in algal DM (%)	12.1	16.1	20.5	20.4	9.6	16.4
CP in algae : CP in feed conversion ration	0.50	0	0.75	1.00	0.50	0.75
Spared conventional feed CP (mio. tons per year)	0	0	22	2.6	0	0

*Two values for RMDIR are proposed for all algae: one considering the limitations due to high contents of critical minerals, and another provided this issue is resolved. DM: Dry matter, CP: Crude protein. Data sources: See Supplementary Table 6-1.

6.4.2.2 Microalgae

Data for contents of critical minerals in microalgae could not be found (see Task 2), but microalgae are seen as promising tools for extracting heavy metals from contaminated or waste waters due to their ability to extract and concentrate heavy metals within them (Kumar et al 2015 and Leong and Chang, 2020). Microalgae are commercially cultivated in systems, where water supply can be controlled (racing ponds and photobioreactors), and their contents of critical minerals will therefore depend entirely on quality of the supplied water in those systems. Hence, microalgae that are grown in wastewater to remove contaminants are not likely to be suitable as animal feeds. Due to the lack of information about contents of critical minerals, no RMDIR could be assigned to these algae, but a potential RMDIR was proposed provided critical minerals are not an issue, see Table 37.

In contrast to macroalgae, most research on nutritional value of microalgae has been in the form of feeding trials. *Chlorella* sp., *Nannochloropsis* sp. And *Spirulina* sp. Can be fed to dairy cows up to 5% in DM without negative effects on feed intake or milk production, but preference of other feeds over the algae indicates a low palatability. Inclusion of up to 5% *Chlorella sp.* In diets for pigs or 10% in diets for chicken had no negative effect on animal performance. Adding 1% *Spirulina sp.* to feed as-fed did not affect performance in pigs, but 2% inclusion had a negative impact on FCR in chicken. In fish, Spirulina sp. could be included in diets with up to 10% of feed as-fed, but higher inclusion rates reduced growth performance. No data could be found for nutritional value of *Dunaliella* or *Haematococcus pluvialis* in any of the animal species, or for *Nannochloropsis* sp. In the monogastric species.

Chlorella sp. Fulfilled EAA requirements for all the animal species, except laying hens where requirements were only Met for Thr and Val. Except for Met and Trp, *Haematococcus pluvialis* seems to have the best EAA profile and is a particular rich source of Leu, Phe and His.

Table 37 Recommended maximal dietary inclusion rate (RMDIR) for microalgae and EU market potential for microalgae as feed (for explanation of calculations: see section 6.6)

Milk:

Annual production in EU (x1,000 tons):	**160,282**
Feed conversion rate (kg diet DM/kg produce):	**0.79**
CP contens in diets (% of diet DM):**	**17.0**

Microalgae species	**Spirulina**	**Chlorella**	**Haematococcus**	**Nanochloropsis**	**Dunaliella**
Recommended maximal dietary inclusion rate (% of diet DM)*					
Maximal dietary inclusion rate if critical mineral issue solved*	7%	7%			
Market potental of algae as feed in EU (x1000 tons DM/yr)	8,864	8,864			
Spared conventional feed (x1000 tons DM/yr)	8,864	8,864			
CP content in algal DM (%)	52.0	30.0			
CP in algae : CP in feed conversion ration	0.75	0.75			
Spared conventional feed CP (x1000 tons per year)	3,457	1,994			
Enteric methane mitigation upon addition to basal ration	0%	0%			

Beef:

Annual production in EU (x1,000 tons):	**6,802**
Feed conversion rate (kg diet DM/kg produce):	**4.75**
CP contens in diets (% of diet DM):**	**15.5**

Microalgae species	**Spirulina**	**Chlorella**	**Haematococcus**	**Nanochloropsis**	**Dunaliella**
Recommended maximal dietary inclusion rate (% of diet DM)*					
Maximal dietary inclusion rate if critical mineral issue solved*	8%	8%			
Market potential of algae as feed in EU (x1000 tons DM/yr)	2,585	2,585			
Spared conventional feed (x1000 tons DM/yr)	2,585	2,585			
CP content in algal DM (%)	52.0	30.0			
CP in algae : CP in feed conversion ration	0.75	0.75			
Spared conventional feed CP (x1000 tons per year)	1,008	582			
Enteric methane mitigation upon addition to basal ration	0%	0%			

Pork:

Annual production in EU (x1,000 tons):	**23,394**
Feed conversion rate (kg diet DM/kg produce):	**2.60**
CP contens in diets (% of diet DM):**	**16.3**

Microlgae species	**Spirulina**	**Chlorella**	**Haematococcus**	**Nanochloropsis**	**Dunaliella**
Recommended maximal dietary inclusion rate (% of diet DM)*					
Maximal dietary inclusion rate if critical mineral issue solved*	5%	5%			
Market potential of algae as feed in EU (x1000 tons DM/yr)	3,041	3,041			
Spared conventional feed (mio. tons DM/yr)	3,041	3,041			
CP content in algal DM (%)	52.0	30.0			
CP in algae : CP in feed conversion ration	0.65	0.65			
Spared conventional feed CP (mio. tons per year)	1,028	593			

Eggs:

Annual production in EU (x1,000 tons):	**7,060**
Feed conversion rate (kg diet DM/kg produce):	**1.78**
CP contens in diets (% of diet DM):**	**18.4**

Microalgae species	**Spirulina**	**Chlorella**	**Haematococcus**	**Nanochloropsis**	**Dunaliella**
Recommended maximal dietary inclusion rate (% of diet DM)					
Maximal dietary inclusion rate if critical mineral issue solved*		5%			
Market potential of algae as feed in EU (x1000 tons DM/yr)		628			
Spared conventional feed (mio. tons DM/yr)		628			
CP content in algal DM (%)	52.0	30.0			
CP in algae : CP in feed conversion ration		0.65			
Spared conventional feed CP (mio. tons per year)		122.5			

Chicken meat:

Annual production in EU (x1,000 tons):	**12,300**
Feed conversion rate (kg diet DM/kg produce):	**1.30**
CP contens in diets (% of diet DM):**	**22.2**

Microalgae species	**Spirulina**	**Chlorella**	**Haematococcus**	**Nanochloropsis**	**Dunaliella**
Recommended maximal dietary inclusion rate (% of diet DM)*					
Maximal dietary inclusion rate if critical mineral issue solved*		10%			
Market potential of algae as feed in EU (x1000 tons DM/yr)					
Spared conventional feed (mio. tons DM/yr)					
CP content in algal DM (%)	52.0	30.0			
CP in algae : CP in feed conversion ration		0.65			
Spared conventional feed CP (mio. tons per year)					

Salmon filet:

Annual production in EU (x1,000 tons):	**1,070**
Feed conversion rate (kg diet DM/kg produce):	**1.35**
CP contens in diets (% of diet DM):**	**35.6**

Macroalgae species	**Spirulina**	**Chlorella**	**Haematococcus**	**Nanochloropsis**	**Dunaliella**
Recommended maximal dietary inclusion rate (% of diet DM)*					
Maximal dietary inclusion rate if critical mineral issue solved*	15%	20%		10%	
Market potential of algae as feed in EU (x1000 tons DM/yr)					
Spared conventional feed (mio. tons DM/yr)					
CP content in algal DM (%)	52.0	30.0	21.0	28.5	40.0
CP in algae : CP in feed conversion ration	0.85	0.85		0.75	0.75
Spared conventional feed CP (mio. tons per year)					

*Data for content of critical minerals was not available for microalgae, and no RMDIR could be proposed. A potential RMDIR is proposed provided any mineral issues are resolved. DM, CP, and sources of information: See Table 36.

6.5 Critical analysis and identified barriers

The main limiting factor and barrier for inclusion of macroalgae in feed for food-producing animals is high content of one of the critical minerals. It should be noted that the EU regulation on contents of critical minerals in animal feeds has been installed due to human health concerns and the risk of transfer of these minerals to animal-derived foods. It should therefore be of significant interest to the algae industry to develop cost-efficient procedures to extract these critical minerals from the algae biomass – whether it is to be used for human food or animal feed.

The second most important barrier is low digestibility of OM, CP/amino acids, and hence low nutritional value. There are, however, considerable knowledge gaps regarding the nutritional value of most of the algae for most of the food-producing animals, and it has only been possible to find few publications from in vivo trials with the selected algae species. The knowledge about digestibility of the organic components and particularly of protein and individual EAA in algae is extremely scarce, most often non-existent. The most solid scientific evidence is for rumen degradability of OM determined in vitro in laboratory systems simulating rumen fermentation and for methane reducing properties of *Asparagopsis* sp.

It is a challenge that standard methods, used by contract laboratories for analyses of feed composition are developed and validated predominantly against terrestrial feeds. Certain analytic procedures are developed to distinguish between carbohydrates that can be digested by gastrointestinal enzymes produced by the animal itself versus carbohydrates that can only be utilized provided the animal has a significant microbial fermentation in the forestomaches (ruminant animals) or hindgut. It is presently unknown, where the special carbohydrates produced by algae will fit into the following categories commonly used in feed analyses to describe carbohydrate quality:

- Sugar and starch versus neutral detergent and acid detergent fibre and lignin.
- Easily digestible carbohydrates versus non-starch polysaccharides.

It is also unknown, whether classification of algae carbohydrates into these categories hold any information about their actual intestinal digestibility or rumen fermentability. However, a substantial part of the carbohydrate fraction, particularly in brown macroalgae, but also green macroalgae and microalgae, is resistant to degradation by enzymes produced in the gastrointestinal tract of the animal. Among the algae species, *Palmaria palmata* was the only one with a rumen DM degradability and protein content approaching values seen in high quality (protein) feeds.

The warmer water red algae, *Asparagopsis armata* or *Asparagopsis taxiformis*, have been used in experiments as feed additives to reduce methane emission from dairy cows and fattening calves by 26 and 40-98%, respectively, at dietary inclusion levels around 0.2% to 0.5% of dietary DM. Inclusion rates above 0.5% have been associated with substantial reductions in milk production and feed intake (Roque et al 2019). Current research investigates potential anti-methanogenic actions of Nordic hemisphere species, but results have predominantly been obtained in vitro in laboratory systems simulating rumen fermentation, and hitherto no Nordic algae have been identified that are capable of reducing methane emission from dairy cows in vivo (Nielsen MO, unpublished observations).

As a result of the significant knowledge gaps, it can be anticipated that the estimated RMDIR's shown in Table 36 are associated with significant uncertainty. In contrast, existing data regarding the potential of *Asparagopsis taxiformis* or *Asparagopsis armata* to reduce enteric methane formation, when added to ruminant diets at low inclusion rates (<0.5% of dietary organic matter) appear quite accurate.

6.6 Information feeding into the relational database

Table 36 and Table 37 show estimates for the potential in EU for production of algae biomass as feed for food-producing animals and as anti-methanogenic feed additives for cattle. Associated spin-offs in terms of reduced use of conventional feeds and feed proteins and reduction in methane emission is also estimated. This data feeds into the relational database. The estimations were based on the following calculations and assumptions.

Total DM and CP consumption per year for production of milk, beef, pork, eggs, chicken meat and salmon in the EU was calculated by multiplying the annual production of these foods in the EU (see section 6.3) with the average FCR for that production, i.e., kg feed DM consumed per kg of product and a standard level of CP in diet DM.

A value for RMDIR was assigned to each algae species when used in the different food-production systems. The first step here was to consider if contents of critical minerals could exclude the algae altogether as feeds in the food chain. This was the case for *Saccharina latissima* and *Ulva* sp. In all production system, and hence RMDIR for these 2 species were set to 0%. However, Table 36 also provides estimates for the highest possible RMDIR for these 2 and other algae species provided the mineral limitations could be overcome by e.g., post-harvest processing or genetic improvements.

For species that passed the first step, the next step was to calculate the highest possible RMDIR before hitting the upper limit for iodine content in diets. This iodine-dictated RMDIR was calculated as follows: 5.68 mg iodine/kg feed DM (upper limit for content of iodine in diets is 5 mg/kg feed as-fed with 88% DM) divided by the iodine content in the algae in mg/kg. High iodine content became the most limiting factor for dietary inclusion of *Alaria esculenta* (RMDIR=1.3%), *Asparagopsis taxiformis* (RMDIR=0.15%) and *Palmaria palmata* (RMDIR=0.88%). However, for *Asparagopsis taxiformis* a higher value of 0.5% was assigned in Table 36 for cattle based on the assumption that iodine content can be controlled in the type of on-land system needed for cultivation of this tropical algae, and the 0.5% is assumed to be the maximal level of inclusion to achieve the highest possible methane reductions without negative side-effects in the form of reduced feed intake and animal productivity.

For species, where neither critical minerals nor iodine restricted intake, the assigned RMDIR was a best-bet estimate based on observations on nutritional properties of the algae. The assigned values for RMDIR are shown in Table 37, and they were positively related to the digestibility of OM and CP in the algae, with greatest emphasis on data from in vivo experiments. However, such information was not available for all the selected algae and was not determined in all animal species. Other traits were also considered for certain algae species when proposing a RMDIR for the different animal species – both here and now and in the future if mineral constraints could be overcome:

<u>*Gracilaria* sp.:</u> Assigned RMDIR ranged from 10% in fish to 2% in egg-laying hens. This alga had the best protein quality and is a rich source of EAA that are often the most limiting in monogastric nutrition (Met, Thr, Trp, Phe), but digestibility is low. The latter limits RMDIR especially in animals with highest demand for digestible OM (dairy cows versus calves) and EAA (layers versus broilers). Fish has responded well to high dietary levels of *Gracilaria* sp. In fattening calves, rumen fermentation is assumed to compensate for low intestinal digestibility to justify a quite high RMDIR. High intestinal digestive capacity in pigs pulls in the same direction.

<u>*Palmaria palmata:*</u> due to high digestibility and positive outcomes in feeding trials with cattle and under the assumption that this alga does not contain other anti-nutritional

factors than iodine, RMDIR could be increased from the 0.88% to 10% in all animal species if the issue with high levels of iodine was solved.

Alaria esculenta, Saccharina latissima, Ulva sp.: Even if the issue with high contents of iodine and/or mercury/cadmium was solved, RMDIR levels could hardly be suggested to increase above 2% in diets for egg-laying hens and 5% in diets for other animals due to low CP and hence EAA content and low digestibility of OM. However, fish appear to perform well on Ulva enriched diets and here a potential RMDIR of 10% is suggested. In dairy cows no negative effects were observed on animal performance with inclusion of 4% *Saccharina latissima* in dietary DM (Nielsen MO, personal observation)

Microalgae: It has not been possible to find data for contents of critical minerals in any of the 4 microalgae species. Therefore, no RMDIR has been proposed for any of these algae. Provided critical mineral contents can be controlled in these algae, potential RMDIR values between 5% (egg-layers) and 20% (Chlorella in fish) are proposed for three of the species, which have been studied in feeding trials. Sensitivity towards increasing inclusion of the algae in feeding trials were used as criteria to assign a RMDIR value, and it was assumed that the utilization will be similar in poultry and fish.

Accounting for differences between animal species: It was generally assumed that the protein value of algae is lower for chicken than slaughter pigs, since pigs have a longer small intestine and consume less feed per kg body weight than both egg-laying hens and small, very fast-growing chicken. Pigs also count on hind-gut fermentation to some extent, which could improve utilization of algae OM. In fish, the underlying research was conducted with different species, including herbivorous species, however, differences in feeds appear to be a more important determinant for feed digestibility than the species of grower fish (Karasov and Douglas, 2013). RMDIR values for microalgae for salmon growers are therefore partly based on observations in other fish species, due to the lack of studies in salmon.

