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Algae potential for (waste)water treatment and fertilisers/plant biostimulants production

Annex to the Final Report

European Maritime, Aquaculture and Fisheries Fund (EMFAF)

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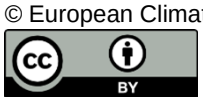

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Contents

List of acronyms **8**

Glossary **9**

Target audience **10**

Relation to the EU Algae Initiative **11**

Executive summary **12**

1. Industrial symbiosis for integrating wastewater treatment and algae production on land **13**

1.1. Relevant wastewater/effluent streams for the production of algae 14

1.2. Integrating algae production within the horticulture (hydroponics) sector 15

1.2.1. Average nutrient concentrations in hydroponic effluents 16
1.2.2. Algae growth in hydroponic effluents 17
1.2.3. Opportunities for further synergies and challenges 18

1.3. Integrating algae production within the aquaculture sector 19

1.3.1. Algae growth in aquaculture effluents 20
1.3.2. Challenges for implementation 23

1.4. Integrating algae and anaerobic digestion of manure 24

1.4.1. Average nutrient concentrations in manure-based digestates 24
1.4.2. Algae growth in manure-based digestate 25
1.4.3. Opportunities for further synergies and challenges 26

1.5. Integrating algae and urban wastewater treatment 28

1.5.1. Economic Analysis 30
1.5.2. Environmental Analysis 35
1.5.3. Algae-Based Tertiary Treatment for Nutrient Recovery 37

1.6. Beyond wastewater treatment: integrating industrial side-streams with algae 39

1.6.1. Existing initiatives 39
1.6.2. Challenges and recommendations when using side/waste streams for algae cultivation 39

2. Beyond land: macroalgae production to clean natural waters **41**

2.1. Assessment of the environmental conditions of the EU coastal marine areas and sea basins 41

2.2. Macroalgae farm nutrient assimilation potential in the Baltic Sea and North Sea 44

2.3. Quantifying the impact of macroalgae cultivation on eutrophication: A scenario-based analysis in the Baltic Sea 47

2.4. Current practices for macroalgae aquaculture in the Baltic Sea 52

2.5. Available technologies for the collection and processing of macroalgae into products 54

3. Algae potential to be used as fertilising products 57

3.1. Microalgae biomass in fertilisation practices 58

3.2. Algae extract as plant biostimulants 61

4. Legal requirements for producing algae-based fertilisers/biostimulants in wastewater and policy recommendations 63

4.1. Boundaries of this study 63

4.2. Legal background for using algae as fertilising products in the European market 64

4.2.1. Product Function Categories (PFC) 65
4.2.2. Component Material Categories (CMC) 69

4.3. Algae cultivated in the selected effluents – current legal status and policy recommendations for use in EU fertilising products 72

4.3.1. Algae grown on urban wastewater 72
4.3.2. Algae grown on manure-derived digestate 76
4.3.3. Algae grown on aquaculture and horticulture effluents 78

5. Identification and quantification of contaminants when growing algae in wastewaters 80

5.1. Quantification of contaminants listed in the Fertilising Product Regulation 80

5.2. Potential contaminants present in the selected wastewaters/effluents and their quantification 83

5.2.1. Urban wastewater 83
5.2.2. Horticulture effluents 84
5.2.3. Aquaculture effluents 85
5.2.4. Manure-based digestate 87
5.2.5. Organic pollutants and pathogens pertinent to all effluents 87

6. Roadmap for simultaneous wastewater treatment and fertilisers/ biostimulants production from algae 91

6.1. Objectives 91

6.2. Situation analysis 91

6.3. Business case and economic assessment 93

6.4. Environmental assessment 94

6.5. Research and innovation priorities 95

6.6. Policy recommendations 96

List of acronyms

ABPR	Animal By-Product Regulation
CEN	European Committee for Standardization
CMC	Component Material Category
ESPP	European Sustainable Phosphorous Platform
EU	European Union
FPR	Fertilising Product Regulation
ISO	International Organization for Standardization
JRC	Joint Research Centre
OJEU	Official Journal of the European Union
PCB	Polychlorinated biphenyl
PE/PEY	Person-equivalent/Person-equivalent per year
PFAs	Per- and polyfluoroalkyl substances
PFC	Product Function Category
RAS	Recirculating Aquaculture System
SSD	Sewage Sludge Directive
TRL	Technology Readiness Level
UWWTD	Urban Wastewater Treatment Directive

Glossary

Algae - the European Standard EN 17399:2024 regards algae as a functional group of organisms consisting of microalgae, macroalgae (seaweed), cyanobacteria, and Labyrinthulomycetes. According to the European Algae Biomass Association (EABA), common traits of algae are oxygenic photosynthesis, chlorophyll as the main photosynthetic pigment, lack of differentiated tissues, and being primary producers in aquatic ecosystems. There are exceptions because some algae can grow in the dark using simple organic compounds, and some algae do not possess photosynthetic organelles and are unable to perform photosynthesis (Labyrinthulomycetes), but these are not analysed in this report.

Cyanobacteria - also known as "blue-green algae", cyanobacteria are, as their name suggests, bacteria. Therefore, they are prokaryotic organisms and not eukaryotic like other microalgae and seaweed. Besides chlorophyll, they also produce other pigments that confer their blue hue. Several species produce toxins and are associated with harmful algal blooms, but others are known to be safe and are approved for human consumption.

Fertiliser - for the purposes of the Fertilising Product Regulation, "*a fertiliser shall be an EU fertilising product the function of which is to provide nutrients to plants or mushrooms*" and meet all relevant requirements of that Regulation.

Organic fertiliser - for the purposes of the Fertilising Product Regulation, an organic fertiliser is defined as a fertiliser containing organic carbon and nutrients of solely biological origin and that meets all relevant requirements set out in that Regulation. This is not to be confused with fertilisers suitable for organic production according to Regulation (EU) 2018/848.

Plant biostimulant - for the purposes of the Fertilising Product Regulation, a plant biostimulant is "*a product stimulating plant nutrition processes independently of the product's nutrient content with the sole aim of improving one or more of the following characteristics of the plant or the plant rhizosphere: (a) nutrient use efficiency; (b) tolerance to abiotic stress; (c) quality traits; (d) availability of confined nutrients in soil or rhizosphere"* and shall meet all relevant requirements set out in that Regulation.

Wastewater - according to the Urban Wastewater Treatment Directive, the term "wastewater" applies to different mixtures of domestic wastewater, urban runoff, and non-domestic wastewater from other origins. For this report, we will adhere to this definition of wastewater and use the terms "liquid effluent" or "effluent" to refer to other liquid streams generated by industrial or agricultural activities requiring treatment before discharge but that are not covered by the Urban Wastewater Treatment Directive.

Target audience

Chapter 1 is targeted at **wastewater treatment operators**, **animal husbandry** farmers, and **aquaculture** and **horticulture** operators considering using algae as an alternative treatment for their effluents or cultivating algae as a way to diversify their activities. It is also intended for **algae producers** looking for more sustainable sources of nutrients.

Chapter 2 is aimed at **policymakers**, **researchers**, and **industry** stakeholders interested in macroalgae cultivation as a tool for nutrient removal and sustainable blue economy development. It outlines regional efforts, environmental benefits, and market opportunities for advancing macroalgae farming.

Chapter 3 and the first part of **Chapter 4**, regarding the analysis of the Fertilising Product Regulation, is targeted at **algae producers** intending to enter the fertilising products market or **fertiliser producers** considering the inclusion of algae products in their portfolio.

The second part of **Chapter 4 and Chapter 5**, regarding the legal analysis and contaminant quantification when using wastewaters for obtaining algae-based fertilising products, is intended for **policy officers at DG GROW**, **DG ENV**, and **DG SANTE**, with recommendations to amend the existing legislation when necessary to expand the possibilities of using wastewaters and effluents for the production of algae fertilisers and biostimulants whenever no/limited added risk is perceived.

Chapter 6 presents a roadmap that is intended for **all stakeholders** interested in producing algae-based fertilising products from algae grown on wastewaters/effluents or from macroalgae grown on eutrophicated open waters. Moreover, it summarises the main conclusions and recommendations of the previous chapters.

Relation to the EU Algae Initiative

In 2022, the European Commission published the Communication "Towards a Strong and Sustainable EU Algae Sector", in which 23 actions were proposed to unlock the vast potential of algae in the EU. This report contributes to the implementation of the following of the 23 actions:

- Action 2) – work with Member States to facilitate access to marine space, identify optimal sites for seaweed farming and include seaweed farming and sea multi-use in maritime spatial plans.
    - **Chapter 2** analyses the potential of seaweed farming in marine space for nutrient removal from eutrophicated waters.
- Action 3) – by the end of 2026, together with the European Committee for Standardization (CEN), develop standard testing, quantification and extraction methods for algae ingredients and contaminants.
    - **Chapter 4** provides a list of existing methods and recommends the development of novel ones, when necessary, with supporting information on similar existing methods that can be used as a starting point.
- Action 5) – starting in 2023, assess the market potential, efficiency and safety of algae-based materials when used in EU fertilising products and the need to amend Regulation (EU) 2019/1009 on EU fertilising products to include algae-based materials.
    - **Chapters 3, 4 and 5** provide technical and legal support for the further development of algae-based fertilising products.
- Action 8) – work with the algae industry and Member States to: a) identify valid and safe alternatives to the use of nutrients and CO_2 from various sources for microalgae cultivation and organic certification; and b) promote the extraction of nutrients from algae biomass.
    - **Chapter 1** provides information on potential sustainable nutrient sources for algae cultivation (organic certification is covered by another report), while **Chapter 3** explores the potential of using algae as fertilising products.

Executive summary

This report examined the potential for integrating algae cultivation with nutrient recovery in two scenarios: (i) the integration of algae cultivation with wastewater or effluent treatment; and (ii) the cultivation of macroalgae in eutrophicated open waters. The resulting biomass is intended for use in fertilising products, and a legal analysis was carried out to assess the implications of using wastewater or effluent for this purpose, with a particular focus on the European market.

Four types of wastewaters/effluents were highlighted as promising for integration with algae systems based on results from European projects, reaching a TRL of at least 5-6: urban wastewater, horticulture effluent, aquaculture effluent, and manure-based digestate. However, careful consideration must be given to the area requirements of an algae treatment system, which depend on the volume and nutrient concentration of the wastewater. It may not always be practical to install an algae system on-site. In such cases, collaborating with other industries through an industrial symbiosis arrangement may be a more viable option; this was most relevant for aquaculture effluent and digestate due to their high volume and high nutrient concentration, respectively. For urban wastewater, the implementation of algae seems more feasible for small agglomerations.

Additionally, the type of wastewater can influence the legal status of the resulting biomass, thereby affecting its final application. This is particularly relevant if contaminants are present, as algae are known to bioaccumulate various substances. Algae produced in horticulture and aquaculture effluents, as well as manure-based digestate, could be components of fertilising products to be commercialised in the European market with minimal alteration to the current legal framework (Fertilising Product Regulation). Algae produced in urban wastewater have sewage sludge status, and their use as a fertilising product is restricted in the European market. Regardless of the cultivation medium used, the production of biostimulants using algae appears to be the most economically promising route, as the cost of algae production remains too high to compete with conventional fertilisers.