Substituting conventional feed protein with algae protein: Finally, it was assumed that the ability of algae CP to substitute feed CP in the diet would increase with increasing CP digestibility. A substitution ratio for conventional feed CP with algae CP was therefore defined. For algae with in vitro/in vivo CP digestibility in ranges of <25%, 25-50%, 50-75% and >75%, a substitution ratio was set to 0, 0.5:1, 0.75:1 and 1:1, respectively, and used to calculate the amount of spared conventional feed protein.

Table 38, Table 39 and Table 40 provide an overview of the knowledge base. Cells are empty when data are not available, they are yellow when data are available but based on strong assumptions and they contain a "✓" when data are available.

Table 38 Overview of available data in the relational database resulting from section 6 (part a)

Products	Production volumes			
	France	Denmark	The Netherlands	EU
Chicken meat	✓	✓	✓	✓
Eggs	✓	✓	✓	✓
Salmon meat	✓	✓	✓	✓
Pig meat	✓	✓	✓	✓
Milk	✓	✓	✓	✓
Beef meat	✓	✓	✓	✓

Table 39 Overview of available data in the relational database resulting from section 6 (part b)

	Conventional feed amount	Conventional feed GHG emissions
Chicken meat	✓	✓
Eggs	✓	✓
Salmon meat	✓	✓
Pig meat	✓	✓
Milk	✓	✓
Beef meat	✓	✓

6.7 Discussion

Research on use of algae as feed for food producing animals is still in its infancy, and there are huge knowledge gaps regarding nutritional value of algae (e.g., digestibility and assimilation). A significant research effort is called upon to fill these gaps and to develop methods to overcome the identified significant barriers for upscaled use of algae as feeds. It must be stressed, therefore, that the estimations in Table 33 to Table 37 regarding nutritional value of algae and the proposed RMDIR are associated with great uncertainty.

High content of unwanted-critical minerals (As, Cd, Hg, I) in macroalgae exceeding the EU defined maximum levels (ie., reject values) in feed, appears to be one of the major biological barriers for inclusion of certain algae species in diets for food-producing animals. Cost-efficient post-harvest treatments and/or cultivation methods need to be developed to overcome this barrier, since these minerals are of high concern – irrespectively of whether algae biomass is produced for human food consumption or animal feed. Blanching has been shown to be efficient in dramatically reducing iodine contents in macroalgae (Nielsen et al 2020), and ensiling of *Saccharina latissima* followed by removal of the produced juice reduced Cd and Hg by 35-37% (Bruhn et al 2019). Application of mineral reducing treatments to *Palmaria palmata* would mean that the full potential of 10% inclusion in animal diets could be reached. For all the selected algae species except *Palmaria palmata*, another major barrier for use as feeds is poor digestibility of OM due to the complex algae cell wall structure. Thus there is a need for future research to develop cost-efficient methods and/or breeding schedules to increase digestibility of algae OM to make them more competitive to terrestrial feeds.

Despite the limitations, even at a low RMDIR of 0.88% for *Palmaria palmata* (dictated by iodine), the total market potential for this alga in the EU, if prices can become competitive, amounts to 845.000 tons DM/year, demonstrating the huge market potential for the algae industry.

Table 40 Overview of available data in the relational database resulting from section 6 (part c)

	Recommended maximal dietary inclusion rate						Maximum dietary inclusion rate if critical mineral issues solved					
	Chicken meat	Eggs	Salmon meat	Pig meat	Milk	Beef meat	Chicken meat	Eggs	Salmon meat	Pig meat	Milk	Beef meat
Ulva in photobioreactor	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
Ulva in rope system	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
Asparagopsis in photobioreactors												
Asparagopsis in rope system												
Saccharina in rope system	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
Alaria in rope system	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
Palmaria in rope system	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
Haematococcus in photobioreactor												
Nannochloropsis in photobioreactor												
Chlorella in photobioreactor							✓	✓	✓	✓	✓	✓
Spirulina in photobioreactor									✓	✓	✓	✓

7 DATABASE OF RESULTS

7.1 Introduction

A relational database has been developed that includes all key data and results from section 2 to section 6. The database provides easy access to the key information gathered in the study while establishing the connections between the different tasks in the study. It is also used to generate additional results by linking data. A relational database allows for the storage of a large number datapoints in combination with storing their relationships. Setting the relations avoids multiple entries of identical information and allows for gathering and combining data in queries to generate additional output tables.

7.2 Structure of the database

An overview of the structure of the relational database and the study in this report is depicted in Figure 38. It is divided between information on member states, algae characteristics, data on animal feeds and results of the livestock nutritional needs in the feeds. Using the data on costs, and feed inclusion assessment aims is to arrive at the final results on the algae cultivation potential and carbon capture potential, carbon break-even price and at the algae diet demand.

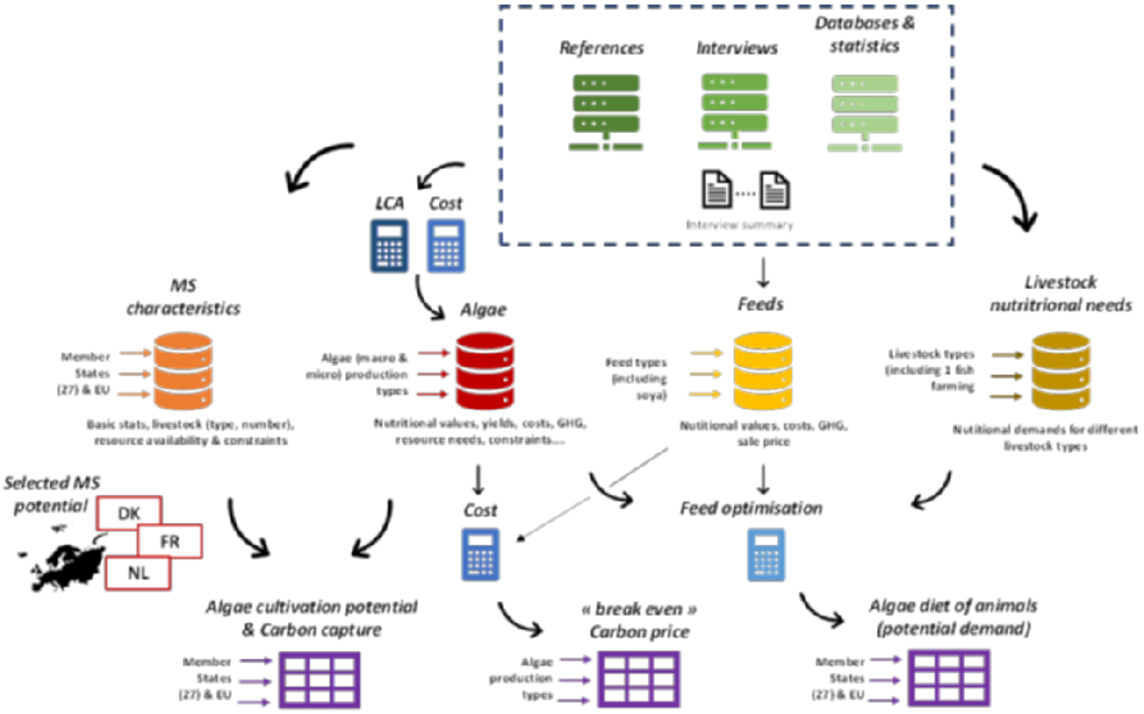


Figure 38 Structure of setting up the relational database

The database tool selected is Microsoft Access. Data collection was done in Microsoft-Excel, allowing for flexible development, and data process prior to uploading. After completion, the data was uploaded into the MS-Access relational format. From this addition, additional functionalities were implemented. An early exploratory test confirmed this is a feasible approach for the study.

The database consists of several tables which can be interlinked through attributes. The literature data is collected in these tables, listing the literature source. For all tables in database the literature source is listed in two formats:

- Author(s), publication year.
- The Reference number (Refnr).

- Here, the reference number refers to table *T00_References* that lists for each Refnr the bibliographic data of the reference: authors in BibTeX format, title, year of publication, journal or source, and the digital object identifier (DOI) or web address (URL) of the reference.

Each standard table has the following structure:

- Each line is characterized by the datatype which can be:
  - Literature data: each line can list, multiple data but from a single literature source.
  - Base/optimistic/conservative/base including estimate based on combination of literature sources. These are based on the average, minimum and maximum values the range in literature.

Generating the base, conservative and optimistic scenarios was done during data collection outside the database, doing this within the database was discarded in an early stage because it would make the process and the database much more complex. In addition, queries have been defined, in which data from the tables are combined using arithmetic operations to provide additional results.

Conventions in the database are as follows:

- The measure for seaweed is dry weight basis.
- The measure for feed amount is dry weight basis.
- The measure for product types (meat, eggs, etc.) is fresh weight basis.
- Units are EUR and metric tonnes (t), (kg, or weight percentage, or ppm or for trace components. Greenhouse gas emissions are in CO2 equivalents CO2eq.

The database allows for browsing results. Experience users may use the contents to define user-define queries to provide custom output results.

7.3 Overview of database contents

The database has the following key variations:

- Algae species: Ulva sp. Asparagopsis sp., Saccharina latissima, Alaria esculenta. Gracilaria sp, Palmaria palmata, Haematococcus pluvialis, Nannochloropsis sp, Chlorella sp, Spirulina sp, Dunaliella.
- Cultivation systems: marine rope systems (ROP), Open raceway ponds (RP), closed photobioreactors (PBR).
- Drying: natural gas drying, emission free drying (estimate only, for future use).
- Livestock products: Chicken meat, eggs, salmon meat, pig meat, milk, beef meat.
- Countries, either:
  - Focus member states France Denmark, Netherlands, and EU.
  - Or all EU 27 member states.
- Diet: the diet can be either:
  - Conventional diet (non-algae).
  - Algae diet, consisting of (i) conventional feed and (ii) algae feed.

In addition, to these keys, for making queries additional keys are available:

- Table T11: Landbased/marine, Phylum, Production Method, Land-based/marine, Fresh/salt, Open/closed.
- Table T51: Animal (chicken, fish, chicken, cattle), animal type, animal category, animal type.

Table 41 lists the data tables in the relational database, with a description of the table and a description of the parameters listed. In addition, in relevant tables the Refnr is listed referring to the full bibliographic data of the data source, and as well as the author/year for a quick identification of the data source.

Table 41 Data tables in the relational database

Data table	Description	Table contents
T_00	References	Refnr, Authors, Title, Journal/Source, year, DOI/URL
T11 Characteristics	Cultivation species, cultivation method and characteristics to be used as reference keys in	Production system, algae type, algae species, phylum, production method, salt/fresh water, open/closed
T12 prod data	Productivity data	Productivity data in various units of measurements (per ha, per m, net, gross), CO_2 uptake, Location
T13 Algae composition	Algae composition	Algae composition, extensive list of algae composition parameters, see below
T21 Algae costs	Algae cultivation costs	Fresh algae cultivation cost in EUR/tonne$_{dw}$ Breakdown of algae costs in CAPEX and OPEX Drying costs (from reference) used for obtaining dry weight cost Drying costs from the drying inventory T31 Dried algae costs
T31 Cultivation impact	GHG emissions in cultivation and drying	GHG emissions for respectively scope 1.1, 1.2, 2, 3, Total carbon footprint, Net carbon footprint, drying GHG from T21, Total carbon footprint including drying, net carbon footprint including drying.
T23 Drying	Drying cost and GHG emissions	Drying cost and GHG emissions
T31 CarbonPricCult	Carbon break-even price assessment	Algae cost, algae market price, CO_2 captured, CO_2 break-even price
T41 Mapping	Mapping results	Per country: CO_2 extrapolated, Yield, effective yield, CO_2 captured, and effective CO_2 captured, N-update and effective N-uptake for combinations Macro and micro, open and closed, and area restricted and CO_2 restricted.
T51 Products	Characterisation of livestock products for defining query key	Animal, animal categorie, animal type
T52 Production	Production volumes	Production volumes
T53 Reference diet	Reference diet	Conventional feed amount Conventional feed GHG emissions
T54 Algae diet	Algae diet	Recommended maximal dietary inclusion rate

		Maximum dietary inclusion rate if critical mineral issues solved Methane reduction efficiency

The algae composition is listed as a single level table, addressing the following categories:

Basic composition (% of DM):
- DM %, C, N, P, Ash, Crude protein, Total (crude) lipid, Carbohydrates

Carbohydrate composition (% DM):
- Cellulose, Starch, Alginate, Laminarin, Fucoidan, Ulvan, Agar, Floridian starch, other

Lipid composition (% of Fatty Acids):
- Polyunsaturated, Monounsaturated, Saturated, Omega 3 FA, EPA,

Essential amino acids (% DM), Essential and semi-essential amino acids (% of AA):
- Lys, Met, Thr, Trp, Ile, Leu, Val, Phe, His, Cys, Arg, Glu, Asp, Tyr

Macrominerals (ppm in DM):
- Ca, P, Mg, Na, K, Cl, S

Critical minerals (ppm in DM):
- I, Cd, Pb, As, As-in, Hg, Carotene

High value molecules:
- Lutein, Astaxanthin, Violaxanthin, Phyco- bili- protein, Polyphenols, Antioxidant activity

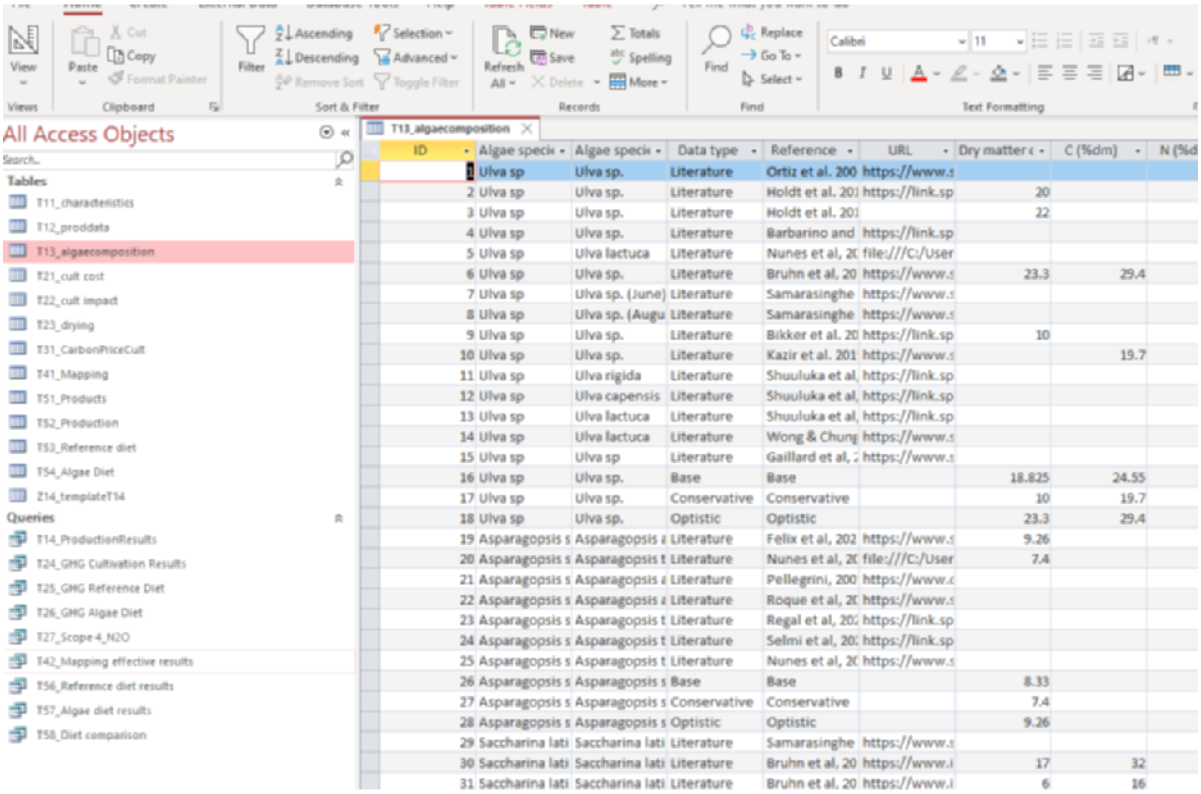
Table 42 lists the query tables in the relational database, with a description of the table and a description of the parameters listed. Query tables results from combining results: e.g. multiplying the algae productivity (amount of algae per hectares) and algae crude protein content from different tables can give the amount of crude protein per hectare. The queries can be made for all keys available in the database. To limit the information to the most important tables the queries available are restrict to (i) base scenario’s (ii) recommended inclusion rates for algae.