With regard to macroalgae cultivation in eutrophicated waters, anchored systems are better suited to sheltered, shallow areas, while floating cultivation systems are more appropriate for nutrient-rich, cold, or temperate EU waters. Floating systems also offer greater scalability and flexibility for large-scale, offshore seaweed farming. *Fucus vesiculosus* is more effective in high-salinity areas, whereas *Ulva intestinalis* performs better in low-salinity environments. On average, these species can remove approximately 150 kgN/km² and 30 kgP/km², respectively.

1. Industrial symbiosis for integrating wastewater treatment and algae production on land

According to the CEN Workshop Agreement (CWA) on Industrial Symbiosis ([1]), this concept can be defined as "*the use by one company or sector of underutilised resources broadly defined (including waste, by-products, residues, energy, water, logistics, capacity, expertise, equipment and materials) from another, with the result of keeping resources in productive use for longer. It presents a systems approach to a more sustainable and integrated industrial economy that identifies business opportunities to improve resource utilisation and productivity.*"

Industrial symbiosis hubs are still scarce in Europe, with a few notable examples including the Kalundborg ecosystem in Denmark ([2]), the Smart Delta Resources in Belgium and the Netherlands ([3]), and the Sotenäs Centre of Symbiosis in Sweden.

Integrating algae technology with other industries can further advance the concept of industrial symbiosis, whereby one or more industries supply their effluents to a centralised treatment facility that supports algal growth for nutrient removal or recovery. Alternatively, the same facility may incorporate an algae cultivation step within its operations to foster internal symbiosis between different processes, enabling more efficient resource utilisation.

From the perspective of the "effluent generator", integration with algae production offers a potentially more sustainable and cost-effective means of reducing nutrient levels to comply with discharge standards. For the algae producer, this collaboration provides access to a more sustainable and lower-cost nutrient source compared to conventional mineral fertilisers.

The following sections highlight relevant streams that can be integrated with algae cultivation and present calculations on nutrient removal capacity and the area footprint required. Wherever possible, data from large-scale systems has been used; however, such data was not always available. It is important to note that algae productivity is highly dependent on environmental conditions, particularly light and temperature. Therefore, the values used in the calculations should be interpreted with caution. They primarily reflect best-case scenarios, and actual large-scale implementation would likely result in lower productivity and, consequently, larger required area footprints for the algae systems considered. For further details on the bioremediation potential and industrial

([1]) CEN (2018). Industrial Symbiosis: Core Elements and Implementation Approaches. Available here.
([2]) Also described in https://data.europa.eu/doi/10.2777/381211
([3]) See footnote 2.

symbiosis applications of microalgae, refer to the EU4Algae report on this topic ([4]).

1.1. Relevant wastewater/effluent streams for the production of algae

The use of algae for urban wastewater treatment is a promising approach that can help meet the goals of the revised Urban Wastewater Treatment Directive (UWWTD), which requires more stringent nitrogen and phosphorus levels in the discharge water, alongside ambitions to make this sector more circular. Algae offer a promising solution for wastewater treatment by absorbing nitrogen, phosphorus, and other nutrients during growth, while simultaneously generating valuable biomass that can be used in various bioeconomy applications, particularly fertilising products, which are the focus of this report. However, large-scale implementations of wastewater treatment using microalgae are currently non-existent.

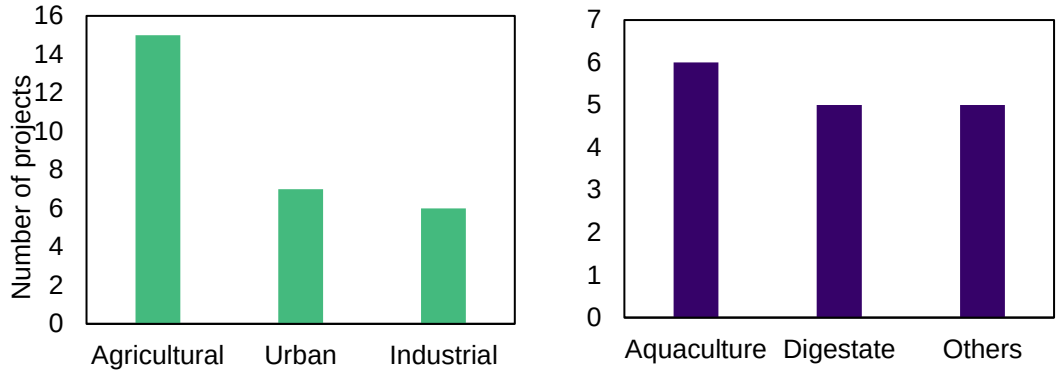
In addition to urban wastewater, agricultural and industrial effluents can also be used for algae cultivation. This study focused on the most promising streams – those with the highest likelihood of near-term implementation. To identify these, desk research was carried out using the CORDIS database to review European projects developed over the past decade, with the findings presented in Figure 1.

Since 2015, 26 European projects have explored the integration of wastewater or effluents with algae cultivation. The primary type of effluent used originated from agriculture, while the use of industrial effluents was more limited and varied significantly in source. As a result, agricultural effluents were further subdivided to determine the most relevant ones, with aquaculture effluents and digestate ([5]) emerging as the most frequently investigated (Figure 1). These two effluent types, along with urban wastewater, were therefore selected as the focus of this study.

([4]) EU4Algae, Developing a monitoring framework to assess bioremediation offered by algae in Europe. This report will soon be available at https://op.europa.eu/en/home under a “EU4Algae” term search on all collections.

([5]) Digestate can be produced from various organic streams and may be directly applied to land as a fertilising material. However, manure-based digestate is currently regulated under the Nitrates Directive (Directive 91/676/EEC), which limits its land application to 170 kg N/ha. This restriction has resulted in a surplus of manure-based digestate in Nitrate Vulnerable Zones (NVZs), necessitating its treatment and discharge. This excess represents a potentially promising stream for algae cultivation and is therefore considered an eligible liquid effluent within the scope of this report. Specifically, this report refers to wet digestate that has not undergone any separation process (i.e., with low dry matter content), or to the liquid fraction of digestate obtained following separation. The solid fraction of digestate and dry digestate are not considered relevant to this document.

Figure 1 – Number of European projects investigating the use of wastewater/effluents for algae cultivation



Left: wastewaters/effluents grouped by source; Right: types of agricultural effluents mainly investigated in the projects. Occasionally, the same project investigated more than one effluent type, so that the sum of each type does not correspond to the total number of projects surveyed.

Effluent from horticultural (hydroponic) production was also selected due to its high production volumes and suitability for algae cultivation, particularly for the production of fertilising products. Although only three European projects were identified for this stream – Algacycle, REALM, and Locality – both REALM and Locality are expected to reach a relevant scale, paving the way for the commercialisation of this technology in the medium term.

Finally, the survey indicated that aquaculture effluent was the only stream used for land-based macroalgae cultivation.

1.2. Integrating algae production within the horticulture (hydroponics) sector

Hydroponics refers to the cultivation of plants without soil, supplying nutrients directly to the roots through a water-based system. These systems can achieve high yields within limited space and with minimal resources, as they typically use less water and fertiliser than traditional agricultural methods. The global hydroponics market was valued at USD 5 billion in 2023 and is projected to grow at a rate of 12.4% from 2024 to 2030 ([6]).

However, hydroponic systems also present certain drawbacks, including high initial investment costs, significant energy demands, and environmental risks linked to the effluent they produce. Conventional hydroponics often operate as open-loop systems, in which excess nutrient solution is applied to plants to maintain high productivity. This generates an effluent that must be treated before discharge into water bodies. Consequently, hydroponic systems stand to benefit

([6]) Grand View Research (2023). Hydroponics Market Summary. Available here.

from integration with microalgae cultivation, using the nutrient-rich effluent as a growth medium. The resulting microalgal biomass can then be processed and marketed as a fertilising product, as explored in the following chapters.

A similar system, called aquaponics, is increasingly supported in the EU. It is defined by the European Commission as "*an innovative aquaculture production system which combines fish production in recirculating aquaculture systems (RAS) with plant production by hydroponics (the technique of growing plants without soil) in one production system*". In this report, two algae aquaponics setups are analysed: (i) a system where the hydroponic component is replaced by an algae cultivation unit, as described in this section; and (ii) a system where the RAS is integrated with algae cultivation, which is further detailed in Section 1.3.

1.2.1. Average nutrient concentrations in hydroponic effluents

A mapping of studies proposing treatment options for hydroponic effluents was carried out, and the relevant data is presented in Table 1. The table shows that, although nitrate concentrations typically hover around 250 mg/L, there is significant variation when the effluent is monitored over several weeks. This observation is further confirmed by the findings from the Horizon Europe REALM project, which explores the integration of microalgae with hydroponic effluent. The project identified variability in effluent quality as one of the major challenges currently hindering the implementation of this technology.

Phosphorus concentrations also varied considerably between different facilities, leading to a fluctuating N/P ratio – an important parameter for healthy microalgae growth and complete nutrient removal.

Nevertheless, hydroponic effluent presents considerable potential for algae cultivation. It contains nitrogen in the form of nitrate, which is generally non-toxic to microalgae, particularly within the concentration range observed in Table 1. Additionally, it exhibits low COD levels (<50 mg/L), minimising the risk of microbial contamination, and maintains a neutral pH, which is favourable for the growth of most microalgae species studied.

Table 1 – Relevant data from hydroponic effluents

Crop	Location	N-Nitrate (mg/L)	P-Phosphate (mg/L)	Daily effluent production (L/d)	Ref
Cucumber	Finland	186 - 270	11 – 32	n.a.	([7])
Oak lettuce	Thailand	264	5.1	n.a.	([8])
Tomato	South Korea	123 - 433	33 – 185	726	([9])
Berries	Portugal	422	94	n.a.	([10])

1.2.2. Algae growth in hydroponic effluents

Only a limited number of studies have evaluated the use of effluent from hydroponic systems for microalgae cultivation, but the results to date have been promising ([11]). The REALM project, which is currently scaling up this technology for broader implementation across Europe, also confirms the suitability of hydroponic effluent for microalgae cultivation.

Although microalgae have been shown to grow in untreated effluent, it is generally recommended to pre-treat the stream before introducing it into the algae cultivation system. Pre-treatment helps to remove coarse particles and indigenous microorganisms, thereby improving the quality of the resulting algal biomass and reducing the risk of system failure due to contamination. Pre-treatment can be achieved through sequential filtration – starting with a coarse filter followed by a 0.2 µm filter – or alternatively, by replacing the fine filter with a UV system or chemical treatment to eliminate microbial contaminants.

Algae grown on hydroponic effluent achieved a volumetric productivity of 0.5 g/L/d with an N uptake of 90 mg/g_{algae}, resulting in a daily uptake of 0.045 gN/L ([12]). From Table 1, we assume an average content of 0.25 gN/L in the effluent, resulting in the need for 5.5 $L_{algae\ system}$/ ($L_{effluent\ generated}$/d).

([7]) Salazar et al. (2021). Nutrient removal from hydroponic effluent by Nordic microalgae: From screening to a greenhouse photobioreactor operation. *Algal Research*. https://doi.org/10.1016/j.algal.2021.102247
([8]) Maneechote et al. (2025). Optimizing the nutrient and light conditions for the enhancement of biomass and high value molecules productions in Spirulina using hydroponic effluent - A sustainable circular economy approach. *Biomass and Bioenergy*. https://doi.org/10.1016/j.biombioe.2025.107638
([9]) Jae Kwon et al. (2021). Waste nutrient solutions from full-scale open hydroponic cultivation: Dynamics of effluent quality and removal of nitrogen and phosphorus using a pilot-scale sequencing batch reactor. *Journal of Environmental Management.* https://doi.org/10.1016/j.jenvman.2020.111893
([10]) REALM project. Available here.
([11]) See footnotes 7 and 8.
([12]) See footnote 7.

If we take the example of the tomato production system in Table 1, with a daily effluent production of 726 L, an algae system of 4,000 L would be required to treat this effluent. With a footprint of 0.027 m^2/L for the algae reactor ([13]), an area of 108 m^2 would be needed.

For a generic system generating an effluent with an average content of 0.25 gN/L, the area requirement is 0.15 $m^2/(L_{effluent\ generated}/d)$ with an algae production of 2.8 $g/(L_{effluent\ generated}/d)$.

These calculations represent only one possible algae system. The REALM project reported lower algae productivities of 0.1 g/L/d in open ponds. Nevertheless, the N uptake of the algae was similar, of 100 mg/g_{algae}, resulting in a daily uptake of 0.01 gN/L. This results in a much higher requirement of 25 $L_{algae\ system}/(L_{effluent\ generated}/d)$, but with the same expected algae production of 2.75 $g/(L_{effluent\ generated}/d)$.

Both scenarios result in a reasonable size requirement for the algae production system; however, this requirement increases with higher daily effluent volumes. Therefore, optimising the algae cultivation step is essential to maximise productivity while minimising the volume required for the algae reactor. The development of new reactor designs with a reduced area footprint would also offer significant advantages for this application.

1.2.3. Opportunities for further synergies and challenges

Algae production is highly dependent on temperature and light availability. Therefore, to achieve higher treatment efficiency, the installation of algae cultivation facilities in the southern regions of Europe is recommended. Nonetheless, hydroponic systems are also commonly found in northern countries. An additional synergy, beyond nutrient exchange, is the potential to leverage the existing greenhouse infrastructure of hydroponic systems to create more favourable conditions for algae growth. While retrofitting existing systems may be challenging, this presents a design opportunity for future hydroponic installations to optimise space by co-locating crop and algae cultivation within the same greenhouse environment.

The main challenges associated with integrating hydroponics and algae systems include: (i) the variability of effluent quality, as previously discussed, and (ii) fluctuations in algae productivity due to weather conditions, which can impact treatment performance. These challenges can be mitigated using buffer tanks and effluent recirculation until discharge thresholds are met. In addition,

([13]) Average footprint of the Helios reactors produced by LGEM, which are an accurate representation of commercial tubular algae reactors.

phosphorus supplementation may be required when the effluent's nitrogen-to-phosphorus (N/P) ratio falls outside the optimal range.

Finally, a survey of the hydroponic sector indicates growing interest in systems that resemble recirculating aquaculture systems (RAS), which enable internal nutrient and water reuse while minimising effluent production. As such, the future integration of algae and hydroponic systems may be driven more by market demand for algae biomass than by the hydroponic sector's need for effluent treatment.

1.3. Integrating algae production within the aquaculture sector

Land-based aquaculture is gaining importance due to its ability to avoid the direct discharge of organic matter and nutrients into natural water bodies, while also enabling inland countries to establish local fish production systems. Within this context, Recirculating Aquaculture Systems (RAS) are increasingly adopted as they significantly reduce the water footprint by recirculating water between the culture tanks and treatment stages. RAS typically consists of mechanical filters to remove fish sludge (solids), biological filters to treat COD, BOD, and nutrients, and in some cases, chemical precipitation units to remove phosphorus. However, phosphorus is largely eliminated through mechanical filtration, as it is primarily bound to particulate matter in fish sludge ([14]). The biological filtration process plays a crucial role in converting ammonia, which is highly toxic to fish even at low concentrations, into nitrate, a less harmful molecule. Nevertheless, nitrate can accumulate over time and must be managed. This can be achieved either by diluting the system with fresh water before recirculation or by incorporating a denitrification step, though the latter adds to treatment costs. Furthermore, both nitrification and denitrification processes may emit NO_x, which are potent greenhouse gases, thereby influencing the overall environmental impact of the system.

Therefore, integrating an algae tank into the RAS treatment process can effectively support nitrogen removal, reducing the demand for freshwater inputs and potentially replacing the nitrification system. This substitution can significantly lower the system's environmental impact by reducing energy consumption and greenhouse gas emissions. Moreover, microalgae increase dissolved oxygen levels through photosynthesis, promoting a healthier aquatic environment and decreasing the need for supplementary oxygenation ([15]).

([14]) FAO & Eurofish International Organisation (2015). A Guide to Recirculation Aquaculture. Available here.
([15]) Huang et al. (2022). Effect of adding microalgae to whiteleg shrimp culture on water quality, shrimp development and yield. *Aquaculture Reports.* https://doi.org/10.1016/j.aqrep.2021.100916

As previously mentioned, a similar system, called aquaponics, is increasingly supported in the EU. Aquaponics is defined by the European Commission as "*an innovative aquaculture production system which combines fish production in recirculating aquaculture systems (RAS) with plant production by hydroponics (the technique of growing plants without soil) in one production system*". In this report, two configurations of algae aquaponics are analysed: (i) a system in which the hydroponic component is replaced with an algae cultivation system, as described in Section 1.2, and (ii) a system in which the RAS is integrated with algae cultivation, as described in this section.

1.3.1. Algae growth in aquaculture effluents

Certain combinations of fish and algal species have proven effective in aquaculture effluent treatment systems. Commonly farmed species such as tilapia, catfish, turbot, and salmon produce nutrient-rich effluents that provide a suitable growth medium for microalgae. Among the algal species, *Chlorella*, *Isochrysis*, and *Scenedesmus* are frequently cultivated due to their high nutrient uptake efficiency and biomass yield.

The nutrient concentrations in aquaculture effluents are summarised in Tables 2 and 3. Nitrogen typically occurs as a mixture of ammonia, nitrate, and nitrite; however, significant levels of organic nitrogen may also be present, particularly when mechanical filtration systems are sub-optimal. It is important to note that effluent composition varies depending on the fish species, system configuration, and environmental conditions.

Nutrient concentrations in aquaculture wastewater are often relatively low, which limits the potential algae biomass yield, as demonstrated in the calculations below. To ensure high-quality algae production and reduce the risk of system failure due to contamination, it is advisable to treat the effluent before introducing it into the algae cultivation system. This pre-treatment typically involves sequential filtration – starting with a coarse filter, followed by a 0.2 µm fine filter. Alternatively, the second step can be replaced by UV or chemical treatment to eliminate indigenous organisms. These treatment methods are already standard in most RAS, making such setups well-suited for integration with algae systems.

A number of studies have assessed the use of effluent from aquaculture systems for both microalgae and macroalgae cultivation, yielding promising results. The suitability of this effluent for algae cultivation is also investigated and confirmed by several companies and European projects: Alga+ (Portuguese company), PureAlgae (Danish company), MariPure (Danish company), Lava Seaweed (Icelandic project), SAFE (European project), Innoaqua (European project), SeaMark (European project), RemediaLife (European project), and AquaVitae Project (European project).

However, data in the literature on algae growth using such effluents are mostly derived from lab-scale experiments, with few relevant figures available from larger-scale studies. Therefore, some assumptions were made based on the data used in the previous section:

- Microalgae volumetric productivity - 0.1 g/L/d
- N uptake - 100 mg/g_{algae}

These assumptions result in a daily uptake of 0.01 gN/L.

Based on Tables 2 and 3, the effluents can be categorised into three groups: low, medium, and high strength. For low-strength effluents, an average nitrogen content of 0.005 gN/L already meets discharge limits and provides insufficient nutrients for algae growth; therefore, such effluents may not be suitable for integration with an algae cultivation system. For the medium strength with an average content of 0.03 gN/L, 3 $L_{algae\ system}$/ ($L_{effluent\ generated}$/d) is needed, and for the high strength with 0.12 gN/L, 12 $L_{algae\ system}$/ ($L_{effluent\ generated}$/d) is needed.

RAS volumes vary for different production facilities. In one of the analysed studies, a system of 1900 m^3 is described with an average water replacement rate of 67 m^3/h (1,608,000 L/d) and a nitrogen concentration of 0.008 gN/L (low-strength effluent). This system would require 0.8 $L_{algae\ system}$/($L_{effluent\ generated}$/d), resulting in the need for an algae system of 1,284 m^3 to treat the effluent. With a footprint of 0.027 m^2/L for the algae reactor, an area of around 35,000 m^2 would be needed with a daily algae production of around 128 kg. Although this effluent may already meet discharge standards, it exemplifies the large volume requirements of algae systems when integrated with RAS, with higher-strength effluents demanding even greater capacity.

To better illustrate this, the algae system can be compared with the aquaculture system. An average fishpond is 1.5 m deep ([16]). Therefore, a system of 1,900 m^3 would require a minimum surface area of 1,266 m^2, whereas the microalgae system necessary to treat all its effluent would require more than 20 times that area – an unattractive prospect for most facilities.

Installing a microalgae treatment system is therefore more suitable for facilities aiming to diversify their outputs, whereby a portion of their effluent could be diverted into an algae reactor to generate valuable biomass as a secondary product. This setup would also promote nutrient removal and oxygenation of the effluent.

([16]) Principles of Designing Inland Fish Farms. https://www.fao.org/4/x5744e/x5744e07.htm#3.%20purpose%20and%20dimensioning%20of%20fish%20farm%20structures

Finding relevant data for macroalgae cultivation on aquaculture effluent proved challenging. One study reported an average nitrogen content of 38 gN/kg_{algae} ([17]) for macroalgae grown on aquaculture effluent, while another indicated that an optimised land-based macroalgae system could reach a productivity of 20 $g_{algae}/m^2/d$ ([18]). Based on these figures, an optimal macroalgae system would be able to remove 0.76 $gN/m^2/d$.

Table 2 – Relevant data from aquaculture effluents and microalgae grown on them

Microalgae Species	Fish Species	Total N (mg/L)	Nitrate-N (mg/L)	Nitrite-N (mg/L)	Ammonia-N (mg/L)	Total P (mg/L)	Reference
Chlorella vulgaris	Trout	20.2	10.3	n.a.	n.a.	2.2	([19])
Isochrysis galbana	Milkfish	n.a.	n.a.	0.2-0.3	1.3-1.9	1.9-3.2	([20])
Tetraselmis tetrahele							
Nannochlorum sp.							
Scenedesmus sp.	Rainbow trout	34.5	30.9	0.06	0.6	0.15	([21])
Isochrysis galbana	Salmon	7.94	0.2-0.3		0.75	0.12	([22])

n.a.: Not available.

Considering the earlier example of an effluent production of 1,608,000 L/day with a nitrogen concentration of 0.008 gN/L, the area required for a macroalgae treatment system would be approximately 17,000 m². Although this is smaller than the land area needed for microalgae cultivation, it still represents a substantial footprint. This underscores the need for careful assessment of algae use in aquaculture effluent treatment, with the economic value of the resulting algal biomass being critical to the viability of such a symbiotic system.