Table 42 Query tables in the relational database

Query Table	Description	Table contents
T14 Production results	Key nutria yields	Crude protein yield, lipids yield and essential ammino yield per area for algae cultivation
T24 GHG Cultivation results	GHG emissions from cultivation	Copy of all GHG emission characteristics Comparison of GHG emissions with and without scope 4 emissions (N_2O effect)
T25 GHG reference diet	GHG emissions of reference diet	CO_2 footprint of reference diet
T26 GHG algae diet	GHG emissions of algae diet	Utility table with intermediate numbers
T27 Scope 4 N2O	Scope 4 N_2O contribution	Calculation of scope 4 N_2O contribution, for use in T26

T42 Mapping effective results	Mapping effective results	Except from mapping table with effective results only for yield, CO_2, N
T56 Reference diet results	Reference diet results	Reference diet: conventional feed use and GHG emissions
T57 Algae diet results	Algae diet results	Algae diet: amount of conventional and amount of algae in algae diet
T58 Diet comparison amounts	Algae diet comparison, amounts of algae	Comparison between reference diet and algae diet amounts, all combinations of focus member states, algae species, and products
T59 Algae diet comparison GHG	Algae diet comparison, GHG emissions	Comparison reference diet and algae diet, for both recommended and maximum inclusion rates if mineral issues solved
T61 Algae diet *Asparagopsis*	Assessment of effect of rumen methane reduction	GHG with and without rumen effect
T61 Algae diet *Saccharina*	Excerpt for Saccharina only	GHG for reference, recommended and maximum inclusion rates

The results of the queries provide additional results to the relevant tasks. Results are discussed within these tasks. For illustration purposes only, a screenshot of the Algae and Climate relational database is depicted in Figure 39.



ID	Algae specie	Algae specie	Data type	Reference	URL	Dry matter (	C (%dm)	N (%d
1	Ulva sp	Ulva sp.	Literature	Ortiz et al. 200	https://www.s			
2	Ulva sp	Ulva sp.	Literature	Holdt et al. 201	https://link.sp	20		
3	Ulva sp	Ulva sp.	Literature	Holdt et al. 201		22		
4	Ulva sp	Ulva sp.	Literature	Barbarino and	https://link.sp			
5	Ulva sp	Ulva lactuca	Literature	Nunes et al, 20	file:///C:/User			
6	Ulva sp	Ulva sp.	Literature	Bruhn et al, 20	https://www.s	23.3	29.4	
7	Ulva sp	Ulva sp. (June)	Literature	Samarasinghe	https://www.s			
8	Ulva sp	Ulva sp. (Augu	Literature	Samarasinghe	https://www.s			
9	Ulva sp	Ulva sp.	Literature	Bikker et al. 20	https://link.sp	10		
10	Ulva sp	Ulva sp.	Literature	Kazir et al. 201	https://www.s		19.7	
11	Ulva sp	Ulva rigida	Literature	Shuuluka et al,	https://link.sp			
12	Ulva sp	Ulva capensis	Literature	Shuuluka et al,	https://link.sp			
13	Ulva sp	Ulva lactuca	Literature	Shuuluka et al,	https://link.sp			
14	Ulva sp	Ulva lactuca	Literature	Wong & Chung	https://www.s			
15	Ulva sp	Ulva sp	Literature	Gaillard et al, 2	https://www.s			
16	Ulva sp	Ulva sp.	Base	Base		18.825	24.55	
17	Ulva sp	Ulva sp.	Conservative	Conservative		10	19.7	
18	Ulva sp	Ulva sp.	Optistic	Optistic		23.3	29.4	
19	Asparagopsis s	Asparagopsis a	Literature	Felix et al, 202	https://www.s	9.26		
20	Asparagopsis s	Asparagopsis t	Literature	Nunes et al, 20	file:///C:/User	7.4		
21	Asparagopsis s	Asparagopsis a	Literature	Pellegrini, 200	https://www.c			
22	Asparagopsis s	Asparagopsis a	Literature	Roque et al, 20	https://www.s			
23	Asparagopsis s	Asparagopsis t	Literature	Regal et al, 202	https://link.sp			
24	Asparagopsis s	Asparagopsis t	Literature	Selmi et al, 202	https://link.sp			
25	Asparagopsis s	Asparagopsis t	Literature	Nunes et al, 20	https://www.s			
26	Asparagopsis s	Asparagopsis s	Base	Base		8.33		
27	Asparagopsis s	Asparagopsis s	Conservative	Conservative		7.4		
28	Asparagopsis s	Asparagopsis s	Optistic	Optistic		9.26		
29	Saccharina lati	Saccharina lati	Literature	Samarasinghe	https://www.s			
30	Saccharina lati	Saccharina lati	Literature	Bruhn et al, 20	https://www.i	17	32	
31	Saccharina lati	Saccharina lati	Literature	Bruhn et al, 20	https://www.i	6	16	

Figure 39 Screenshot of the Algae and Climate relational database

7.4 Development of the user guide

A user guide has been developed and is available in Annex 11.7 of this report. The user guide aims to make available the database for users that are not familiar with relational databases, guiding them through the basic structure. It also contains a guideline for more advanced use in making additional queries. The user guide contains the following elements:

- Introduction and objective.
- Database contents.
- Database structure.
- Accessing standard tables.
- Accessing standard queries.
- Selection of data for selected keys.
- Selecting scenario (literature, base, optimistic, conservative, base including estimate).
- How to write a custom query.

7.5 Discussion

The relational database effectively files information from literature, key results from the tasks and filing of scenarios. The database lists data directly from literature and for complex the complex analysis for the feed assessment and mapping tasks it is restricted to the key outcome results. The database allows for adding additional data points. A limitation is that when adding additional datapoints, the values for base, optimistic and conservative scenarios need to be updated by the user since it was found that automating this in the database would make the structure too complex and less user-friendly. The data tables can effectively be combined to generate additional results. Multiple query tables are added with this information.

8 CONCLUSION, LIMITATIONS AND FURTHER RESEARCH

Building on an extensive review of the available literature, complemented by a survey and in-depth interviews with recognized EU algae experts, the study has addressed the following questions for 10 microalgae and macroalgae production systems seen as having a high development potential in the EU.

8.1 What biomass and nutritional yields can algae provide?

With present cultivation systems and yields, microalgae production systems can deliver higher nutritional yield (in tonnes of crude protein per area per year) as compared to macroalgae. Within macroalgae production systems, land-based production of fast-growing species such as *Ulva* performs similarly to low yielding microalgae systems, with kelp production at sea having the lowest nutritional yield per unit of surface area.

Nutritional yields and compositions are overall highly variable between species, both between and within the groups of micro- and macroalgae. Also, large variations are reported for the same production systems and species depending on cultivation and stress conditions. These results need to be seen in the perspectives that 1) marine cultivation systems are not yet fully optimized towards area efficiency, nor necessarily towards protein production; 2) availability of land is scarce.

8.2 What are the greenhouse gas emissions of different types of algae production technologies?

With regards to CO_2 uptake, the CO_2 fixation efficiency is generally higher for (semi) closed systems (independently of the algae species) as compared to open systems, with average efficiency of 60% versus 30%, respectively. Values reported in the literature for carbon footprint are highly variable, as individual studies apply different system boundaries for their assessments. Most studies do not include estimates of the emission capture at scope I, nor drying or emissions embodied in the material inputs for construction phase (scope III).

For soy-based feed reported, CO_2 footprint vary from 0,5 to 6 kg CO_2e per kg dw feed as compared to a total carbon footprint, i.e. excluding CO_2 assimilation in the biomass, ranging from 21 to 1087 kg CO_2/kg dw microalgae and 1.5 to 16 kg CO_2/kg dw macroalgae biomass from offshore production systems.

For *Saccharina latissima,* offshore production, the net carbon footprint varied from – 0,7 to 3,1 kg CO_2e/kg dw algae with a base value 0,5 kg CO_2e/kg dw algae. The total CO_2 footprint ranges from 0,4 to 4.6 kg CO_2/kg dw, with a base value of 7,6 kg CO_2e/kg dw algae. For technological mature cultivation systems, net negative CO_2 footprints are observed at the time of harvest. The latter documenting the opportunity for the cultivation systems to deliver non-financial profits from climate change mitigation services.

To be able to compare carbon footprint between terrestrial and aquatic biomass production systems, the system boundaries need to the same. Including emission capture in the net carbon footprint accounting is based on the fact the offshore cultivation systems represent an engineered ecosystem service; i.e. an artificial green engineered seeded growth substrate designed for emission capture and utilisation that supports natural ecosystem services through water quality restoration. Land-based unfertilised algae production systems that captures emissions in industrial process waters prior to their release delivers the same restorative services to marine systems, by contributing to a net reduction in anthropogenic nutrient flows from the agrifood system which have exceeded the regulatory capacity of the earth ecosystem.

To compare with soy-based feed, carbon capture should be included as well and in addition carbon emissions from the soil system. For terrestrial systems, net negative emissions may only be obtained at the time of harvest upon successful implementation of regenerative agricultural practices with proven restoration of the soil organic carbon content to pre-industrialised levels. Fertilizer production and use would need to be included together with other chemical inputs, irrigation, construction, and use of infrastructure machinery etc. For these reasons a transparent and complete reporting of scope I-IV emissions and emission capture is needed before a meaningful comparison of carbon footprint can take place.

The green engineered algae production systems presented in this report have no fertilizer inputs as the algae feeds on CO_2 dissolved in marine waters and excess nitrogen emitted to the aquatic system mainly from the agricultural sector. As such the engineered ecosystem services from offshore algae production systems have the potential to deliver value in terms of non-financial profits by turning “pressures” on the state of the environment into “progress” or “growth positive targets” in terms of water quality restoration and mitigation of ocean acidification and climate change.

As such, we argue that algae represent a nature-based emission capture and utilisation technology that may substitute resource and emission intensive land-based proteins. At farm stage, gate-to-gate, we have presented net negative emissions in best cases. The use of land-based and off-shore algae production systems as nature-based emission capture and utilisation provide progress in the distance to target measures according to the water framework directive. Lastly, in the case of the methane inhibiting effect of enteric fermentation at scope IV, a significant contribution to the goal of a future climate neutral agricultural sector.

8.3 What are the costs of different types of algae production technologies?

Biomass cost information is very scarce, in particular for macroalgae. Costs for marine macroalgae reported in literature are on average around 10 €/t_{dw}, but very uncertain since a variation of an order of magnitude is observed, so possibly costs could be lower. Costs of land-based cultivation are reported lower, but again with limited data and a large uncertainty range that overlaps with marine. The costs of macroalgae reported are currently significantly higher than of conventional feeds.

Considering microalgae, the average price of 1 kg of crude proteins from soybeans meal is between 0.85 to 0.92 €, compared to 94 € on average for 1 kg of crude protein from microalgae, making algae-based feed not yet competitive with existing feeds. The analysis of microalgae costs stressed their high dependency on labour and energy prices, highlighting the potential role renewable energy (e.g. photovoltaic energy) can play to address energy costs in the long run.

8.4 Under which conditions would algae production be competitive?

As a result of the relatively low amount of carbon captured by algae production systems, levelling out costs with additional revenues from the purchase of carbon credits would require carbon credit prices being significantly (unrealistically) higher than today’s (EUR 80/ton of CO_2) and future credit prices (between EUR 150/ton of CO_2 and EUR 200/ton of CO_2).

Obtaining additional revenues from the sale of carbon at the actual market price would not be sufficient to deliver algae feed that is competitive with existing alternatives in the market (soybeans meal). However, algae production can still represent a promising avenue in the fight against climate change (lower carbon and environmental footprint compared to conventional feed) and for algae farmers to obtain an additional income from carbon credits.

8.5 What could be the potential total algae production in Europe and What will be the resulting carbon dioxide captured?

If algae production were expanded to capture the CO_2 emission from point sources at the EU scale, it could: (1) deliver a potential yield from algae production ranging between 146 mill.to 392 mill. ton dw/yr; with (2) a total amount of CO_2 captured by algae production systems ranging from 160 mill. to 719 mill. t CO_2/yr. The availability of land is likely to be the main constraint for all countries, with water availability being a constraint for countries already facing water over-exploitation (that is likely to deteriorate even further in the future because of climate change).

The performance of systems in relation to light or length of the growing season, and the costs of fertilizer and of infrastructure required for transporting CO_2 from emission points to production areas, will impose additional limitations to this potential development. Additionally, countries will face challenges in production, upscaling, post-processing, and market in relation to regulations, technology, costs, and social awareness. In relation to regulation, the challenge will be to bring EU and national food and feed regulations up to date with regards to algae being a unique and diverse group of organisms not comparable to animals, plants, or fungi.

8.6 Which share of animal’s feed requirements could be met by algae production?

At present, neither macro- nor microalgae can be marketed at a price that make them competitive to terrestrial plants as feeds for livestock. However, there is a huge future potential for marketing of certain algae species as livestock feeds, provided technical solutions can be developed to overcome certain barriers. Refinement of algae production systems to achieve both substantial reductions of production costs as well as dramatic increments in production of algae biomass is one of the major barriers, not least for exploitation of the tropical red macroalgae *Asparagopsis sp.* as an instrument (feed additive) to achieve dramatic reductions in methane emission from ruminant livestock (appr. 30% in dairy cattle, and 50-75% in beef animals).

High content of unwanted critical minerals (As, Cd, Hg, I, Pb) in macroalgae exceeding the maximum levels (i.e., reject values) in feed biomass defined by the European Food Safety Association (EFSA), is one of the major biological barriers for inclusion of certain algae species at all in diets for food-producing animals, or in the case iodine limiting the maximal possible dietary inclusion for some species to a very low level (<0.5% of diet dry matter). These maximal contents of critical minerals have been defined due to human health concerns, hence high contents should be of equally great concern, when algae are marketed directly for human consumption.

For all the selected algae species, except *Palmaria palmata*, another major barrier for use as feed is poor digestibility of organic matter and hence low nutritional value due to the complex algae cell wall structure. Hence, research and development are needed to develop cost-efficient post-harvest treatments and/or cultivation methods and/or algae breeding schedules to overcome these barriers and make cultivated algae competitive to terrestrial feeds. Despite the limitations for dietary inclusion of *Palmaria palmata* (dictated by iodine), the total market potential for this algae species in the EU, if prices become competitive, would amount to 845,000 tons DM/year, and if technologies to reduce iodine were applied, this number would increase more than 10-fold, demonstrating the huge market potential for the algae industry.

9 RECOMMENDATIONS

Overall, the study stresses that algae production is an area where production and Research & Development are evolving in parallel. This results in a significant variability in values estimated for criteria investigated in the present study. Continued support of algae cultivation in combination with research and development is important to bring down algae production cost, as well as to provide better data on costs and environmental impacts. Interviewees highlighted the necessity to upscale algae production to achieve cost reductions, as well as the necessity to investigate novel value-added applications to add to the economics.

The potential of algae production goes beyond the species and production systems considered in the analysis. Respondents to the online survey identified additional 40 macro- and microalgae species as having potential and requiring further investigation, as well as additional land-based production systems such as ponds, raceway ponds and heterotrophic production/fermentation. Survey respondents also confirmed the need to further investigate post-harvest processing and algae breeding to support upscaling of biomass production in a sustainable manner, economically as well as environmentally, and not least to overcome identified barriers for inclusion of algae in animal diets, i.e. high contents of critical minerals in algae feed and low nutritional value.

Future work should consider the benefits of algae production and consumption, compared to other protein sources (direct benefits but also avoided costs). There are likely many (environmental) benefits and avoided costs that might be calculated, which would also help stimulate the demand for algae products. To document the non-financial profits from algae cultivation, it is important to adopt a harmonized CO_2 accounting framework that differentiates between scales of restorative environmental impacts. Reporting CO_2 emissions according to scope I to IV would enable as transparent quantification of the algae cultivation system value in terms of non-financial profits such as I) water quality restoration obtained through mitigating eutrophication (scope IV, local scale), and ii) mitigation of ocean acidification and climate change (scope I, global scale).

Such accounting systems would allow for the assessment of algae production systems design and to identify pathways towards optimal non-financial profits contributing to bringing the food system inside the planetary boundaries – algae as an emission capture and utilization technology that contributes to solving the global societal challenges associated to the transgression of the planetary boundaries. If designed in the right way, algae could provide a regenerative circular blue economy that thrives by turning emissions into revenue streams with a documented net negative carbon footprint.

To assess the total potential of algae production Europe, the estimation of land-based marine algae production potential should be complemented with a similar analysis for marine production systems. Furthermore, the potential for land-based marine algae production can be further refined by improving the estimation of the constraints parameters and by including additional parameters, such as competition with other uses. Future research at the local scale can contribute to get a better understanding of algae production limitations. This information can then be used to refine European level assessments of algae production potential.

Research on use of algae as feed for food producing animals (especially terrestrial species) is still in its infancy, and there are significant knowledge gaps regarding nutritional value of the algae (e.g., digestibility and other aspects of nutritional quality). A substantial research effort is required to develop methodologies (e.g., post-harvest processing, algae breeding) to overcome identified biological barriers for the use of algae as feeds (high contents of critical minerals, low digestibility) and improve the nutritional quality of algae biomass. For the tropical red algae, *Asparagopsis sp.,* cost-efficient upscaled production represents the main (only?) barrier for exploiting its potential as a methane mitigating instrument in ruminant livestock production.

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11 ANNEXES

11.1 Interviewed experts and stakeholders from the EU

All experts interviewed agreed to have their name and affiliation published.

Microalgae:

- Professor at WUR Wageningen University and Research, (Wageningen, the Netherlands), director of AlgaePARC (Wageningen, the Netherlands)
- Chief Scientific and Technical Officer of AlgoSource (Saint-Nazaire, France)
- Scientific Consultant at Archimede Ricerche Srl (Genoa, Italy)
- General manager of the European Algae Biomass Association

Macroalgae:

- Research manager, Ocean Rainforest, Faroe Islands
- Co-founder and chief product officer, VoltaGreenTech, Stockholm, Sweden
- Research Specialist, Hortimare, Texel, the Netherlands
- Associate professor, KTH Royal Institute of Technology, Stockholm, Sweden. Head of Blue Food and Kristineberg Research Station. Involved in the spin-off company Nordic Seafarm
- Founder and CEO of Maripure, Aalborg, Denmark
- Founder and CEO of PureAlgae Aps, Grenaa, Denmark

11.2 interviewed experts and stakeholders from CHINA

No Chinese experts have been interviewed.

11.3 Interview guidance (English)

Who are you?

Type of organisation:

Position:

Cultivation

Discussion on cultivation methods applied. Possible subjects:

- What species do you consider in your work?
- Which of these species are relevant for feed applications?
- What type of cultivation system do you consider?
- (Land based only) What resources do you use for algae cultivation:
  1. Use of CO2 for production? Quantity, quality (bottle, side stream, etc.) system
  2. Use of fertiliser (grow media) for production? Quantity, type, price
  3. Use of fresh water (artificial sea water? Recyclability?) for production? Quantity, price
  4. Use of land area for production? Area
- What are the main challenges faced today with algae production?
- Do you have specific challenges with respect to regulation, technology and upscaling, access to input at adequate prices, climate, access to financial resources, partnerships, etc.
- Can you share/recommend data on or reference production system considered. E.g. providing:
  1. Production scale: Now, expected production scale in 1 year, expected production scale in 5 years:
  2. Biomass yields per hectare, max, average, and main factors influencing biomass yield:
  3. Costs - CAPEX (and main components of CAPEX)), OPEX (and main components of OPEX)

Post-harvest processing

- Discussion on cultivation post-harvesting processes applied. Possible subjects:
- Which type of processing do you apply and what is it the main purpose?
- What are the main inputs required for post-harvest processing (energy source, additives)?

Markets

Discussion on markets for algae that are targeted. Possible subjects:

- What are the markets you target (food, feed, pharma, cosmetics, chemicals, fuels, R&D other (please specify))?
- What are your main clients and are these inside or outside the EU?
- What are the main challenges in (developing) seaweed/ microalgae markets?

Looking ahead

Discussion on the future of algae. Possible subjects:

- Are there any new developments in algae for food that you think are important?
- Novel species (which ones, why, likely challenges to be faced).
- Innovative technologies for cultivation or post-processing.

New markets that are emerging.

- Do you see a role of algae in climate change mitigation?
- Do you see a role for carbon or nutrients credits in algae cultivation?

Request for additional information

- Do you have any relevant literature, reports or other information that you could share.

Last input/comment/suggestions

- Open contribution by the interviewee to complement and provide a different perspective to the questions above.

11.4 Interview guidance (Chinese)

在应对气候变化方面，藻类养殖有哪些潜力？

您的身份信息

1.当前日期是：____ （格式为2019年1月7日）

2.名：______ 。 ____

3.姓：____ 。 ________

4.邮箱地址：____ 。____

5.来自单位名称： ____ 。

6.您的单位属于： ____ 。

- 研究机构
- 公司企业
- 国家机构
- 商业协会
- 消费者协会
- 环境组织
- NGO组织
- 商会
- 其他：____ 。

7.您是在外企就职吗？如果是，请问总部是在哪个国家？如果不是请填写中国： ____ 。

8.您的单位的规模大小：____

- 很小：1到9名成员
- 小：10到49名成员
- 中：50到249名成员
- 大：多于250名成员

9.请问您的单位在海藻产业中负责哪些环节？（可多选）

- 海藻前期处理

- 养殖生产
- 海藻加工
- 海藻养殖技术服务
- 海藻产品销售
- 相关研究
- 其他

10.请问你的工作主要在以下哪个领域

- 微藻
- 大型藻类
- 两个都有

用于生产的海藻种类

本项欧盟研究主要针对以下10个藻类物种：

	物种	宏观/微藻	生产方法
1	Saccharina latissima (Laminariales, Phaophyceae)	大型藻类	绳索系统
2	Alaria esculenta (Laminariales, Phaophyceae)	大型藻类	绳索系统
3	Palmaria palmate (Rhodophyceae)	大型藻类	绳索系统
4	Asparagopsis sp. (Rhodophyceae)	大型藻类	绳索系统
5	Asparagopsis sp. (Rhodophyceae)	大型藻类	光生物反应器
6	Ulva sp. (Chlorophyceae)	大型藻类	绳索系统
7	Spirulina (Spirulinales, Cyanophyceae)	微藻	光生物反应器
8	Chlorella sp. (Chlorellales, Treboxiophyceae)	微藻	光生物反应器
9	Haematococcus pluvialis (Chlamydomonadale, Chloriphyceae)	微藻	光生物反应器

10	Nannochloropsis sp. (Eustigmatales, Eustigmatophyceae)	微藻	光生物反应器

11. 除了上面列出的10个物种外，您觉得还有哪些物种是有养殖生产的可能性，值得我们将它（们）列为研究对象？

据我所知，没有了。

据我所知，还有其他物种值得研究。

12.其他值得研究的物种有：________。

13.您认为，哪个藻类物种和种植技术在欧洲拥有最大潜力？（请详细阐述）

14.您认为，哪个藻类物质在作为动物和鱼类饲料方面具有最大潜力？（请详细阐述）

养殖系统的特点

15. 请选择以下您所熟知的养殖系统，并分享给我们您的见解。

- Saccharina latissima (Laminariales, Phaophyceae) 绳索系统
- Alaria esculenta (Laminariales, Phaophyceae) 绳索系统
- Palmaria palmate (Rhodophyceae) 绳索系统
- Asparagopsis sp. (Rhodophyceae) 绳索系统
- Asparagopsis sp. (Rhodophyceae) 光生物反应器
- Ulva sp. (Chlorophyceae) 绳索系统
- Spirulina (Spirulinales, Cyanophyceae) 光生物反应器
- Chlorella sp. (Chlorellales, Treboxiophyceae) 光生物反应器
- Chlorella sp. (Chlorellales, Trebouxiophyceae) 光生物反应器
- Haematococcus pluvialis (Chlamydomonadale, Chloriphyceae）光生物反应器
- Nannochloropsis sp. (Eustigmatales, Eustigmatophyceae) 光生物反应器
- 无

16. 欧洲目前的产量是：_______ （单位：吨/每年，干重）

17. 未来五年，预计欧洲总产量 _______ （单位：吨/每年，干重）

18. 目前每公顷种植面积的产量是：_______ （单位：吨/公顷/每年，干重）

19. 每千克干重生物质对应的二氧化碳吸收量为：_______ （单位：吨二氧化碳/千克海藻，干重）

20. 目前海藻的市场价格：_______ （单位：欧元/千克海藻，干重）

21. 养殖海藻需要的氮肥用量是：_______ （单位：千克 氮/千克海藻，干重）

22. 养殖海藻需要的磷肥用量是：_______ （单位：千克 磷/千克海藻，干重）

23. 养殖海藻需要的淡水用量是：_______ （单位：立方米 淡水/千克海藻，干重）

24. 养殖海藻的总支出是：_______ （单位：欧元/千克海藻，干重）

25.养殖海藻需要的资本性支出是：_______ （单位：欧元/千克海藻，干重）

26.养殖海藻需要的经验管理维护支出是：_______ （单位：欧元/千克海藻，干重）

27. 当今生产面临的主要挑战（多选）

- 法规
- 技术
- 高成本
- 生产资料的获取
- 生产资料的价格
- 气候
- 财政资源/补贴
- 合伙人
- 缺乏知识
- 社会认知与接受度
- 其他，请注明

28. 扩大生产面临的主要挑战（多选）

- 法规
- 技术
- 高成本

- 生产资料的获取
- 生产资料的价格
- 气候
- 财政资源/补贴
- 合伙人
- 缺乏知识
- 社会认知与接受度
- 其他，请注明

29. 海藻收割后的处理步骤有哪些？请具体描述。

30. 海藻收割后的处理的主要困难点（多选）

- 法规
- 技术
- 高成本
- 生产资料的获取
- 生产资料的价格
- 气候
- 财政资源/补贴
- 合伙人
- 缺乏知识
- 社会认知与接受度
- 其他，请注明

31. 海藻收割后的处理的处理费用为：_______（单位：欧元/千克海藻，干重）

32. 海藻收割后的处理的资本性支出为：_______（单位：欧元/千克海藻，干重）

33. 海藻收割后的处理的经验管理维护支出为：_______（单位：欧元/千克海藻，干重）

34. 这个物种的主要用途为：

- 食品
- 动物饲料 - 家禽
- 动物饲料 - 鱼类养殖
- 动物饲料 - 其他
- 能源（生物能源）
- 特殊化学品（用于药类，营养素，化妆品生产）
- 其他，请注明

35.主要消费市场为？（消费者类群；地区：欧盟或非欧盟）

36. 目前消费市场可能面临的主要挑战来自哪些方面（多选）

- 法规
- 技术
- 高成本
- 生产资料的获取
- 生产资料的价格
- 气候
- 财政资源/补贴
- 合伙人
- 缺乏知识
- 社会认知与接受度
- 其他，请注明

未来发展

28. 您认为，哪些新颖的藻类物种，将来可能会带来机遇呢？（请详述）

39. 您认为，哪些新型/创新养殖技术，将来可能会带来机遇呢？（请详述）

40.你最看好哪个新兴市场，以及您觉得哪个市场最有发展机遇呢？（请详述）

您对本次问卷调查的评价与建议

41. 请问您有什么想要补充的吗？

42. 请问可以分享给我们您的信息来源吗？（比如网站链接，或者您参与的项目名称)

非常感谢您的参与和贡献！

11.5 Interview summaries experts EU

Position and affiliation of interviewee: Professor at WUR Wageningen University and Research, director of AlgaePARC (Wageningen, the Netherlands)

The activities of WUR (WUR, 2022) and AlgaeParc (AlgaeParc, 2022) cover the full microalgae process chain, from development of new strains through genetic engineering, algae cultivation harvesting to process and applications including biorefinery, all in cooperation with research partners and industry. AlgaePARC was founded in 2010 when there was almost no algae industry in Europe. It was aimed at comparing concepts, scale-up and increasing efficiency and reducing microalgae production costs. For this, techno-economics evaluations and environmental assessments are included.

AlgaePARC considers both open ponds systems, as well as photobioreactor (different types e.g. flat panels, tubulars, etc.) as required for the species to be cultivated. Both are though to stay relevant, each suitable for specific algae species and applications. Nowadays, the tubular photobioreactors are commercially available and these are applied by AlgaeParc. New trends are the development of indoor algae cultivation aimed at year-round production in northern countries, which is most beneficial for biorefinery applications. Downstream processing is generally concentration by membrane separation, drying and for some species also milling. The energy demand of drying has an important impact. One relevant concept explored was a cascading concept where the oil was extracted from the algae, and where the solid residue was used for feed purposes.

AlgaeParc provides technology development through project performed trials, includingwith larger amounts of biomass. The trials are predominantly autotrophic algae production, but also more recently mixotrophic algae production. Only small-scale heterotrophic algae have been considered, but there are plans to include on short term a pilot-scale fermentor at AlgaePARC. Commercially, heterotrophic microalgae are produced and sold by large companies (such as Corbion, VERAMARIS (Evonik) +DSM), DSM, Fermentalg, Allmicroalage). Downstream operations are important since they have a large impact on efficiency and economics. Harvesting has highest impact in open pond systems due to the low microalgae concentrations reached. Separation technologies used include membranes filtration and centrifugation.

The market in algae has largely increased the past year to now 30 000 tons/yr, but this is still minor compared to the world market of soy which is 350 million tonnes/yr. Still there is a lot of interest because we need these kind or technologies, which use land much more efficiently, up to 40 times less land use. Interesting markets at present, are those for nutraceuticals and vegan food, e.g., algae protein bars. Typical autotrophic algae production costs in Europe are currently 20 EUR/kg_{dw} , in one hectare production facility. The largest cost is in energy and nutrients use. Even when using seawater, nitrogen, phosphorous, and CO_2 needs to be added. Advantage of algae cultivation as opposed to conventional crops is that the nutrients can be 100% used because the cultivation is contained, in opposite to agriculture where 50% of the nutrients are lost in the soil and water. Scale-up is required to reduce the costs of algae cultivation. Still, here there is a chicken-and-egg problem where prices are high because of the small production facilities and present market volume, hindering further market expansion. Scale-up will be an important decision maker and the extremely high efficiency of land use without requiring arable land needs to be seriously considered.