([17]) Praeger et al. (2019). Maximising the productivity of the attached cultivation of Ulva tepida in land-based systems. *Algal Research.* https://doi.org/10.1016/j.algal.2019.101507
([18]) See footnote 21.
([19]) Esteves et al. (2022). Microalgal Growth in Aquaculture Effluent: Coupling Biomass Valorisation with Nutrients Removal. *Applied Sciences*. https://doi.org/10.3390/app122412608
([20]) Piñosa et al. (2023). Optimization of stocking density for Isochrysis galbana, Nannochlorum sp., and Tetraselmis tetrahele in the bioremediation of aquaculture wastewater. *Aquaculture International.* http://dx.doi.org/10.1007/s10499-023-01340-z
([21]) Bhatti et al. (2023). Phycoremediation and simultaneous production of protein-rich algal biomass from aquaculture and agriculture wastewaters. *Journal of Chemical Technology & Biotechnology*. https://doi.org/10.1002/jctb.7409; only one example was taken, but this study brings more information on the composition of several effluents from aquaculture of different fish.
([22]) Borg-Stoveland et al. (2024). Successful growth of coastal marine microalgae in wastewater from a salmon recirculating aquaculture system. *Journal of Applied Phycology*. https://doi.org/10.1007/s10811-024-03310-1

Table 3 – Relevant data from aquaculture effluents and macroalgae grown on them

Macroalgae Species	Fish Species	Nitrate-N (mg/L)	Nitrite-N (mg/L)	Ammonia-N (mg/L)	Phosphate (mg/L)	Reference
Ulva lactuca L.	Shrimp	12.9	0.6	1.2	63.6	([23])
	Catfish	12.4	0.1	38.9	28.0	
	Trout	8.9	0.2	0	2.3	
	Pikeperch	9.4	0	11.7	10.8	
Caulerpa lentillifera	Sailfin Mollies	121.6	0.52	1.27	0.4	([24])
Ulva pseudorotundata	Thicklip gray mullet	356	n.a.	185	148.1	([25])
Ulva rigida						

n.a.: Not available.

1.3.2. Challenges for implementation

As previously mentioned, algae production is highly dependent on temperature and light availability. However, aquaculture is also a major industry in northern countries. Consequently, the need for supplemental lighting and heating to maintain algal productivity and treatment capacity may pose a significant challenge in terms of both economic and environmental sustainability.

Another key challenge is the large volume of effluent typically generated in aquaculture systems, which often contains relatively low nutrient concentrations. This makes continuous treatment systems more suitable – where algae are immobilised and continuously supplied with fresh effluent to ensure sufficient nutrient availability for optimal growth. While such fixed-biomass systems are already employed for macroalgae, commercial microalgae systems generally rely on suspended biomass cultivation. Nevertheless, some film systems, such as rotating algae biofilm reactors, are currently being tested at pilot scale. These systems have demonstrated higher aerial productivity than suspended

([23]) Sebök and Hanelt (2023). Cultivation of the brackish-water macroalga Ulva lactuca in wastewater from land-based fish and shrimp aquacultures in Germany. *Aquaculture.* https://doi.org/10.1016/j.aquaculture.2023.739463
([24]) Bambaranda et al. (2019). Capacity of Caulerpa lentillifera in the Removal of Fish Culture Effluent in a Recirculating Aquaculture System. *Processes*. https://doi.org/10.3390/pr7070440
([25]) Massocato et al. (2022). Growth, biofiltration and photosynthetic performance of Ulva spp. cultivated in fishpond effluents: An outdoor study. *Frontiers in Marine Science.* https://doi.org/10.3389/fmars.2022.981468

cultures ([26]). As a result, they may be especially well-suited for integration with aquaculture facilities, offering a promising approach to significantly reducing the land footprint required for algae-based effluent treatment.

1.4. Integrating algae and anaerobic digestion of manure

Digestate obtained from anaerobic digestion (AD) of organic waste is a nutrient-rich by-product that is generally applied directly to land as a fertilising material ([27]). However, the Nitrates Directive restricts the amount of manure-derived nitrogen that can be applied to soil in certain areas – such as Nitrate Vulnerable Zones – to minimise the risk of eutrophication in water bodies.

This results in a local surplus of manure-based digestate that can be exported or locally treated for nutrient removal and further discharge. Moreover, with the RePowerEU strategy, the AD sector in the EU is projected to grow significantly in the coming years, leading to a substantial increase in digestate production. However, this expansion is unlikely to be matched by an increase in available arable land, resulting in surplus digestate that must either be exported or further treated before safe discharge. Algae cultivation offers a promising solution by recovering nutrients from digestate and converting them into valuable biomass, while simultaneously treating the effluent to meet discharge standards.

1.4.1. Average nutrient concentrations in manure-based digestates

Table 4 demonstrates significant variability in digestate composition, primarily influenced by the mode of operation and the quality of the feedstock. Notably, the $N\text{-}NH_4^+$ content ranges from 1,500 to nearly 6,000 mg N/L. Additional variation arises from factors such as the age of the animals producing the manure and the type of feed used, as illustrated by the wide range reported for the AD plant in Greece. These high concentrations of ammonia necessitate substantial dilution before the digestate can be introduced into an algae reactor, as elevated ammonia levels are toxic to algal growth. This represents a critical consideration for the viability of the technology, as further discussed in Section 1.4.3.

Phosphorus concentrations also vary significantly between facilities, resulting in a fluctuating N/P ratio – an important factor for ensuring healthy algal growth and effective nutrient removal. In general, the liquid fraction of digestate is relatively

([26]) Gross et al. (2013). Development of a rotating algal biofilm growth system for attached microalgae growth with in situ biomass harvest. *Bioresource Technology.* https://dx.doi.org/10.1016/j.biortech.2013.10.016
([27]) More information on current uses of digestate is available here.

low in phosphorus and may require supplementation to adequately support microalgae cultivation.

Table 4 – Relevant data from manure-based digestate

Input for AD	Location	N-NH_4^+ (mg/kg)	P-Phosphate (mg/kg)	Daily effluent production (t/d)	Reference
Pig manure	France	1930	103	-	([28])
Cow manure	Belgium	5800	-	41	([29])
Pig slurry, biowaste, sewage sludge	Belgium	3300	290	147	([30])
Pig slurry, agro-industry residues	Netherlands	4700	620	315	
Livestock residues, corn silage, food waste	Greece	1500 - 4000	50 – 300	-	([31])
Cow manure + additives	Italy	1830	760	51	([32])

1.4.2. Algae growth in manure-based digestate

Several studies have investigated the use of digestate for microalgae cultivation; however, relatively few have focused specifically on manure-based digestate. Generally, the literature concludes that, provided suitable dilution is applied to reduce ammonia toxicity and improve light penetration, and any nutrient imbalances are corrected, algal growth on digestate is successful and can even surpass growth in conventional mineral media.

Although microalgae can grow in untreated (liquid) digestate, it is advisable to treat the stream prior to its use in algae cultivation. This helps remove coarse particles and indigenous organisms, thereby enhancing the quality of the algal biomass and reducing the risk of system failure due to contamination. Treatment

([28]) ALG-AD - Seasonal variation of algae biomass cultivated using nutrient rich digestate. Available here.
([29]) Internal communication from the SEMPRE-BIO project.
([30]) SYSTEMIC - Document on product characteristics, lab results and field trials (year 4). Available here.
([31]) Poster of Demo 3: https://fuelphoria.eu/demos/ plus internal communication with project partners.
([32]) Ledda et al. (2016). Integration of microalgae production with anaerobic digestion of dairy cattle manure: an overall mass and energy balance of the process. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2015.07.151

can be achieved through sedimentation and coarse filtration, followed by UV disinfection or chemical treatment to eliminate remaining organisms. This final step may not be necessary if the digestate has already undergone pasteurisation, as is often legally required. Further information on digestate handling and treatment for algae cultivation is available in the deliverables of the ALG-AD project, which examined the integration of microalgae production with anaerobic digestion systems ([33]).

Algae grown on manure-based digestate could achieve a volumetric productivity of 0.4 g/L/d with an N uptake of 90 mg/g_{algae} ([34]), resulting in a daily uptake of 0.036 gN/L.

Considering the example of the AD system in Italy, as reported in Table 4, with an N content of 1.8 g/L in the digestate, the volume of the algae system required would be 50 $L_{algae}/(kg_{digestate}/d)$. Given a daily effluent production of 51 tonnes, this translates to an algae system volume of approximately 2,550 m^3. Assuming a reactor footprint of 0.027 m^2 per litre, the total area required would be around 70,000 m^2, with an expected algae yield of about 1 tonne per day.

Once again, these calculations represent only one possible algae system. If productivity increases or decreases, or if the quality of the digestate changes, the required space will also vary. For instance, for the Belgian farm listed in Table 4, an area of 100,000 m^2 would be needed. Further information and calculations on algae growth on (non-manure) digestate can be found in the deliverables from the AlgaeBiogas project.

One of the largest algae farms in Europe occupies an area of 20,000 m^2; therefore, it seems unlikely that farmers would implement an algae facility of such scale on their own farms. In this case, the concept of industrial symbiosis is more appropriate, whereby an algae farm is established near the digestate-producing farm to utilise this stream as a sustainable nutrient source, thereby relieving the farmer of the operational burden.

1.4.3. Opportunities for further synergies and challenges

The considerations above focus on nutrient supply to the algae through the use of digestate. Nevertheless, the anaerobic digestion process also generates CO_2 as a by-product, which serves as the carbon source during photosynthesis for algal growth. Generally, algae require approximately 1.8 kg CO_2 per kg of algae produced, although this amount may increase when accounting for losses due to the limited solubility of CO_2 in the growth medium. Therefore, utilising the CO_2

([33]) ALG-AD Best Practice Guideline Part 1. Available here.
([34]) Ledda et al. (2016). Integration of microalgae production with anaerobic digestion of dairy cattle manure: an overall mass and energy balance of the process. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2015.07.151

produced by the anaerobic digestion plant for algae cultivation presents an additional opportunity for synergy. This possibility is being assessed by the SEMPRE-BIO project and implemented by a farmer in Belgium.

As previously mentioned, algae production is highly dependent on temperature and light availability. Therefore, to achieve higher treatment efficiency, the installation of algae facilities in the southern parts of Europe is recommended. Nevertheless, anaerobic digestion systems are predominantly located in northern countries. An additional synergy to maintain favourable conditions for algal growth is the potential use of excess heat from the CHP engines typically employed by anaerobic digestion plants to convert biogas into energy.

Furthermore, anaerobic digestion plants produce sustainable energy that can be used for algae cultivation. However, it is important to minimise the energy consumption of the algae facility, as the energy generated is usually required for other farm activities as well.

Some challenges associated with using digestate for algae cultivation include: (i) variation in effluent quality, particularly regarding ammonia levels, which may lead to culture crashes due to ammonia toxicity if not correctly managed; and (ii) fluctuations in algal productivity caused by weather conditions, potentially affecting treatment capacity. To address the first challenge, accurate characterisation of the digestate – focusing on its ammonia concentration – is recommended. To mitigate the second, practical solutions include the use of a buffer tank and the recirculation of effluent that does not meet discharge limits. Phosphorus supplementation is also often necessary to ensure healthy algal growth on manure-based digestate (and digestates in general).