Species considered are *Nannochloropsis* that is interesting for its high protein and omega-3 fatty acid content. This can be used for aquaculture feed and as nutraceutical. *Galdieria* is interesting extremophile heterocyclic algae grown at very low pH, which has a high protein content (60%), with special sulphur amino acids. Other species considered are *Chlorella* (40% protein), *Spirulina*, *Tetraselmis (all 3 Novel Food in Europe)* and *Nannochloropsis (Novel Food in China).*

An important market for the future is as single cell protein for human consumption and for aquaculture, as a source of protein and especially oils that accumulate in the fish. Relevant here are the omega-3 fatty acids such as DHA (docosahexaenoic acid) for infants as now produced commercially at large scale from algae by DSM. An EPA/DHA (eicosapentaenoic acid) is now produced from heterotrophic algae by DSM/Evonk. These components could also be produced from autotrophic algae. A comparison of the production costs between autotrophic and heterotrophic production of 6000 tonnes of biomass /yr showed that production costs are slightly lower for autotrophic (Ruiz, Wijffels, Dominguez, & Barbosa, 2022), but that would require a 100 ha facility of autotrophic production, which does not exist at the moment. Once more this would require scale-up and significant investments.

To cover the world market of EPA only a limited surface area would be required, about the size of Boa Vista, one of the Cape Verdean Islands.

Position and affiliation of interviewee: Chief Scientific and Technical Officer of AlgoSource (Saint-Nazaire, France)

AlgoSource (AlgoSource, 2022) is a French company that cultivates microalgae for producing microalgae extracts. They also do objectivation of the finished products by performing clinical studies on their products to demonstrate the efficiency. As such they cover the full microalgae value chain. The target markets are mainly nutraceuticals for human use and pets, and R&D is aimed at the development of new nutraceuticals and improved cultivation and extraction techniques. Pharmaceuticals are not considered given the large time-to-market and large investments required.

Spirulina is grown in indoor (greenhouse) raceway ponds and in newly develop intensified photobioreactor for new more sensitive strains such as *Porphyridium cruentum* and *Scenedesmus.* Marine microalgae (e.g. *Nannochloropsis*) have been cultivated in the past for niche markets but these operations have stopped.

During cultivation CO_2 is added in the form of bicarbonate. Nutrients are added from commercial producers. Since recently, certified organic fertilizers are used that have been extracted from agricultural residue streams.

Current challenges in algae cultivation are the high cost compared to Asia and North-Africa. In Europe costs for labour are higher and norms are stricter increasing costs. The production of raw *Spirulina* is therefore not competitive. As for this, the scale of cultivation remains small, and costs remain high. As opposed to many other agricultural activities, microalgae cultivation is done without subsidies.

A competitive edge is obtained by AlgoSource by extracting the active components based on inhouse knowledge. These have a higher market value than the raw algae. Innovation is therefore important. Currently 5 new nutraceutical products are under development. Feed ingredients are also an interesting market. Feed components are part of the codex and can therefore be applied easily.

Sustainability is an important issue and has been addressed in research projects that AlgoSource has participated (results have been shared with the Algae and Climate consortium). The result show that overall algae is not better, or even worse in CO_2 emissions per kg of product than conventional agricultural products. The current emissions are for spirulina are 15 kg CO_2/kg algae (dw). Novel systems using LED will lead to higher emissions (assuming the current French electricity mix) and higher costs given the limited efficiency of photosynthesis efficiency of algae and that of the LED. The project CIMENTALGUE (Vicat, 2022) has shown that this could potentially be reduced to 5 kg/kg by (i) reducing electricity consumption (ii) optimised infrastructure and (iii) reducing emissions associated to the nutrients. Using industrial symbiosis, it is even possible to have a significant net positive take-up of CO_2 (LCA) approach of 10 kg/kg algae(dw), which is over 5 times the CO_2 captured by the algae (1.8 kg CO2/kg algae).

An advantage of algae cultivation that these can be grown to produce proteins and vitamins in non-arable land for example at industrial sites, polluted ground or abandoned landfills and salt marches. This would add to the feed produced in Europe and could be used as additive to conventional feed. This aspect is generally not covered sufficiently when performing assessments such as life cycle assessment studies. Another service that algae could provide is the capture of nutrients from industrial sources. Using the industrial symbiosis approach on these sites, a CO_2 reduction of 200 tonnes per ha could be achieved.

Position and affiliation of interviewee: Scientific Consultant at Archimede Ricerche Srl (Genoa, Italy)

The interviewee has worked since 2008 in microalgae at Archimede Ricerche (Archmede, 2022) and its subsidiary Microalghe Camporosso (MicroalgheComporosso, 2022). Currently he cooperates as an external consultant, for scientific affairs and standardisation. For microalgae farming, Microalghe Camporosso has a 1 ha facility in Italy. Both raceway ponds as green panels photobioreactors are used, both are HACCP certified for producing food grade quality products. A new in-house system is based on photobioreactors using LED artificial light. Species considered: marine microalgae (*Nannochloropsis, Isochrysis, Tetraselmis and Phaeodactylum)* and *Spirulina.* Development of new species is relevant but is not worked at by Archimede*.* These are cultivated using artificial sea water. Nutrients are added as available commercially. Since recycling of nutrients is important for environmental as well as for economic reasons the nutrient effectivity is very high as compared to conventional agriculture.

The markets targeted are European markets for food, feed, and cosmetics.. The most interesting feed market currently are hatcheries for fish farms where specialty feed is required. The market value of these feeds is typically factor 10 higher (10 EUR/kg) than for bulk fish farm feed (order 1 euro/kg). The product can be delivered frozen (20-30%dw) or freeze-dried. The high costs of algae biomass are still a barrier. Competition with Asia on Spirulina is significant.

The environmental benefits on algae are in both CO_2 uptake (mostly for macroalgae) and nutrient uptake. The latter is relevant mitigating nutrient emissions from waste-water treatment, where also bacteria and algae (also using seaweed) could be used together. Being photosynthetic organism microalgae capture CO_2, but microalgae carbon farming is not the most relevant climate tool since they capture and equal amount of CO_2 as plants. Potentially, algae could be interesting if we would take the full life cycle into account including all the emissions from farming. The problem here is that currently there might be a bias since for microalgae studies the full chain emissions are considered whereas for agriculture these could be simplified and some of the externalities are not accounted for. The interviewee is also one of the coordinators for the development of European standards for algae. Very relevant for the Algae and Climate project is the development of standards for sustainability assessment that ensure that comparison is done on an equal basis.

Position and affiliation of interviewee: General manager of the European Algae Biomass Association

The general objective of the European Algae Biomass Association (EABA, 2022) is to promote mutual interchange and cooperation in the field of (micro and macro) algae biomass production and uses in all applications. The interviewee has worked himself on microalgae. Amongst other starting the company Necton (Necton, 2022) a 25 y/o company that produces microalgae for cosmetics applications and Algae for Future (A4F, 2022), a 16 y/o start-up company for aquaculture. He was also involved in over 70 research projects, partly in the companies because algae production operations are generally combined with algae research projects. The main microalgae considered in the production facilities are Chlorella, Nannochloropsis, Haematococcus, all mainly for food applications (entire cells/ harvested by filtration and spray dried). Newest developments in Lisbon are considering biorefinery strategies and extraction of specific compounds: Dunaliella for beta-caroteen and Algae powder for nutraceuticals. For macroalgae, Asparagopsis is under research In Portugal and Sweden, but cultivation is currently somewhat challenging. The interviewee believes seaweed pond cultivation is very promising, more than marine rope systems. The challenge is to get to the very high numbers required to make a significant impact.

The technologies considered in algae cultivation focus on both raceway ponds, was well as photobioreactors (both flat panel and tubular type). The type considered is directly associated with the algae type, where photobioreactors are required for the more for sensitive species and where robust and fast-growing species in raceways ponds. Cultivation of algae is often considered difficult, but it is not difficult with the proper knowledge. For example, the use of treated (micro filtrated) water makes cultivation much easier and could avoid many problems (it can also serve as recycling water/nutrient system up to 98%).

The most interesting market currently is nutraceuticals for human application, and use of algae for feed additives is a logical next step. THe provision of amino acids is very interesting and important specifically as antioxidants and polysaccharides. . Heterotrophic algae growth could be interesting as a source of beta-glucans. Heterotrophic cultivation is presenting as the trending cultivation alternative for high value application markets. Also, the use or algae as a source of bio-stimulants for agriculture is promising. Problems in the market currently is the high price of electricity.

The interviewee stressed the importance of the Algae and Climate study. The information provided by the study will be a critical an important step in breaking the cycle where there is too little information for support of algae and algae information is scarce because there is too little support or information that can mislead. Also, potential inclusion of algae as part of the European taxonomy was mentioned, for which more information would be required.

Position and affiliation of interviewee: Research manager, Ocean Rainforest, Faroe Islands

Ocean Rainforest is one of the major European seaweed producing companies, cultivating Saccharina latissima, Laminaria digitata, Alaria esculenta and Macrocystis pyrifera on ropes in the sea. Ocean Rainforest has developed the macroalgae cultivation rig (MACR) cultivation system, that tolerates offshore high energy environments, and has a production this year of 100 fresh tonnes of seaweed, aiming for 300-600 fresh tonnes in 2023. The area yield is approximately 40-ton fresh seaweed per hectare, assuming bi-annual harvest. Yield potential is controlled by yield per m of cultivation line and harvest efficiency, and the ability to perform bi-annual harvest. Post-harvest processing involves fermentation/ensiling (feed and food), drying (food) and to a very minor degree freezing. Post-harvest processing requires fresh water, electricity and inoculum of lactic acid bacteria for fermentation.

The major markets targeted are food and feed markets in the EU. Macrocystis is highly relevant as cattle feed due to its high digestibility and Saccharina for its positive effects on animal and human gut health due to the fibre content.

Five major challenges for production are: 1) mechanisation of the full process chain: seeding, harvest, post-harvest processing, drying, fermentation, and extractions to reduce manual labour, increase quality and reduce costs; 2) finding investors and capital for scaling up; 3) concentrations of the critical elements, Arsenic, and Iodine in the kelp species. The latter is a concern, but not at present limiting market opportunities, and post-harvest processing (i.e. blanching) has the potential to reduce concentrations of As and I; 4) permits for cultivation in particular in the US, and certain countries in EU; 5) selective breeding for improving yields of in particular Saccharina.

Challenges for market expansion are: 1) Scale of production; 2) insecurity/variability of production and again 3) as a concern, biomass concentrations of iodine and arsenic.

Novel development needs for the food market could be 1) increasing the demands for ‘green’ resources – plant-based products – for increasing the market pull; and 2) scale of production – need for scaling up to meet market demand.

Ocean Rainforest see an indirect potential for macroalgae in climate change mitigation, when macroalgae substitute products with a higher climate foot print, or reduce cattle methane production. Ocean Rainforest does not see a potential for their company economy to only relay on carbon or nutrient credits.

A final remark is a suggestion for the EU food/feed authorities (EFSA) to revise the legislation and limit values for arsenic and iodine in feed and food. Present limit values are based on other organism, such as fish and plants, and do not take into account the special composition of macroalgae.

Position and affiliation of interviewee: co-founder and chief product officer, VoltaGreenTech, Sweden

The activities of VoltaGreenTech covers cultivation of strains of the red macroalgae Asparagopsis (A. taxiformis and A. armata) for feed additives targeting reduction of methane from cattle.

The seaweeds are cultivated in land-based systems – closed and semi-closed systems (open, but in greenhouse). For small scale experimental work, small PBRs are sued and in the pilot factory: towers and raceways.

CO2 is added on an experimental basis in the form of side streams from different industries, and excess heat from the Stockholm power plant is used for temperature regulation of cultures. Waste CO2 from power plant and fermentation gas are also used experimentally as CO2 additives.

Fertiliser used at present is mineral fertiliser for R&D, in future, potentially use of waste streams for fertiliser. Asparagopsis is efficient in taking up nutrients and has a large potential for nutrient bioremediation.

At present the company has no use of freshwater, all is seawater. Use of artificial seawater would give the opportunity of expanding inland, but is too expensive.

Present land area footprint is 800-900 m2, in next 6 months expanding to approx. 2000 m2.

The company faces plenty of challenges: Lack of existing knowledge on infrastructure and technology for Asparagopsis in land-based systems. Keeping a balance between cost and automatization. Finding optimal coastal locations at with possibility for intake of seawater.

VoltaGreenTech experiences no particular challenges with regulations as not so many regulations established yet. Open for more regulations to protect the environment.

Access to financial resources for R&D is not presently a challenge. Expansion and scale-up however, requires investors. As of yet, no challenges in finding the right partners for R&D.

One major challenge is finding employees with qualifications in seaweed cultivation. This calls for practical/academic education of seaweed cultivation professionals. Educational programmes as for fish aquaculture is needed, potentially as part of aquaculture educations.

Post-harvest processing is freeze-drying, but looking into other energy efficient options.

The company addresses food/feed markets inside EU. The main challenge in developing market is social/consumer acceptance.

VoltaGreenTech only see a potential for carbon credits for coastal, not land-based algae production. Only a climate mitigation potential if algae or algae waste streams are processed into building materials and stored for longer time.

Position and affiliation of interviewee: Research Specialist, Hortimare, Netherlands

Hortimare works with seed development and produces seed and seedlings for large-scale cultivation of several macroalgae species on ropes in the sea: kelps (*Saccharina latissima, Laminaria digitata, Alaria, Macrocystis* and *Undaria*), *Asparagopsis, Palmaria palmata*.

No use of CO_2, fertiliser, land area and fresh water.

The major challenge, especially for the kelps, is domestication of the species, which is needed for real up-scaling of production. For this reason, we are still far from the actual production potential. Another major challenge is transfer of knowledge and education/training of future seaweed farmers. Obtaining permits is a challenge for seaweed farmers, as well as raising capital for establishing farms. Establishing of farms offshore is not seen a major challenge.

Post-processing in future – silage is viewed as the most cost-efficient option for large-scale storage. Salting is also an option.

Market for Hortimare is the global market – working with seaweed farmers inside and out-side EU. Consultancy/help on getting started and farming seaweed is also provided.

Challenges in developing market is distance to customers, and the vulnerability of shipping live seed across the globe. This generates a need for local producers.

Role of algae in climate change mitigation is controversial, as seaweed production in large scale is efficient in drawing CO_2 out of the atmosphere, however, the necessary scale of production in order to take up sufficient CO_2 in unrealistic. Sequestrating (dumping to the seabed) of all this seaweed, instead of making use of it would be absurd. The potential for carbon and nutrient credits can be a means to make ends meet for seaweed farmer business cases.

As a last comment, it is important to keep the equality in seaweed cultivation and make access to seaweed cultivation and knowledge on seaweed cultivation accessible for everybody, also local rural actors, not only large companies.

Position and affiliation of interviewee: Associate professor, KTH Royal Institute of Technology, Sweden. Head of Blue Food and Kristineberg Research Station. Involved in the spin-off company Nordic Seafarm

The species cultivated are Saccharina latissima, Laminaria digitata, Ulva fenestrata and Palmaria palmata. All are cultivated at sea on ropes, as this is the easiest and cheapest way to cultivate large volumes of biomass. Land-based cultivations are also in play, but only for small amounts of expensive, high-quality algae for restaurants.

No CO2 addition, or use of fertiliser, fresh water, or land for the marine production.

The main challenges in the cultivation are un-controlled sporulation in the Ulva cultivation. For scaling up, obtaining the permits for cultivation sites are a bottleneck, and the harvest machines and post-harvest processing (drying) are also challenges. At present a two-step drying including air-drying is being developed. The energy sources in play in future could be waste heat from industries, especially on the west coast.

The purposes for cultivation are food, feed, cosmetics, and materials, also as part of a new Horizon EU project: CIRCALGAE, coordinated by KTH. On the material side KTH has experimented in producing concrete with algae, and biomaterials with algae.

The markets that KTH cooperate with are both inside and outside the EU, including companies like Orkla, Marinova, and IKEA.