Beyond technical challenges, there are legal limitations to the possible applications of the produced algal biomass (further discussed in Chapter 4). When grown on manure-based digestate, algae would, in principle, still be subject to the Nitrates Directive and, therefore, would not resolve the problem of excess digestate for land application. Consequently, the production of biostimulants from algae cultivated on manure-based digestate is a more realistic route for treating excess digestate.

Finally, the use of manure for applications other than those described in the Animal By-Products Regulation remains a legal grey area. Consequently, the use of manure-based digestate for algae cultivation requires local environmental permits (further discussed in Chapter 4). As an alternative, digestates from other sources—such as plant-based residues, food waste, or energy crops—can be considered for algae cultivation. However, these are not restricted by the Nitrates Directive and are therefore primarily directed towards land application as fertilising material. Nevertheless, AD plants are sometimes located in non-agricultural areas, and the use of an algae system to treat the liquid fraction of

digestate – thereby avoiding long-distance transportation – can present an attractive solution for such facilities.

1.5. Integrating algae and urban wastewater treatment

Urban wastewater treatment is undergoing a paradigm shift driven by the need for greater sustainability and resource recovery. The recently recast EU Urban Wastewater Treatment Directive (2024/3019) emphasises reducing greenhouse gas (GHG) emissions, improving energy efficiency, and transitioning towards a circular economy within the wastewater sector. In this context, algae-based treatment technologies have gained attention as innovative solutions capable of simultaneously treating wastewater and recovering nutrients in the form of biomass.

For the integration of microalgae in urban wastewater treatment, two specific approaches are reviewed:

1. Primary wastewater treatment and algae technology: This approach considers algae as a component of secondary treatment, capturing pollutants such as COD, BOD, N and P, among others, while reducing energy and chemical input.
2. Algae technology as a tertiary treatment for nutrient recovery: This approach explores the potential for algae to extract nitrogen and phosphorus from treated effluent (tertiary treatment), converting these nutrients into valuable bioproducts and assisting treatment plants in meeting more stringent discharge limits for nitrogen and phosphorus.

In Approach 1, microalgae are integrated as a core component of the wastewater treatment train, performing major treatment functions rather than serving merely as an add-on. This may involve replacing conventional secondary treatment – and possibly even primary clarification – with a high-rate algal pond or algal biofilm system. In practice, raw sewage would undergo preliminary screening and grit removal before entering an algal reactor (such as a pond or photobioreactor), where algae and symbiotic bacteria treat the organic carbon and nutrients. The algae supply oxygen to support bacterial degradation of organic matter (replacing mechanical aeration), while simultaneously assimilating nitrogen and phosphorus into their biomass. This integrated method is sometimes referred to as a “single pot” treatment system, as it seeks to replicate the functions of multiple units (e.g. primary clarifier, aeration tank, secondary clarifier) within a single, combined

biological stage ([35]). The treated water would then undergo clarification (with algal biomass separation) and, if necessary, disinfection before discharge or reuse.

Approach 2 involves a conventional wastewater treatment plant with an additional algae cultivation stage at the end of the process. In this configuration, primary and secondary treatments are carried out using traditional methods, resulting in a relatively clean effluent that still contains residual nutrients. This effluent is then directed to an algal reactor, where microalgae absorb the remaining nitrogen and phosphorus. The objective is to polish the effluent to very low nutrient concentrations while simultaneously producing algal biomass enriched with these nutrients – thereby effectively "recovering" them in a reusable form. Following the algal stage, the water can be discharged or reused. Often, this effluent will be very low in nutrients and may also have received additional disinfection through sunlight exposure in open ponds. This approach can be regarded as retrofitting algae technology onto existing treatment infrastructure to enhance nutrient removal and support resource recovery.

At present, algae-based urban wastewater treatment has seen limited full-scale implementation, primarily due to technical and economic challenges. A key technical obstacle is maintaining a stable and viable algal culture over extended periods ([36]). To make large-scale treatment feasible, more efficient cultivation techniques are required. Many existing systems have been scaled up from laboratory or pilot setups, which often struggle to perform effectively at an industrial scale ([37]).

Nevertheless, there are already some initiatives at higher TRL, as this topic has been studied by past and ongoing European projects, such as Algeco, Algaenauts, Walnut, and Rhemediation. The two later are ongoing and expected to publish public reports from 2026 onward. Moreover, one British company, I-PHYC, proposes a specific algae set-up for the treatment of the tertiary wastewater with algae.

With the publication of the new Urban Wastewater Treatment Directive, there is a renewed incentive for improving the current facilities, reducing their environmental footprint while increasing their nutrient removal capacity. Therefore, it is likely that operators will look at algae as a possible alternative or add-on to the current systems.

Urban wastewaters have a highly diverse composition that varies depending on the geographical location of each treatment plant. As a result, the previously used

([35]) Gowd et al. (2023). Life cycle assessment of comparing different nutrient recovery systems from municipal wastewater: A path towards self-reliance and sustainability. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2023.137331
([36]) Nguyen et al. (2022). Nutrient Removal by Algae-Based Wastewater Treatment. *Current Polution Reports*. https://doi.org/10.1007/s40726-022-00230-x
([37]) Acién Fernández et al. (2019). Chapter 21 - Costs analysis of microalgae production. In *Biofuels from Algae (Second Edition)*. https://doi.org/10.1016/B978-0-444-64192-2.00021-4

method of presenting a table of average compositions was considered unsuitable for this type of effluent. Furthermore, the removal capacity of the system can vary significantly depending on the specific algae-bacteria consortia employed, making it difficult and potentially inaccurate to propose generalised figures for the efficiency of such systems.

Accordingly, for urban wastewaters, the sections below compile and synthesise available evidence from practical applications and academic research. Emphasis is placed on the economic and environmental benefits and challenges of integrating algae into urban wastewater treatment. Where available, indicative figures relating to area requirements and treatment capacities are also provided as a roadmap for implementing this technology.

1.5.1. Economic Analysis

Estimating the overall expenses of algae-based wastewater treatment is complex, as it depends on a wide range of variables. Existing case studies vary in scope, cost categories, and the specific parameters considered. However, a relative comparison of wastewater treatment costs (€/m³) and/or biomass production costs (€/kg) can offer clearer insights into how certain variables influence overall expenditure. Similarly, the treatment costs of conventional systems can serve as a benchmark for assessing the feasibility of algae-based alternatives.

The cost data available in the literature (Table 5) are not conclusive in identifying a single optimal approach to algae-based wastewater treatment. They are influenced by multiple factors, including project objectives and the baseline costs of conventional treatment systems used for comparison. It is also important to note that the costs of conventional treatment systems vary depending on several parameters and local considerations. Furthermore, many studies on algae-based systems include assumptions about potential cost savings, such as reduced labour requirements or lower energy consumption, which remain speculative.

Overall, algae-based systems have generally resulted in significantly higher costs than their conventional counterparts. The sole exception was one study that reported a treatment cost of €0.18/m³; however, it remains unclear how the authors arrived at such a low figure for an algae-based system. The higher cost of algae-based treatment is to be expected, given that conventional technologies are mature, whereas algae-based systems are still under development and undergoing optimisation.

Combining wastewater treatment with biomass production may help to offset costs, making it essential to evaluate the trade-offs between these two objectives. Key differentiating factors include nutrient concentration, wastewater flow rate,

nutrient removal efficiency, and retention time, each influencing whether the system is optimised for higher biomass production or improved nutrient removal.

When focusing solely on algae-based wastewater treatment, the use of treated wastewater (post-secondary treatment) in raceway reactors may be more economically viable for larger populations, due to their high treatment capacity and scalability. Their design supports large-scale operations; however, the economic return is relatively modest when compared to other systems. In contrast, thin-layer cascade reactors are more cost-efficient in terms of biomass production. Although they have a higher treatment cost per volume of water and a lower overall capacity, they achieve a lower net cost for producing microalgae biomass. This makes them a cost-effective solution for smaller-scale applications, where biomass yield efficiency is prioritised over treatment volume. Overall, raceway reactors are more suitable for scalability and high-volume treatment, whereas thin-layer cascade reactors offer greater cost-efficiency for biomass production, making them well-suited to smaller installations focused on maximising output value ([38]).

In conventional wastewater treatment plants, land requirements are relatively modest, with just 1 hectare sufficient to treat wastewater for 30,000 to 50,000 population equivalents per year (p.e.y.). In contrast, microalgae-based treatment systems may require 30 to 50 hectares to manage the same capacity. This substantial land demand limits their applicability to smaller towns – typically ranging from 200 to 15,000 p.e.y. – where effective wastewater treatment is often lacking. For these smaller communities, conventional systems are not only expensive but also overly complex, frequently resulting in operational challenges. Microalgae-based alternatives offer a simpler solution, with lower capital (CAPEX) and operational (OPEX) costs, requiring less machinery and consuming less energy ([39]).

Labour costs appear to be a significant cost category in algae-based systems, likely because all reviewed studies were conducted at a small scale but involved advanced technology. However, in some cases, labour falls under a broader category such as "labour and others," which includes not only staffing for process operation but also general costs such as supervision, management, maintenance, taxes, and contingencies. Findings indicate that reducing manpower requirements can substantially lower overall costs by approximately €0.65 to €0.97 per cubic metre of wastewater treated ([40]).

Location also plays a critical role in cost variability. For instance, the construction and labour costs for open ponds are often based on assumptions relevant to

([38]) Acién Fernández et al. (2019). Chapter 21 - Costs analysis of microalgae production. In *Biofuels from Algae (Second Edition)*. https://doi.org/10.1016/B978-0-444-64192-2.00021-4
([39]) Acién et al. (2016). Wastewater treatment using microalgae: how realistic a contribution might it be to significant urban wastewater treatment? *Applied Microbiology and Biotechnology*. https://doi.org/10.1007/s00253-016-7835-7
([40]) See footnote 38.

developed countries. In low-income countries, where labour costs are typically much lower, these expenses could be significantly reduced ([41]).

In conclusion, integrating microalgae cultivation with wastewater treatment can prioritise wastewater purification, biomass production, or a combination of both. System design should take into account various factors, including location, economic constraints, wastewater source and characteristics, land availability, and the intended end use of the biomass. In developed countries with established wastewater infrastructure, the focus may shift towards maximising nutrient recovery while minimising the cost of biomass production. Technologies such as closed photobioreactors can improve productivity and reduce spatial requirements; however, their costs remain significantly higher than those of open pond systems.

Open pond systems continue to offer a more cost-effective solution for algae-based wastewater treatment, with operational costs, particularly labour, constituting the majority of total expenses. Currently, most studies focus on small-scale applications, and the practical feasibility of these systems appears to be largely limited to towns with populations under 10,000.

Further research should address cost distribution at larger scales. A comprehensive cost–benefit analysis comparing algae-based and conventional wastewater treatment systems could help identify major cost drivers and highlight opportunities for optimisation, particularly when accounting for the added value of biomass production. At present, the combined approach of wastewater treatment and biomass generation appears to be the most economically viable strategy for implementing algae in the treatment process. Nevertheless, further advancements are needed to enhance both cost-efficiency and technological maturity.