New developments in algae for food are to find cheap affordable healthy seafood, and there is a need to include the low trophic species, here also the algae. The focus is development of new tasty Nordic foods, and new plant-based proteins. All this is happening super-fast driven by the need for a protein shift to plant-based proteins. Germany alone has 16.000 million vegetarians. It is in the development of plant-based proteins, that algae have a potential for large positive impact on climate change mitigation, substituting the imported less sustainable proteins.

Regarding climate change mitigation, the binding of CO2 in for instance building materials may pose an option for C sequestrations. But also, the ‘climate-smart’ cultivation of algae, contributes to the substitution of less sustainable materials. The uptake of nutrients and mitigation of eutrophication is more relevant for future potential of the algae cultivation than the climate change mitigation.

Regarding nutrient credits, the returning, via algae, of nutrients from sea to land this could play an important role for re-mineralising our soils to produce more healthy foods.

A final comment is that the algae have a great role to play in the future biomass supplies. However, it is crucial that we produce the algae in a sustainable way.

Position and affiliation of interviewee: Founder and CEO of Maripure, Denmark

Maripure is a start-up company working in macroalgae production with focus on two species of *Asparagopsis* and a third species in marine, controlled environment/closed land-based systems. All species are presently cultivated for cattle feed with methane reducing properties. Addition of CO_2 for growth enhancement is being developed. Presently both clean and side-stream CO_2 is used, aiming for side-stream CO_2 use for future production. Fertiliser additions are either natural load from pure seawater, mineral fertiliser, or side-streams for fish aquaculture. The environmental benefits are being explored in cooperation with fish farmers. Use of waste streams as nutrient source is key for feasible scale up of production.

Freshwater is not used, only seawater and experimental use of (fresh) industrial process water.

Area wise – estimating that with 2 hectares production, all of Denmark’s cattle could be provided with methane reduction feed additives.

Key focus in post-processing at present is exploring different energy and yield efficient techniques, and at the same time working directly with the national Food Authorities in order to incorporate food/feed legislation into the post-harvest processing.

Markets are to support through cattle feed products, the food industry. Also exploring non-feed applications. Market clients are inside the EU for the moment, but with future perspectives out-side the EU.

Algae do have a purpose in climate change mitigation, regarding *Asparagopsis* through the methane reduction.

1. Major challenges identified for production and market development are:
2. Technical challenges in working with the stability of the bioactives of the species in cultivation.
3. Economy of scale, challenges in CAPEX when scaling up in land-based production.
4. Regulatory and perception around the role of bromoform in Asparagopsis – there needs to be a discussion in the doses, potential harm and safety processes.
5. Asparagopsis is ‘over-hyped’ generating an impression that the work on Asparagopsis is further than it really is.
6. Science-industrial cooperation.
7. Public science works much slower than needed for generating the timely development in private companies.
8. Projects are often of shorter duration – up to 4-5 years.
9. Legislation/regulation:
    a. What is the framework of working with non-native species (such as Asparagopsis). How should production be controlled/managed in land-based systems?
    b. Organic production, there is a lack of consistency of the EU legislation on organic production of seaweeds in land-based and marine systems. The legislation needs revision, as land-based algae production cannot use aquaculture side-streams as fertiliser as opposed to sea based.
    c. More legislation is needed – i.e., on standardising nutrient/carbon credits.

Nutrient credits could have a potential for seaweed farmers, and for stimulating development towards re-use of nutrients for environmental benefits.

A final point is that the diversity in seaweed needs to be dissolved for more efficient and targeted development, so that; for example, R&D or companies are split up in organisations/groups/environments related to more specialised, discrete clusters on either products or different species.

Position and affiliation of interviewee: Founder and CEO of PureAlgae Aps, Denmark

PureAlgae is a start-up company developing cultivation technology for production of macroalgae in closed, land-based systems. The species in production and development are Ulva, Palmaria palmata and Gracilaria. All are at present produced for the food and nutraceutical markets, but Ulva in particular is also relevant for feed.

CO2 is used in the production and integrated in the cultivation systems. The production is however still at the experimental level, so no numbers on the volumes and prices for CO2 are available. In future, the CO2 source will be from industrial waste streams. Mineral fertilizers are presently used in the R&D production, but in future side-streams from the land-based fish industry will be the primary resource. Freshwater is not used in the production and there is no recycling of the water. The land footprint of the production is approximately 2.5 tonnes of fresh Ulva pr 20 m2 (total area) per year.

The market for land-based cultivation systems is being developed both in EU and outside. Primary customers are land-based fish producers with a need to bring down nutrient emissions. At present, the only post-processing of algae by PureAlgae is freezing of the biomass. Drying is not carried out by PureAlgae.

The major challenges are:

- Investment willingness from private investors.
- In developing seaweed markets the major diversity in seaweed species is a major challenge.
- Technology – this is the focus of PureAlgae.

PureAlgae do not see a role for algae production in carbon change mitigation and do not approve of the Carbon credit system. Implementation of a carbon credit system would need a thorough Life Cycle Analysis of the whole production process. Nutrient credits systems on the contrary, has a great potential to stimulate the re-use of nutrients and reduce nutrient emissions to coastal waters.

A final comment is that regulations are needed for various processes in the algae value chain– at a national and EU level. We need i.e., regulations dealing with cultivation of invasive / nonindigenous species.

At present there is a pronounced lack of regulations, and the management is to a large extent left to the companies, who may not always have the willingness or knowledge to act according to best practice with respect to the environment.

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11.6 Survey to EU4Algae

The following questions were adapted to a google questionnaire and shared via the EU4ALGAE forum. Following the survey was translated into Chinese and sent to the top 10 algae producers in China.

Context

The European Commission has launched a study to provide sound and up-to-date knowledge on the potential for scaling up the aquaculture production of marine algae for animal and fish feed in the EU. In addition, the environmental and economic performance are assessed with focus on climate change mitigation. The study was launched in December 2021 and has a 12-month duration. It is carried out by ACTeon (France – coordinator), the universities of Aarhus and Copenhagen (Denmark) and TNO (the Netherlands, Organisation for Applied Scientific Research).

Limited to focus on the top 10 EU relevant combinations of algae species and production systems, the study team has assembled information from different sources, such as study reports, scientific articles, knowledge available on the internet and expert input.

You are an expert in algae cultivation – and we need your help!

With your help, the present survey aims to consolidate the knowledge base by:

1. Collating experts' opinions on today and future's developments in the field of algae cultivation in Europe and their potential use in animal feed.
2. Collecting additional information on specific algae production types and their key constraints and challenges.

All information collected via the survey will be stored and handled in a confidential manner (and compliant with the GDPR).

Many thanks for taking the time to filling in the questionnaire and contributing to the EC study. If you have questions or comments to the study itself, do contact us at: xxxxxxxx.

Who are you?

First name:

Surname:

Email:

Organisation name:

My organisation is a:

- Academic/research institution
- Company/business organisation
- Public authority
- Business association
- Consumer association
- Environmental organisation
- Non-governmental organisation
- Trade union
- Other

Country of origin of organisation:

Organisation size:

- Micro (1 to 9 employees)
- Small (10 to 49 employees)
- Medium (50 to 249 employees)
- Large (250 or more)

Please specify your organisation's roles and responsibilities in the algae industry/value chain (more options possible):

- Pre-processing of algae (supplier)
- Production/cultivation of algae (producer)
- Processing of algae into end-products (processor)
- Provide technology/services for algae production (technology/service provider)
- Sales of algae end-products (end-product sales and marketing)
- Research and development (R&D)
- Non-governmental organisation
- Industry associations
- Educational organisations
- Other, please specify

To which subsector is your work most related:

- Micro-algae/cyanobacteria
- Macroalgae
- Both

Species in production

The study has selected 10 combinations of algae species and cultivation methods that will receive particular attention – see table below.

	Species	Macro / Microalgae	Cultivation method
1	*Saccharina latissima* (Laminariales, Phaophyceae)	Macroalgae	Rope system
2	*Alaria esculenta* (Laminariales, Phaophyceae)	Macroalgae	Rope system
3	*Palmaria palmata* *(Rhodophyceae)*	Macroalgae	Rope system
4	*Asparagopsis* sp. *(Rhodophyceae)*	Macroalgae	Rope system
5	*Asparagopsis* sp. *(Rhodophyceae)*	Macroalgae	Photobioreactor
6	*Ulva* sp. (Chlorophyceae)	Macroalgae	Rope system
7	*Spirulina*	Microalgae	Photobioreactor

	(Spirulinales, Cyanophyceae)		
8	*Chlorella* sp. *(Chlorellales, Trebouxiophyceae)*	Microalgae	Photobioreactor
9	*Haematococcus pluvialis* *(Chlamydomonadale, Chlorophyceae)*	Microalgae	Photobioreactor
10	*Nannochloropsis* sp. *(Eustigmatales, Eustigmatophyceae)*	Microalgae	Photobioreactor

Would you identify additional species and cultivation methods that should also receive attention in the study?

Yes ☐ No ☐

If yes: which ones and why? (Please explain)

Which species and cultivation methods do you believe offer the highest potential?

Species/cultivation methods : ____________________

Why? : _____________________

Which species and cultivation methods do offer the highest potential as input to animal and/or fish feeds?

Species/cultivation methods : ____________________

Why? : _____________________

Looking ahead

- Which novel algae species might offer opportunities in the future? And why?
- Which novel/innovative cultivation technologies might offer opportunities in the future? And why?
- Which novel market niches (with high potential) might represent opportunities in the future? And why?

Production system characteristics (for each species of the table)

Could you share your knowledge on the characteristics of these species and cultivation methods? From a scrolling list of species including a category “algae in general”:

- Present production in Europe (tonnes of wet weight)
- Main challenges faced today with production (multiple choice)
- Regulation
- Technology
- High costs
- Access to input at adequate prices
- Climate

- Access to financial resources/availability of funding
- Partnerships
- Knowledge gaps
- Social awareness and acceptance
- Others – please specify
- Expected production in 5 years in Europe

Main challenges faced for upscaling production:

- Regulation
- Technology
- High costs
- Access to input at adequate prices
- Climate
- Access to financial resources,
- Partnerships
- Knowledge gaps
- Social awareness and acceptance
- Others – please specify
  - Yields, resource use, cost and revenues
  - Biomass yields/ha
  - Use of CO2 for production/ha
  - Use of fertiliser for production/ha
  - Use of fresh water for production/ha
  - Costs price – capital costs (€/kg), operation and maintenance costs (€/kg)
  - Market price (€/kg)

Post-harvest processing

From a scrolling list of species including a category “algae in general”:

Which type of post-harvest processing is currently practised? And why?

- Washing
- Fermenting/ensiling
- Drying
- Milling
- Other

What are the challenges faced with post-harvest processing?

- Regulation
- Technology
- High costs
- Access to inputs at adequate prices
- Climate
- Access to financial resources/funding
- Partnerships
- Knowledge gaps
- Social awareness and acceptance
- Others – please specify

What are post-harvest processing costs?

- CAPEX
- OPEX
- Total costs

Use of biomass/markets

From a scrolling list of species including a category “algae in general”:

What are the main uses of algae?

- Food
- Animal feed
- Livestock
- Aquaculture
- Other
- Fertiliser / Biostimulants / Crop nutrients
- Energy (biofuels)
- Specialty chemicals (Pharmaceutical, Nutraceuticals, Cosmeceuticals)
- Others – please specify

What are the main markets?

- Type of final consumers
- EU/non-EU

What are the main challenges of entry into / expansion of current and emergent markets?

- Regulation
- Technology
- High costs
- Access to input at adequate prices
- Climate
- Access to financial resources
- Partnerships
- Knowledge gaps
- Social awareness and acceptance
- Others – please specify

Last input/comment/suggestions

Before closing the questionnaire

- Additional comments or thoughts you would like to share with us that might provide a different perspective to the questions above?
- Key references and projects that provide data on the performance and costs of different cultivation techniques (please provide internet links or attachments.

Many thanks for your contributions!

11.7 Relational database user guide

This document is the user guide to the database that was prepared in the framework of the "Algae and Climate" project. The algae and climate project aims to investigate the projects on the potential role of algae for greenhouse gas emission reduction by use in animal feed applications.

Introduction and objective

The database results from the both the data inventory and assessment results within the project. The aim of the database is to:

- List and document the relevant data including literature references.
- List the key assessment results.
- Provide additional overviews and data.

For a detailed description of the work and results of the project and contents of the database the reader is referred to the final report of the project.

Database contents

The database contains data the following subjects:

- Composition on algae species, these include selected macroalgae and microalgae species.
- Productivity data on algae cultivation.
- Costs of algae cultivation.
- Greenhouse gas impact from life cycle analysis of algae cultivation.
- Production volumes of selected life-stock products in selected European member states.
- Feed requirements for selected life-stock products.
- Substitution potential of feed with algae products.
- Greenhouse gas reduction potential with algae for feed applications.
- Costs of greenhouse gas reduction.

References, via the Reference number (Refnr) the bibliographic data can be accessed throught the table "References".

Database structure

The database is implemented in the software tool Microsoft Access, which is part of the Microsoft Office suite. A software license for this tool is required.

The database consists of data tables and query tables. The first lists results from the Algae and Climate study, the queries are tables with selections from these tables, or combine data to provide additional results.

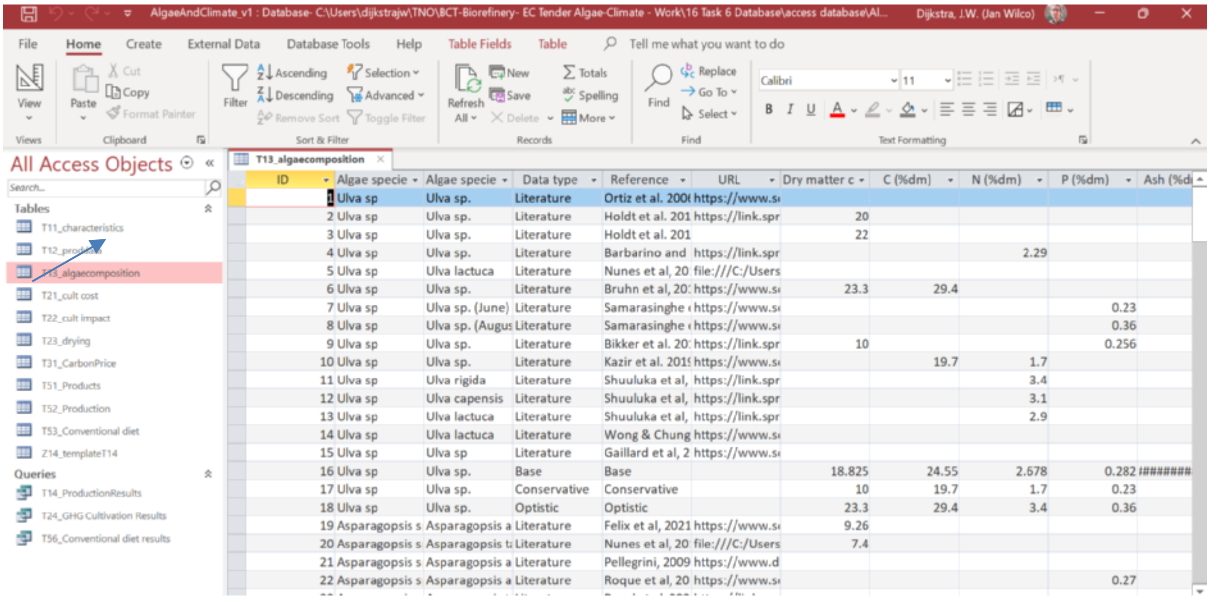
Within both the tables the following datatypes can be distinguished

- Categories. These lists the specifics for which data are provided, such as algae type, algae type-cultivation system type combination, feed type, member state, livestock product etc.
- Reference, Refnr: here the literature sources to data are listed.
- Data-type: here the user can select between:
  - "Literature" where an overview of all available literature data is provided, and 3 scenarios results from literature:
  - "Base": average or typical value from literature.
  - "Conservative": conservative estimate for data, based on range in literature.
  - "Optimistic": optimistic estimate based on the range in literature.