([41]) Chaudry (2021). Integrating Microalgae Cultivation with Wastewater Treatment: a Peek into Economics. *Applied Biochemistry and Biotechnology*. https://doi.org/10.1007/s12010-021-03612-x

Table 5 – Overview of wastewater treatment costs and biomass production costs

WW type	Objective	Process stage	System	Wastewater treatment cost	Unit	Biomass Production Cost	Unit	Reference
Urban	Compare costs between countries	Primary, secondary and tertiary	Conventional (small plants)	17-30	€/p.e.y.			([42])
Urban	Compare costs between countries	Primary, secondary and tertiary	Conventional (large plants)	30-40	€/p.e.y.			
Urban	Financing treatment costs	Not specified (assumed at least primary and secondary)	Conventional	0.31*	€/m³			([43])
Urban	Cost recovery calculation	Primary, secondary and tertiary	Conventional	0.36*	€/m³			([44])
Assumed urban	Compare costs between reuse sectors	Tertiary and distribution	Conventional	0.31*	€/m³			([45])
Assumed urban	Compare costs between reuse cases	Tertiary and distribution	Conventional	0.17-0.71	€/m³			([46])
Urban	Compare costs between technologies	Tertiary	Conventional	0.06-0.23	€/m³			([47])
Municipal (~2000 PE)	Compare different retention times	After primary	HRAP (OP)	0.45	€/m³			

([42]) Zessner et al. (2010). Cost comparison of wastewater treatment in Danubian countries. *Water Science & Technology*. https://doi.org/10.2166/wst.2010.271
([43]) Pajares et al. (2019). Cost of Urban Wastewater Treatment and Ecotaxes: Evidence from Municipalities in Southern Europe. *Water*. https://doi.org/10.3390/w11030423
([44]) Ruiz-Rosa et al. (2020). Developing a methodology to recover the cost of wastewater reuse: A proposal based on the polluter pays principle. *Utilities Policy*. https://doi.org/10.1016/j.jup.2020.101067
([45]) Areosa et al. (2024). Treated wastewater reuse for irrigation: A feasibility study in Portugal. *Science of The Total Environment*. https://doi.org/10.1016/j.scitotenv.2024.176698
([46]) Hernández-Chover et al. (2022). A Tariff Model for Reclaimed Water in Industrial Sectors: An Opportunity from the Circular Economy. *Water.* https://doi.org/10.3390/w14233912.
([47]) Pistocchi et al. (2017). The potential of water reuse for agricultural irrigation in the EU. Available here.

WW type	Objective	Process stage	System	Wastewater treatment cost	Unit	Biomass Production Cost	Unit	Reference
Municipal (~2000 PE)	Compare different retention times	After primary	HRAP (OP)	0.73	€/m³			([48])
Municipal (~2000 PE)	Compare different retention times	After primary	HRAP (OP)	0.47	€/m³			
Urban	Compare different types of wastewater sources	After primary (sewage)	OP	0.18	€/m³	0.66	€/kg	([49])
Urban	Compare different systems	Secondary	Raceway (OP)	1.51	€/m³	3.58	€/kg	([50])
Urban	Compare different systems	Secondary	Thin-layer cascade (OP)	2.18	€/m³	1.42	€/kg	
Urban	Compare different systems (+ manpower reduction)	Secondary	Raceway (OP)	1.10	€/m³	2.61	€/kg	
Urban	Compare different systems (+ manpower reduction)	Secondary	Thin-layer cascade (OP)	1.18	€/m³	0.77	€/kg	
Urban	Compare different systems + (potential scale-up opportunity)	After primary	PBR (1500L)	1.60	€/m³	2.40	€/kg	([51])

Note: Costs for conventional wastewater treatment are presented under the category “conventional” in the “system” field, as all studies calculated costs based on data from various plants, assumptions, and mixed technologies. The specific technologies used are not always explicitly stated in all studies. Additionally, costs marked with an asterisk (*) represent the average values provided by the respective study, which also include ranges

([48]) Vázquez Romero et al. (2021). Techno-economic análisis of microalgae-based wastewater treatment in small populations. Available here.
([49]) Chaudry (2021). Integrating Microalgae Cultivation with Wastewater Treatment: a Peek into Economics. *Applied Biochemistry and Biotechnology*. https://doi.org/10.1007/s12010-021-03612-x
([50]) Acién Fernández et al. (2019). Chapter 21 - Costs analysis of microalgae production. In *Biofuels from Algae (Second Edition)*. https://doi.org/10.1016/B978-0-444-64192-2.00021-4
([51]) Gouveia et al. (2016). Microalgae biomass production using wastewater: Treatment and costs: Scale-up considerations. *Algae Research.* https://doi.org/10.1016/j.algal.2016.03.010

1.5.2. Environmental Analysis

1.5.2.1. Algal Integration in Secondary Treatment

When algae are used in place of energy-intensive processes, there is potential for significant environmental benefits. Several studies suggest that well-optimised algal treatment systems can reduce net energy consumption and emissions compared to conventional treatment plants. Case studies from New Zealand and other regions have demonstrated that high-rate algal ponds can achieve comparable treatment performance to conventional systems while imposing lower overall environmental burdens ([52]). One study found that an algae-based sewage treatment system in a sunny climate not only met effluent quality standards but also contributed to CO_2 capture and exhibited a lower eutrophication impact than an equivalent conventional process ([53]).

Microalgae-based systems have the potential to reduce the energy consumption of wastewater treatment by up to 50%, while recovering as much as 90% of the wastewater's nutrients. Such systems can fix approximately 25 tonnes of nitrogen and 2.5 tonnes of phosphorus per hectare per year into algal biomass ([54]), illustrating their high nutrient removal efficiency. A major contributor to this energy reduction is the replacement of mechanical aeration with algal photosynthesis, which provides oxygen naturally and reduces electricity demand.

Moreover, evidence from integrated algae demonstration projects indicates that the energy required for mixing raceway ponds is significantly lower than that needed to operate blowers for aeration in equivalent conventional processes ([55]). In one case, the integration of an algal reactor reduced the aeration energy demand in the main treatment line by several kilowatt-hours per cubic metre, nearly offsetting the energy required for algae cultivation ([56]).

An innovative development in this field is the use of microbial fuel cells (MFCs) or algal turf scrubbers as integrated treatment units. A recent comparative environmental assessment of nutrient recovery systems reported that a single-pot configuration – where a fuel cell treats raw wastewater and simultaneously recovers nutrients – achieved a negative carbon footprint of –234 g CO_2-eq per

([52]) Sangma and Chalie-u (2023). Chapter 8 - Life cycle assessment of wastewater treatment by microalgae. In *Valorization of Microalgal Biomass and Wastewater Treatment*. https://doi.org/10.1016/B978-0-323-91869-5.00008-9
([53]) See footnote 52.
([54]) Acién Fernández et al. (2018). Recovery of Nutrients From Wastewaters Using Microalgae. *Frontiers in Sustainable Food Systems*. https://doi.org/10.3389/fsufs.2018.00059
([55]) See footnote 54.
([56]) Crippa et al. (2024). Life Cycle Assessment of Microalgal Biomass Valorization from a Wastewater Treatment Process. *Waste and Biomass Valorization*. https://doi.org/10.1007/s12649-024-02695-x

m³, effectively acting as a carbon sink ([57]). Although this example specifically involved an MFC, the authors concluded that single-pot configurations generally perform better environmentally than add-on tertiary units. This suggests that microalgae, when employed in integrated setups, could similarly avoid the environmental overhead associated with running multiple, separate treatment stages. In essence, integrated approaches benefit from process simplification, leading to reduced cumulative impacts.

Regarding eutrophication, the integration of algae into secondary treatment processes can significantly reduce nutrient levels in discharged effluent. Moreover, one study indicated that if the resulting algal biomass is used as a fertilising product, it can further reduce the overall eutrophication and GHG impacts of the system – particularly when its biostimulant effect on improving crop nutrient uptake is considered ([58]). In summary, this approach is expected to yield a substantially lower eutrophication impact than conventional baseline treatment, both by reducing nutrient discharge into water bodies and enabling nutrient recycling. This aligns directly with the goals of the EU directive to protect water bodies from nutrient pollution and promote circular nutrient use.

However, it should be noted that if an algal system is not well optimised, its GHG performance may be comparable to that of conventional systems. One study found that an algal-based disinfection unit (an open pond replacing a UV treatment stage) achieved a slightly lower GWP and reduced human toxicity relative to the baseline, but the overall benefit was modest due to the electricity still required for circulation ([59]).

Finally, a known limitation of algae-based primary treatment is the substantial surface area required to manage municipal wastewater flows. Retention times in algal ponds are typically measured in days to achieve effective treatment, whereas activated sludge processes can accomplish similar outcomes within hours by maintaining higher microbial densities. For algal systems to be feasible, sufficient land availability is essential. Estimates suggest that up to 1 hectare of pond area could treat and recover nutrients from the wastewater generated by a few thousand people, while producing approximately 200 tonnes of biomass per year ([60]). In many urban areas, allocating such land for wastewater treatment is likely to be impractical. Potential mitigations include the use of advanced high-rate pond designs or multi-layer systems to reduce the land footprint.

([57]) Gowd et al. (2023). Life cycle assessment of comparing different nutrient recovery systems from municipal wastewater: A path towards self-reliance and sustainability. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2023.137331
([58]) Crippa et al. (2024). Life Cycle Assessment of Microalgal Biomass Valorization from a Wastewater Treatment Process. *Waste and Biomass Valorization*. https://doi.org/10.1007/s12649-024-02695-x
([59]) Sangma and Chalie-u (2023). Chapter 8 - Life cycle assessment of wastewater treatment by microalgae. In *Valorization of Microalgal Biomass and Wastewater Treatment*. https://doi.org/10.1016/B978-0-323-91869-5.00008-9
([60]) Acién Fernández et al. (2018). Recovery of Nutrients From Wastewaters Using Microalgae. *Frontiers in Sustainable Food Systems*. https://doi.org/10.3389/fsufs.2018.00059

Alternatively, algae-based treatment may be more appropriately targeted at rural areas or locations with existing pond infrastructure, where land constraints are less severe.

From an environmental perspective, land occupation may be considered within impact categories such as “land use change” or biodiversity impact, although these factors rarely dominate the numerical results. Nonetheless, qualitatively, land footprint remains a critical constraint and is identified as a key area requiring technological improvement (for example, more efficient photobioreactors or higher-rate ponds could reduce the land required). Best practices for integrating algae into primary treatment, therefore, include careful site selection and, where appropriate, phased implementation – starting with partial flows or pilot ponds – to manage land requirements effectively.

1.5.3. Algae-Based Tertiary Treatment for Nutrient Recovery

From an environmental perspective, integrating algae as a tertiary treatment step in wastewater processing introduces additional processes beyond the baseline plant, resulting in increased resource inputs and environmental impacts. The primary advantage lies in reducing nutrient emissions, thus lowering eutrophication potential, and in the potential environmental credits associated with utilising algal biomass. However, the literature presents mixed findings for this approach, largely driven by the substantial energy demands of algae-based systems. A key finding is that tertiary algae systems can result in significantly higher greenhouse gas emissions and energy use than doing nothing, particularly if operated sub-optimally ([61]). This is mainly due to algae cultivation consuming around 550 kWh per cubic metre of water treated in the pond (including mixing, pumping, and harvesting) – an extremely energy-intensive process that can outweigh the benefits of nutrient recovery. Other studies similarly report global warming potentials in the range of 1.1-2.1 kg CO_2-eq/m³ for microalgae-based nutrient recovery, which is substantially higher than that of conventional treatment methods. These results serve as a caution: if algae-based tertiary treatment depends on grid electricity and is not offset by some form of energy recovery or environmental credit, it can increase the carbon footprint of wastewater treatment.

However, the case for algae-based tertiary treatment for nutrient recovery is not universally negative. There are ways in which these systems can be optimised to deliver net environmental benefits. The associated impacts can be significantly reduced if the power required to operate the algal reactors is supplied by on-site renewable sources (e.g., solar panels or biogas CHP from sludge) or by utilising

([61]) Gowd et al. (2023). Life cycle assessment of comparing different nutrient recovery systems from municipal wastewater: A path towards self-reliance and sustainability. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2023.137331

waste heat and CO_2 from the plant. Some pilot systems, for instance, use flue gas CO_2 from biogas engines to sparge the algae, simultaneously promoting algal growth and capturing CO_2 that would otherwise be released ([62]).

Additionally, if the algal biomass is used as a slow-release fertiliser, it can substitute for synthetic alternatives such as urea or diammonium phosphate. The conventional production of these fertilisers is highly energy-intensive and polluting. By displacing a portion of them, the algae-based system can earn an environmental credit. One analysis showed that nutrient recovery through algae reduced the overall carbon footprint by 56–98% due to the offset in fertiliser production ([63]). Another study concluded that a 5% reduction in chemical fertiliser use, enabled by algal biostimulants, led to improvements in 14 out of 16 environmental impact categories when compared to the baseline system ([64]). This highlights the importance of biomass end-use: in tertiary algae-based treatment, if the algae are discarded or used inefficiently, the system appears environmentally burdensome; however, if they effectively displace high-impact products, the environmental profile can improve – sometimes dramatically.

Finally, from an environmental protection standpoint, algae-based tertiary treatment for nutrient recovery can ensure compliance with very stringent effluent nutrient standards set out in EU Directives and Regulations such as the Urban Wastewater Treatment Directive, the Water Framework Directive, and the Water Reuse Regulation. The revised Urban Wastewater Treatment Directive requires higher removal percentages than before, meaning that current plants will need to adapt their system to meet these new targets (e.g. P removal increased from 75–87.5% to 87.5-90%). Algal polishing can support the achievement of nutrient reduction targets in cases where conventional processes alone fall short. By preventing downstream eutrophication, algae-based tertiary treatment offers an ecological benefit that may not be fully captured by generic environmental assessment midpoints but is highly relevant to water quality objectives. In models that include eutrophication potential as an impact category, algae-based tertiary treatment is expected to reduce the impact of effluent discharge. However, energy use remains a critical factor: if the algal process is overly energy-intensive, the resulting indirect emissions may outweigh the direct benefits of nutrient removal.

([62]) Pechsiri et al. (2023). Comparative life cycle assessment of conventional and novel microalgae production systems and environmental impact mitigation in urban-industrial symbiosis. *Science of The Total Environment*. http://dx.doi.org/10.1016/j.scitotenv.2022.158445
([63]) Gowd et al. (2023). Life cycle assessment of comparing different nutrient recovery systems from municipal wastewater: A path towards self-reliance and sustainability. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2023.137331
([64]) Crippa et al. (2024). Life Cycle Assessment of Microalgal Biomass Valorization from a Wastewater Treatment Process. *Waste and Biomass Valorization*. https://doi.org/10.1007/s12649-024-02695-x

1.6. Beyond wastewater treatment: integrating industrial side-streams with algae

Besides the highlighted streams, several other side streams from various industries can also be utilised for algae cultivation. This can be done either as a treatment step prior to discharge, as in the examples above, or to capitalise on the concept of industrial symbiosis – where a low-value stream from one industry is used by an algae producer as an input to enhance sustainability and/or reduce production costs.

1.6.1. Existing initiatives

Within European projects, the following have investigated or are currently investigating the use of side streams for more sustainable algae cultivation (and still have active websites for consultation). Although the ongoing projects do not yet have public deliverables available, these are expected to be published in the coming months and years, providing relevant information on the topic:

- LOCALITY: side-stream from laundries, besides aquaculture and hydroponics effluent;
- AlgaeBrew: brewery waste streams;
- NENUPHAR: dairy wastewater;
- RedWine: CO_2 and winery wastewater; results available; and
- Life ALGAECAN: fruit and vegetable processing wastewater; results available.

Besides European projects, the use of side-streams for algae cultivation is already implemented by a couple of companies in Europe:

- MiAlgae, Scotland: by-products of whisky distillation; and
- Swedish Algae Factory, Sweden: food industry waste.

1.6.2. Challenges and recommendations when using side/waste streams for algae cultivation

Challenges

- Variability in composition: As already mentioned, variability in the composition of residual streams poses a challenge when using such inputs as a nutrient source for algae cultivation. Therefore, using residues from

industrial processes that must maintain a consistent product quality is a more promising approach when the goal is to produce high-quality algal biomass. In this regard, food-grade industries such as whisky, wine, and fruit and vegetable processing facilities can be an interesting source of nutrients for industrial algae production. However, these inputs may be more suitable for producing food-grade algae rather than fertilising products, which is the focus of this document.

- Missing nutrients: To improve productivity and consistency, the addition of missing elements may be considered – and in some cases, it may even be necessary – to enable algal growth in the effluents concerned.
- Legal constraints: The use of effluents for algae cultivation may result in legal constraints when creating a marketable product. For the specific use of algae biomass as fertilising products, a legal analysis was conducted and is presented in Chapter 3.

Recommendations

- Starting an algae system can result in significant investment costs and requires specialised labour. Therefore, it is recommended to seek assistance from consultants who can guide this process. Several companies already exist with this purpose, such as LGEM (the Netherlands), Varicon Aqua (UK), ProAlgaeTech (Germany), NoirGroups (Estonia), NXO Engineering (France), and Zeni (France).
- From a policy and governmental perspective, Member States should consider offering tax incentives and/or allocating funding to support the establishment of industrial synergies, thereby promoting increased sustainability and the expansion of the European algae industry.

2. Beyond land: macroalgae production to clean natural waters

Macroalgae offer a range of sustainability benefits, including rapid growth, removal of excess nutrients from the environment, and minimal environmental impact during cultivation – all without requiring arable land or freshwater. Macroalgae production yields are 2–20 times higher than terrestrial biomass ([65]) and the global macroalgae market exceeded USD 17 billion in 2023 ([66]) according to the *Commercial Seaweed Market* report by Fortune Business Insights. Despite this growth, reliance on wild stock harvesting in Europe has raised concerns regarding habitat degradation, limited biomass yields, and declining availability ([67]).

Cultivating macroalgae provides a sustainable alternative to traditional nutrient removal methods, such as wastewater treatment and dredging, offering an affordable and scalable solution to address eutrophication in coastal areas. Recognising this potential, the European Green Deal has indirectly prioritised macroalgae cultivation that supports the blue bioeconomy, contributes to climate neutrality, and aligns with goals on circular economy, biodiversity, and zero pollution This approach is further supported by the EU Algae Initiative, aiming to promote sustainable growth while minimising environmental impact.

The following sections analyse nutrient levels across all EU maritime regions and investigate the potential for macroalgae cultivation in the Baltic Sea, emphasising excess nutrient removal and its role in mitigating eutrophication. Additionally, the text highlights several EU projects exploring the industrial applications of macroalgae, including biostimulants, food, feed, and biorefining.

2.1. Assessment of the environmental conditions of the EU coastal marine areas and sea basins

The assessment of environmental conditions – particularly eutrophication levels – in marine ecosystems is largely linked to the evaluation of N and P availability. Table 6 presents the concentrations of these nutrients across various EU maritime regions, highlighting both regional averages and specific sub-basins within each region that exhibit elevated concentrations relative to their respective regional averages. However, comparing nutrient availability across all EU maritime regions is challenging due to methodological inconsistencies.

([65]) Bruhn et al. (2011). Bioenergy potential of Ulva lactuca: Biomass yield, methane production and combustion. *Bioresource Technology*. https://doi.org/10.1016/j.biortech.2010.10.010
([66]) Commercial Seaweed Market Size, Share & Industry Analysis. Available here.
([67]) Recommendations for Monitoring of Sustainable Wild Harvesting of Macroalgae. Available here.

Some maritime regions, such as the Baltic Sea, the North Sea, the coastal waters of the Netherlands and Portugal, and the Western Mediterranean Basin, benefit from comprehensive data coverage and a robust research foundation. For example, HELCOM has been instrumental in establishing systematic monitoring of the Baltic Sea, enhancing methodologies to better understand the impact of anthropogenic pressures on eutrophication. Likewise, under the OSPAR framework, the North Sea marine habitats are assessed, offering valuable insights into their ecological significance and current status ([68]).

The Black Sea has also been the focus of extensive study, particularly concerning eutrophication driven by nutrient inputs from major rivers such as the Danube. Coastal zones are known to experience more pronounced eutrophic effects compared to offshore waters. However, inconsistencies in data and difficulties with cross-border coordination continue to pose significant challenges. Similarly, although substantial research has been carried out on nutrient cycles in parts of the Mediterranean Sea ([69]), many areas – especially in the eastern basin – still lack detailed information on nutrient inputs.

To provide a consistent basis for comparing annual nitrogen and phosphorus inputs, the most comprehensive available report on long-term nutrient loads covering all EU maritime regions was used ([70]). The data in Table 6 represent average nutrient loads from 2000 to 2005 and indicate the highest nutrient load trends in the North-East Atlantic, North Sea, and Mediterranean Sea. However, when these results are analysed alongside mean nutrient concentrations reported by HELCOM, OSPAR, EMODnet, and other relevant sources ([71]), it becomes evident that the offshore areas of the North-East Atlantic and the North Sea do not exhibit excessive nutrient accumulation (N < 10 µmol; P < 0.5 µmol).

The coastal regions of the North-East Atlantic Ocean, North Sea, and Black Sea experience localised eutrophic conditions, primarily near river outflows and densely populated areas. For example, the northwestern Black Sea, the Azov Sea, and the lower reaches of the Danube, Dnipro, and Don Rivers are among the most affected areas, reaching or approaching maximum eutrophication levels ([72]).