- “Base including estimate” additional base scenario for missing datapoints from extrapolating by combination of data sources, see comments.
- Data fields, here datapoint results from the study are listed.

Accessing standard tables

1. Open MS-Access.
2. Open the database via ➔ file ➔ open ➔ select filename. Accdb.
3. click a selected row under “Tables”.



ID	Algae specie	Algae specie	Data type	Reference	URL	Dry matter c	C (%dm)	N (%dm)	P (%dm)	Ash (%d
1	Ulva sp	Ulva sp.	Literature	Ortiz et al. 200	https://www.s					
2	Ulva sp	Ulva sp.	Literature	Holdt et al. 201	https://link.spr	20				
3	Ulva sp	Ulva sp.	Literature	Holdt et al. 201		22				
4	Ulva sp	Ulva sp.	Literature	Barbarino and	https://link.spr			2.29		
5	Ulva sp	Ulva lactuca	Literature	Nunes et al, 20	file:///C:/Users					
6	Ulva sp	Ulva sp.	Literature	Bruhn et al, 20	https://www.s	23.3	29.4			
7	Ulva sp	Ulva sp. (June)	Literature	Samarasinghe	https://www.s				0.23	
8	Ulva sp	Ulva sp. (Augus	Literature	Samarasinghe	https://www.s				0.36	
9	Ulva sp	Ulva sp.	Literature	Bikker et al. 20	https://link.spr	10			0.256	
10	Ulva sp	Ulva sp.	Literature	Kazir et al. 201	https://www.s		19.7	1.7		
11	Ulva sp	Ulva rigida	Literature	Shuuluka et al,	https://link.spr			3.4		
12	Ulva sp	Ulva capensis	Literature	Shuuluka et al,	https://link.spr			3.1		
13	Ulva sp	Ulva lactuca	Literature	Shuuluka et al,	https://link.spr			2.9		
14	Ulva sp	Ulva lactuca	Literature	Wong & Chung	https://www.s					
15	Ulva sp	Ulva sp	Literature	Gaillard et al, 2	https://www.s					
16	Ulva sp	Ulva sp.	Base	Base		18.825	24.55	2.678	0.282	########
17	Ulva sp	Ulva sp.	Conservative	Conservative		10	19.7	1.7	0.23	
18	Ulva sp	Ulva sp.	Optistic	Optistic		23.3	29.4	3.4	0.36	
19	Asparagopsis s	Asparagopsis a	Literature	Felix et al, 2021	https://www.s	9.26				
20	Asparagopsis s	Asparagopsis t	Literature	Nunes et al, 20	file:///C:/Users	7.4				
21	Asparagopsis s	Asparagopsis a	Literature	Pellegrini, 2009	https://www.d					
22	Asparagopsis s	Asparagopsis a	Literature	Roque et al, 20	https://www.s				0.27	

Accessing standard Queries

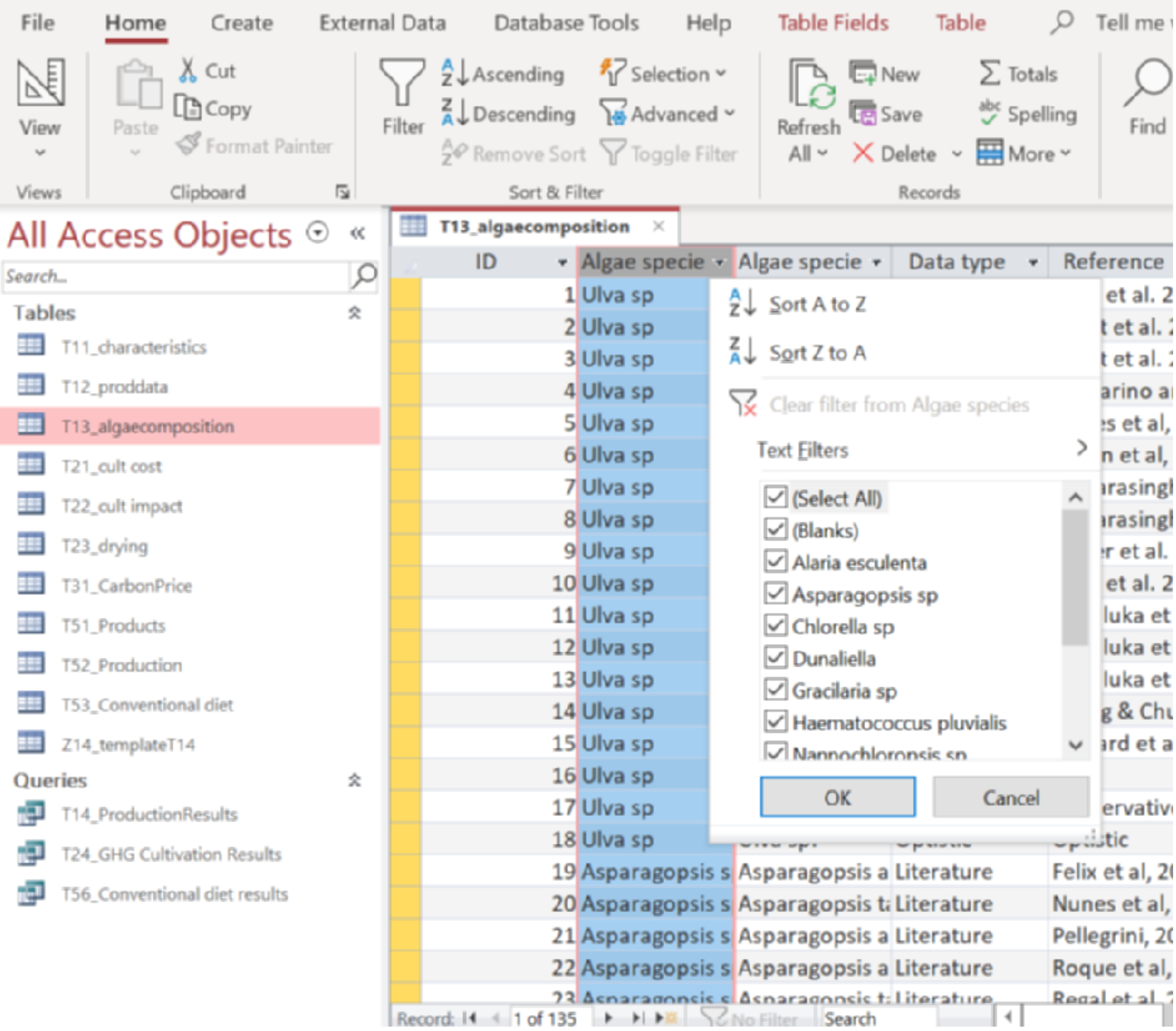
Standard queries can be opened similar to standard tables by clicking the row under “Queries”.

Selection of data for selected keys

Rather than listing all the data in a table, it is possible to list data only for specific record values.

- ➩ Open the relevant table.
- ➩ Click in on the top of the relevant column.
- ➩ Un-Tick the boxes for the values of the keys.

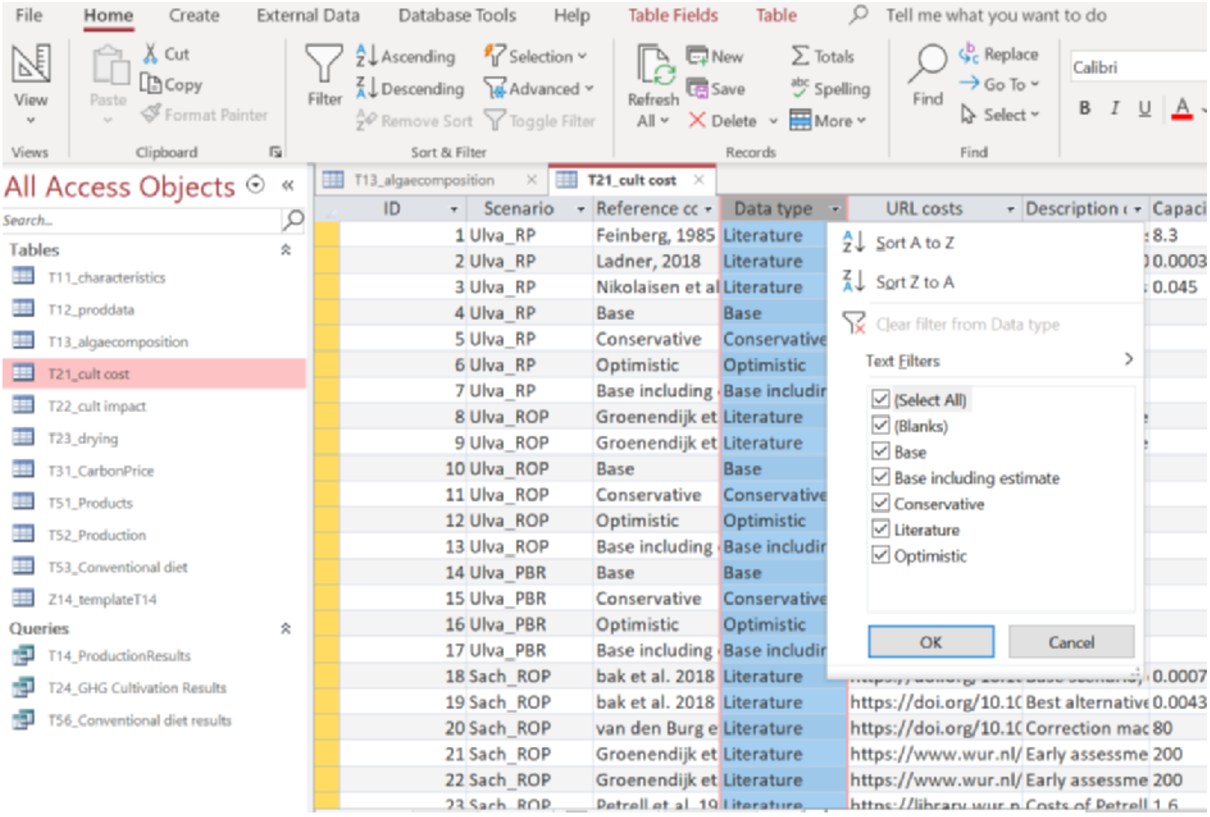
For example, below the data for specific algae species can be selected.



ID	Algae specie	Algae specie	Data type	Reference
1	Ulva sp			et al. 2
2	Ulva sp			t et al.
3	Ulva sp			t et al.
4	Ulva sp			arino a
5	Ulva sp			s et al,
6	Ulva sp			n et al,
7	Ulva sp			rasingl
8	Ulva sp			rasingl
9	Ulva sp			r et al.
10	Ulva sp			et al. 2
11	Ulva sp			luka et
12	Ulva sp			luka et
13	Ulva sp			luka et
14	Ulva sp			g & Chu
15	Ulva sp			rd et a
16	Ulva sp			
17	Ulva sp			ervativ
18	Ulva sp			tic
19	Asparagopsis s	Asparagopsis a	Literature	Felix et al, 2
20	Asparagopsis s	Asparagopsis t	Literature	Nunes et al,
21	Asparagopsis s	Asparagopsis a	Literature	Pellegrini, 2
22	Asparagopsis s	Asparagopsis a	Literature	Roque et al,
23	Asparagopsis s	Asparagopsis t	Literature	Regal et al.

Selecting scenarios (literature, base, optimistic pessimistic)

- Open the relevant table or query.
- Click on the triangle on the top of the column "Data Type."
- Choose between literature, base, optimistic, conservative but (un)ticking the boxes.

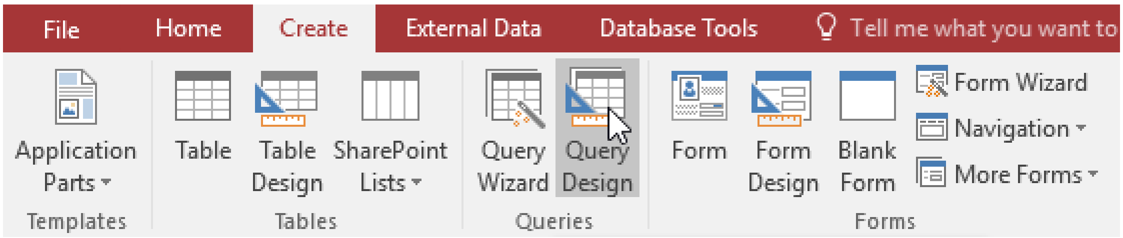


☑ (Select All)
☑ (Blanks)
☑ Base
☑ Base including estimate
☑ Conservative
☑ Literature
☑ Optimistic

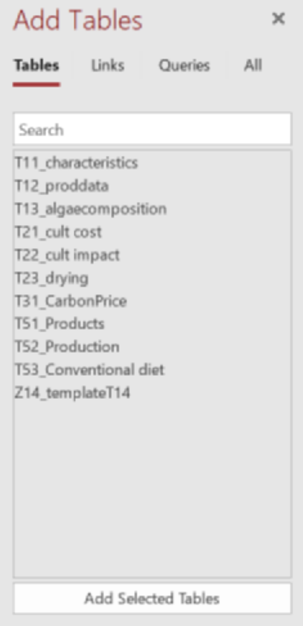
ID	Scenario	Reference cc	Data type	URL costs	Description (	Capaci
1	Ulva_RP	Feinberg, 1985	Literature			8.3
2	Ulva_RP	Ladner, 2018	Literature			0.0003
3	Ulva_RP	Nikolaisen et al	Literature			0.045
4	Ulva_RP	Base	Base			
5	Ulva_RP	Conservative	Conservative			
6	Ulva_RP	Optimistic	Optimistic			
7	Ulva_RP	Base including	Base includir			
8	Ulva_ROP	Groenendijk et	Literature			
9	Ulva_ROP	Groenendijk et	Literature			
10	Ulva_ROP	Base	Base			
11	Ulva_ROP	Conservative	Conservative			
12	Ulva_ROP	Optimistic	Optimistic			
13	Ulva_ROP	Base including	Base includir			
14	Ulva_PBR	Base	Base			
15	Ulva_PBR	Conservative	Conservative			
16	Ulva_PBR	Optimistic	Optimistic			
17	Ulva_PBR	Base including	Base includir			
18	Sach_ROP	bak et al. 2018	Literature			0.0007
19	Sach_ROP	bak et al. 2018	Literature	https://doi.org/10.1(	Best alternative	0.0043
20	Sach_ROP	van den Burg e	Literature	https://doi.org/10.1(	Correction mac	80
21	Sach_ROP	Groenendijk et	Literature	https://www.wur.nl/	Early assessme	200
22	Sach_ROP	Groenendijk et	Literature	https://www.wur.nl/	Early assessme	200

How to write a custom query

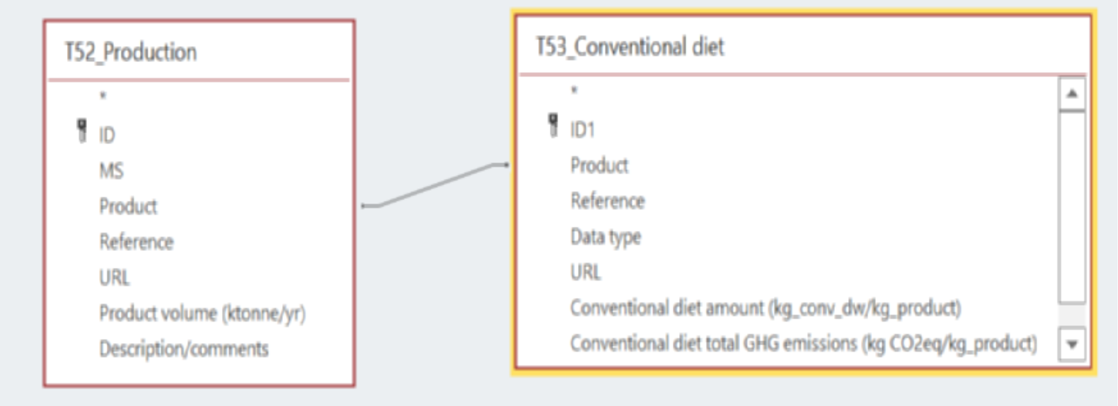
1. Select the **Create** tab on the Ribbon, and locate the **Queries** group.
2. Click the **Query Design** command.



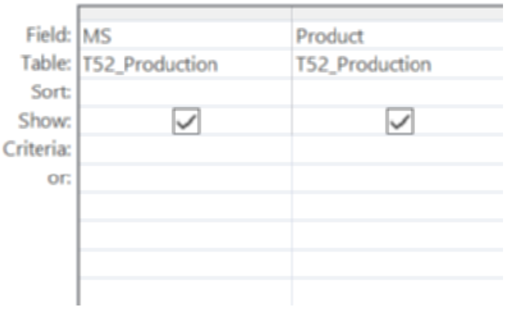
3. Access will switch to **Query Design view**. In the **Show Table** dialog box that appears, select the table you want to run a query on. If for example the user would like to run a query on T5_2 and T5_3, T5_2 and T5_3 should be selected.



4. Once the chosen tables are selected, some links or relationships between the tables can be set. For example, if the user would like to show the records in which the product of the two tables (T5_2 and T5_3) match, it is just necessary to drag the field that one wants to link to the other.



5. In the table window, double-click the field names that the user wants to include in the query. They will be added to the design grid in the bottom part of the screen. In this example, we would like to display the Member State (MS) and the product reported in T5_2.



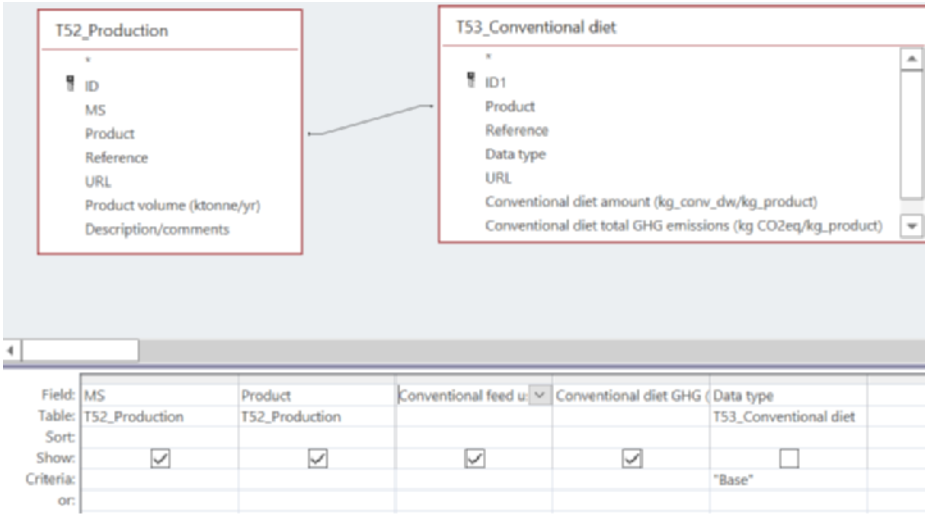
Field:	MS	Product
Table:	T52_Production	T52_Production
Sort:		
Show:	☑	☑
Criteria:		
or:		

6. If the user wants to calculate data from data present in the selected tables (in this case T5_2 and T5_3), the user needs to follow the following steps:

- Click the field row of a blank column in the design grid. Enter the field name for the field that will display the results of the calculation, followed by a colon (:).
- Enter the expression to calculate in Access, using arithmetic operators such as multiplication (*), addition (+), subtraction (-), division (/), and exponentiation (^). For example, the expression Conventional feed use (kton/y): [T52_Production]![Product volume (ktonne/yr)]*[T53_Conventional diet]![Conventional diet amount (kg_conv_dw/kg_product)] will create a new calculated field named Conventional feed use (kton/y) that will display the results of the Product volume from one table multiplied by the Conventional diet amount from another table.
- Save and run the query.

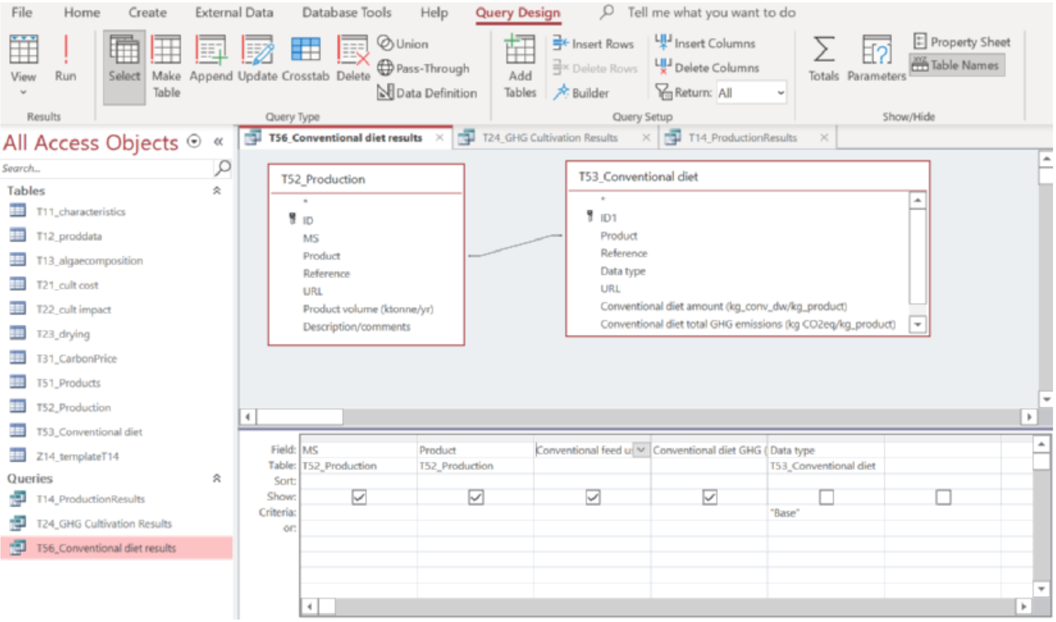
7. If the user would like as well to filter the data based on an additional criteria, the user needs to double-type on the field on which to filter on and type the criteria to apply typing it into the field criteria in the Query Design View.

In this example, the user would like to select the data based on the data type selecting only the "Base" scenario.



Field:	MS	Product	Conventional feed u	Conventional diet GHG (	Data type
Table:	T52_Production	T52_Production			T53_Conventional diet
Sort:					
Show:	☑	☑	☑	☑	☐
Criteria:					"Base"
or:					

To run the query, the user needs to click on view or run in the Access Ribbon.



Field:	MS	Product	Conventional feed u	Conventional diet GHG (	Data type	
Table:	T52_Production	T52_Production			T53_Conventional diet	
Sort:						
Show:	☑	☑	☑	☑	☐	☐
Criteria:					"Base"	
or:						

11.8 Mapping

Table 43 Available CO2 from point sources [t/yr], potentially convertible area [ha] and effective potential for feed production [t dw/yr] from the four simplified production systems

Country code	CO2 from point sources	Convertible area	Effective yield macro open	Effective yield macro closed	Effective yield micro open	Effective yield micro closed	Number of systems that are CO2 limited
AT	22194232.3	141431.7	5148144	2019645	3088886	5748080	2
BE	71469946.8	268932.5	10402758	3840356	9946843	10929977	1
BG	34150596.6	149075.2	5766477	2128794	4752916	6058726	1
CY	7612430.5	11574.5	447721	165284	1059461	470412	1
CZ	91507016.4	405448.6	15683428	5789806	12735506	16478276	1
DE	733845252	2617990	101268220	37384899	102133051	106400572	1
DK	16394118	608565.6	3802757	7605515	2281654	4563309	4
EE	11943521.1	45809.59	1771991	654161	1662242	1861797	1
ES	132033957	534776.4	20686041	7636607	18375851	21734426	1
FI	71977442.2	90654.42	3506664	1294545	10017474	3684384	1
FR	184716700	1144490	42846636	16343311	25707981	46514440	2
GR	52591814.4	94092.15	3639641	1343636	7319476	3824101	1
HR	10408869	26824.64	1037622	383056	1448656	1090209	1
HU	34004841.8	293546	7887717	4191837	4732630	9465260	3
IE	22318700.3	214220.9	5177015	3059074	3106209	6212419	3
IT	209334315	1001287	38731448	14298378	29134142	40694387	1
LT	9296550.4	47588.42	1840799	679563	1293849	1934092	1
LU	2184663.27	9146.184	353790	130608	304051	371720	1
LV	2975452.29	20811.79	690182	297192	414109	828218	3
MT	945470.82	120.81	4673	1725	16612	4910	0
NL	88765103.5	414668.9	16040085	5921472	12353900	16853009	1
PL	208641426	1172266	45345219	16739965	29037710	47643350	1
PT	40484921.5	39457.46	1526280	563453	5425401	1603633	0
RO	67733251.5	364387.5	14095114	5203453	9426788	14809466	1
SE	78948551.5	333715.1	12908658	4765452	10987679	13562878	1
SI	9236182.79	20316.62	785881	290121	1285447	825710	1

SK	35156220.1	201117.1	7779544	2871952	4892874	8173817	1
EU total	2.25E+09	1.03E+07	3.69E+08	1.46E+08	3.13E+08	3.92E+08	

Table 44 Effective CO2capture [t/yr] for the four production system types and most effective technology from the four simplified production systems

Country code	Effective CO2capture macro open	Effective CO2capture macro closed	Effective CO2capture micro open	Effective CO2capture micro closed	Most effective technology
AT	5659529	2220264	5659529	10531765	micro closed
BE	11436104	4221834	18224836	20026158	micro closed
BG	6339283	2340255	8708402	11100938	micro closed
CY	492195	181702	1941170	861899	micro open
CZ	17241324	6364930	23334289	30191880	micro closed
DE	111327586	41098486	187130539	194949590	micro closed
DK	4180500	8361000	4180500	8361000	macro closed
EE	1948010	719141	3045598	3411228	micro closed
ES	22740866	8395180	33668659	39822318	micro closed
FI	3854994	1423137	18354248	6750614	micro open
FR	47102759	17966756	47102759	85224835	micro closed
GR	4001181	1477105	13410913	7006607	micro open
HR	1140693	421106	2654262	1997507	micro open
HU	8671235	4608228	8671235	17342469	micro closed
IE	5691269	3362944	5691269	11382537	micro closed
IT	42578793	15718691	53380250	74561198	micro closed

LT	2023653	747066	2370620	3543689	micro closed
LU	388933	143581	557089	681074	micro closed
LV	758740	326714	758740	1517481	micro closed
MT	5137	1897	30437	8996	micro open
NL	17633409	6509675	22635101	30878472	micro closed
PL	49849536	18402810	53203564	87293248	micro closed
PT	1677892	619422	9940545	2938214	micro open
RO	15495237	5720332	17271979	27134246	micro closed
SE	14190925	5238823	20131881	24850220	micro closed
SI	863945	318940	2355227	1512884	micro open
SK	8552316	3157234	8964836	14976257	micro closed
EU total	4.06E+08	1.60E+08	5.73E+08	7.19E+08	

Table 45 Effective potential for nitrogen uptake [t/yr] from the four simplified production systems, and Water Exploitation Index plus for summer 2015 [%].

Country code	N uptake macro open	N uptake macro closed	N uptake micro open	N uptake micro closed	WEI+
AT	170918	67052	165564	308097	5
BE	345372	127500	533151	585847	50
BG	191447	70676	254756	324748	8
CY	14864	5487	56787	25214	NA
CZ	520690	192222	682623	883236	6
DE	3362105	1241179	5474332	5703071	13
DK	126252	252503	122297	244593	11
EE	58830	21718	89096	99792	2
ES	686777	253535	984946	1164965	60
FI	116421	42979	536937	197483	1
FR	1422508	542598	1377948	2493174	10
GR	120836	44609	392324	204972	21
HR	34449	12717	77648	58435	4
HU	261872	139169	253669	507338	3
IE	171877	101561	166493	332986	3
IT	1285884	474706	1561590	2181219	24
LT	61115	22561	69350	103667	1
LU	11746	4336	16297	19924	31
LV	22914	9867	22196	44392	1
MT	155	57	890	263	100
NL	532531	196593	662169	903321	46
PL	1505461	555767	1556421	2553684	14
PT	50673	18707	290801	85955	46
RO	467958	172755	505276	793787	8
SE	428567	158213	588940	726970	3
SI	26091	9632	68900	44258	8
SK	258281	95349	262258	438117	3
EU total	1.23E+07	4.83E+06	1.68E+07	2.10E+07	

11.9 Electricity prices

Table 46 below shows the unit electricity costs (Unitary cost of electricity at the date of the study in €/kWh) that were used in each production scenario to calculate the total cost of energy. Current energy price data was collected for each country (Unitary cost of electricity 2022-Semester1)[43]. The difference between the two prices is used to calculate the % change.

Table 46 Electricity unitary prices evolution Electricity unitary prices evolution

Production scenario ID	**Countries**	**Date of the study**	**Unitary cost of electricity €/kWh**		
			At the date of the study	*2022-Semester 1*	*Change (%)*
1	Portugal	2021	0,08 €	0,14 €	+61%
2	Portugal	2021	0,05 €	0,14 €	+184%
3	Germany	2021	0,05 €	0,15 €	+192%
6	USA	2017	0,09 €	0,14 €	+58%
7	Iceland	2019	0,14 €	0,14 €	-3%
4	USA	2018	0.14	0.14	0
8	China	2011	0,13 €	0,07 €	-44%
9	Greece	2016	0,12 €	0,37 €	+203%
10	Netherlands	2016	0,10 €	0,13 €	+38%
11	USA	2013	0,11 €	0,14 €	+30%
12	USA	2019	0,14 €	0,14 €	-2%
Average			0.1 €	0.15 €	

These evolution rates are then applied to the initial total cost of electricity (in €) to express what the total cost of electricity would be in 2022 in each production scenario (see table below).

Table 47 Evolution in total cost of electricity

Production scenario ID	**Total electricity cost at the date of the study**	***Change (%)***	**Total electricity cost in 2022**
1	2,76 €	*+61%*	4,43 €
2	2,99 €	*+184%*	8,47 €

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[43] Source of actual electricity prices :
https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_205/default/table?lang=fr (Europe)

https://www.bls.gov/regions/midwest/data/averageenergyprices_selectedareas_table.htm (USA)

https://www.globalpetrolprices.com/China/electricity_prices/ (China)

https://www.statista.com/statistics/643385/electricity-prices-for-households-in-iceland/ (Iceland)

3	0,18 €	*+192%*	0,54 €
6	26,06 €	*+58%*	41,21 €
7	11,55 €	*-3%*	11,20 €
4	0,12 €	*0*	0,12 €
8	2,63 €	*-44%*	1,46 €
9	1,47 €	*+208%*	4,44 €
10	1,20 €	*+38%*	1,65 €
11	0,67 €	*+30%*	0,87 €
12	0,09 €	*-2%*	0,08 €
Average	4,1 €		6,2€

The main findings are listed below:

- On average, the total electricity cost increased from 4,1 € to 6,2 €.
- On average, given the new electricity price, OPEX cost would increase from 13,2 € to 15,25 € (16% increased).
- The cost of electricity represented 30% of the total OPEX cost (4,1/13,2), while it would now represent 40% (6,2/15,25).

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