([68]) Zerbe (2023). Marine Habitats in the North Sea and Baltic Sea. In *Restoration of Ecosystems – Bridging Nature and Humans*. https://doi.org/10.1007/978-3-662-65658-7_13
([69]) Powley et al. (2018). Phosphorus and nitrogen trajectories in the Mediterranean Sea (1950–2030): Diagnosing basin-wide anthropogenic nutrient enrichment. *Progress in Oceanography.* https://doi.org/10.1016/j.pocean.2018.03.003
([70]) JRC (2011). Long term nutrient loads entering European seas. Available here.
([71]) Belgacem (2021). Climatological distribution of dissolved inorganic nutrients in the western Mediterranean Sea (1981–2017). *Earth System Science Data*. https://doi.org/10.5194/essd-13-5915-2021
([72]) Lazar et al. (2024). Black Sea Eutrophication Comparative Analysis of Intensity between Coastal and Offshore Waters. *Sustainability.* https://doi.org/10.3390/su16125146

Table 6 – Metrics for nutrient levels of the EU maritime regions

Maritime region	Averages and sub-basins with elevated nutrient concentrations	Dissolved inorganic nitrogen, µmol/L	Dissolved inorganic phosphorous, µmol/L	Annual N load (k tonnes)	Annual P load (k tonnes)
Baltic Sea	Baltic Sea average	5.8	0.6	630	24
	Gdansk Basin	6.6	0.7		
	Gulf of Riga	10.7	1.4		
	Gulf of Finland	7.0	1.1		
	Bothnian Bay	6.1	0.09		
North Sea	Offshore average	0.5–8	0.2–0.5	1000	44
	Southern North Sea	15–60	0.6–1.2		
	Kattegat and Sound	0.5–7	0.1–0.7		
	Skagerrak	0.5–10	0.1–0.5		
North-East Atlantic	Costal average	10-30	>0.5	1220	55
	Offshore average	5-10	< 0.05		
	Loire river delta	10-70	0.8-2		
	Galician estuaries	8–24	0.5–2		
	Tagus estuary	>50	>3		
Mediterranean Sea	Mediterranean Sea average	3.6*	<0.2*	940	73
	Alboran Sea, Balearic Sea, Gulf of Lion, Liguro-Provencal Basin	< 4*	0.2–0.3*		
Black Sea	Black Sea average	0.5-5	0.1-2.0	550	35
	Danube delta	5.5-12	0.1-1		

* Reported in µmol/kg

Sources: HELCOM, OSPAR Intermediate Assessment, EMODnet map viewer, and Belgacem et al., 2021.

In contrast, while the semi-enclosed Baltic Sea does not receive nutrient loads of the same magnitude as some other EU maritime regions, its limited water exchange exacerbates nutrient retention ([73]). Over the past decades, significant efforts have been made to reduce nutrient inputs, yet reports indicate that 98% of Baltic Sea waters still exhibit elevated or eutrophic concentrations of N. In contrast, the Mediterranean Sea – despite receiving some of the highest nutrient loads – is generally classified as nutrient-poor (oligotrophic), due to its large size, high water exchange rates, and efficient nutrient recycling. However, certain areas, such as the Alboran Sea, Balearic Sea, Gulf of Lion, and Liguro-Provençal Basin, show moderately elevated nitrogen levels.

([73]) State of the Baltic Sea 2023. Available here.

The distribution of P across EU maritime regions has similar patterns to N, with higher concentrations in coastal areas influenced by riverine inputs and human activities. Despite considerable efforts to reduce nutrient loads, the Baltic Sea continues to exhibit elevated phosphorus levels, particularly in enclosed sub-basins with long water residence times. In the North Sea and the Northeast Atlantic, offshore waters maintain relatively low phosphorus concentrations, while coastal areas – especially those near major estuaries – demonstrate enrichment. The Mediterranean Sea has overall low phosphorus concentrations, although specific regions, such as the Gulf of Lion and Liguro-Provençal Basin, exhibit moderately higher levels. The Black Sea shows varying phosphorus concentrations, with higher levels near river outflows and in semi-enclosed areas where nutrient retention is more pronounced ([74];[75]).

Estimating the minimum areas within each EU maritime region where macroalgae farming would not compete for nutrients with local biota is challenging, due to the complexity of standardising aquatic systems of such diversity and scale. However, based on the available data, overall nutrient availability for macroalgae farms in the Black Sea and Mediterranean Sea is more limited. Therefore, the potential establishment of farms is not analysed for these marine areas. In contrast, the Baltic Sea and North Sea are generally considered eutrophic and can thus provide suitable nutrient conditions across the entire basin for further analysis.

2.2. Macroalgae farm nutrient assimilation potential in the Baltic Sea and North Sea

The production of macroalgae is promising due to their ability to absorb nutrients from the environment during the growth phase. When cultivated in eutrophic systems, the harvested macroalgae remove excess nutrients, helping to mitigate their negative effects ([76]). However, macroalgae aquaculture remains an emerging sector in Europe, requiring further technological advancements and the development of methodological expertise ([77]). The following section explores macroalgae aquaculture technologies, floating and anchored (or bottom-fixed), and their role in reducing nutrients in eutrophicated waters.

([74]) Teodoru et al. (2007). Spatial distribution and recent changes in carbon, nitrogen and phosphorus accumulation in sediments of the Black Sea. *Marine Chemistry.* https://doi.org/10.1016/j.marchem.2006.12.013
([75]) Strokal and Kroeze (2012). Nitrogen and phosphorus inputs to the Black Sea in 1970–2050. *Regional Environmental Change*. https://doi.org/10.1007/s10113-012-0328-z
([76]) Kotta et al. (2022). Assessing the potential for sea-based macroalgae cultivation and its application for nutrient removal in the Baltic Sea. *Science of The Total Environment*. https://doi.org/10.1016/j.scitotenv.2022.156230
([77]) Campbell et al. (2019). The Environmental Risks Associated With the Development of Seaweed Farming in Europe - Prioritizing Key Knowledge Gaps. *Frontiers in Marine Science.* https://doi.org/10.3389/fmars.2019.00107

The floating cultivation method involves growing macroalgae on or near the water surface using structures such as rope lines, grids, rafts, and buoys for support. In contrast, the anchored cultivation method attaches seaweed to a substrate that is fixed with poles on the seabed ([78]). This method is commonly used in shallow intertidal areas ([79]) and is particularly suitable for tropical regions where the seabed is accessible and has appropriate topography ([80]). Additionally, anchored seaweed cultivation structures may require natural or artificial barriers for protection against strong wave action.

Floating seaweed cultivation systems are highly adaptable but also have limitations – most notably, the need for design features capable of withstanding wind and wave action. Nonetheless, these systems are generally more suitable for large-scale operations in the deeper waters of temperate maritime regions ([81]).

Regarding nutrient reduction, neither method is inherently more advantageous than the other; rather, their productivity depends on site characteristics, meteorological conditions, the scale of the operation, and the macroalgae species best suited for cultivation in the specific region.

The conditions in the Baltic Sea support the growth of three popular species for seaweed farming: *Saccharina latissima* (sugar kelp), *Ulva intestinalis*, and *Fucus vesiculosus*. According to the Interreg GRASS report, *F. vesiculosus* is the most efficient species in terms of nutrient removal, showing the highest margins of nutrient accumulation (Table 7).

However, it is important to note that each species has its optimal salinity conditions. Localised conditions in the Baltic Sea create specific niches for these species. While the fast-growing *U. intestinalis* thrives in the lower salinity areas of the central and northern Baltic sub-basins, *S. latissim*a is more suited to the higher salinity regions, such as the southern Baltic and near the Danish Straits. On the other hand, *F. vesiculosus* is well-adapted to intermediate salinity zones, playing a crucial role in balancing the nutrient demands in the ecosystem.

To identify the non-competition area in the Baltic Sea, certain assumptions must be extrapolated from broader EU marine assessments. A recent study assessing the potential for seaweed cultivation in EU waters through an integrated modelling approach suggests that the total suitable area could exceed 1 million km². It proposes a precautionary scenario in which only 1% of this area is utilised, maintaining a minimal cultivation footprint while still allowing for substantial

([78]) Corrigan et al. (2022). Quantifying habitat provisioning at macroalgal cultivation sites. *Reviews in Aquaculture.* https://doi.org/10.1111/raq.12669
([79]) Bjerregaard et al. (2016). Seaweed aquaculture for food security, income generation and environmental health in Tropical Developing Countries (English). Available here.
([80]) Pereira and Yarish (2008). Mass Production of Marine Macroalgae. *Encyclopedia of Ecology*. https://doi.org/10.1016/B978-008045405-4.00066-5
([81]) See footnote 80.

production potential ([82]). Applying this precautionary estimate does not conflict with the Recommendation on Coastal and Marine Baltic Sea Protection ([83]), which mandates that at least 12% of the Baltic Sea be designated as Marine Protected Areas (MPAs), with updated targets aiming for 30% protection by 2030 ([84]). While the reference study applies the 1% cultivation threshold only to the total suitable area, applying this same threshold to the entire Baltic Sea area in the context of non-competition areas would correspond to roughly 3,770 km² potentially available for macroalgae cultivation.

Table 7 – Environmental metrics of selected macroalgae species

Macroalgae species	Nutrient removed by harvesting of 1 tonne fresh macroalgae ([85])		Estimated non-competitive area (km²), Baltic Sea	Estimated non-competitive area (km²), North Sea
Saccharina latissimi	1.3 – 3.3 kg N	0.5 kg P	3 770	4 730
Ulva intestinalis	1.8 – 5.1 kg N	0.2 – 0.7 kg P		
Fucus vesiculosus	2.25 – 7.9 kg N	1.0 – 1.9 kg P		

To establish a comparable estimate for the non-competition area in the North Sea, a similar methodological approach can be applied. The total Exclusive Economic Zone (EEZ) area in the North Sea is approximately 473,000 km² ([86]). Applying this 1% estimate to the North Sea, within the context of the non-competitive area, results in an available area of approximately 4,730 km² for macroalgae cultivation. While the exact extent of current usage is unknown, part of this area is already utilised for multi-use initiatives within offshore wind farms. The UNITED Project demonstrated the feasibility of seaweed farming alongside wind energy in Belgium, Denmark, Germany, and the Netherlands, while the OLAMUR Project is assessing similar approaches in the Danish Baltic Sea and the German North Sea. Additionally, North Sea Farm 1 is establishing a commercial-scale seaweed farm within a Dutch wind park, refining cultivation methods, and exploring carbon sequestration potential.

Beyond nutrient uptake, macroalgae play a significant role in heavy metal bioaccumulation, serving as effective biomonitors of environmental pollution ([87]). Hence, the cultivation and utilisation of macroalgae must be approached with caution. While they contribute to the removal of nutrients and heavy metals, improper management can lead to the release of accumulated pollutants and

([82]) Macias et al. (2025). Assessing the potential for seaweed cultivation in EU seas through an integrated modelling approach. *Aquaculture.* https://doi.org/10.1016/j.aquaculture.2024.741353
([83]) New recommendation adopted on Baltic Sea protected areas. Available here.
([84]) State of the Baltic Sea 2023. Available here.
([85]) Guide to macroalgae cultivation and use in the Baltic Sea Region. Available here.
([86]) https://ec.europa.eu/maritimeaffairs
([87]) Dehbi et al. (2023). Analysis of Heavy Metal Contamination in Macroalgae from Surface Waters in Djelfa, Algeria. *Water.* https://doi.org/10.3390/w15050974

microbial contamination. A recent study ([88]) found that macroalgal wrack near river outflows in the Baltic Sea can harbour faecal bacteria, including *E. coli*, highlighting the risk of microbial contamination. Therefore, comprehensive research and monitoring are essential to ensure the sustainable use of macroalgae for environmental remediation.

2.3. Quantifying the impact of macroalgae cultivation on eutrophication: A scenario-based analysis in the Baltic Sea

As discussed previously, the scale of macroalgae cultivation must be considered a key driver of environmental change, with larger operations potentially causing significant ecological consequences. To better understand the upper limits of macroalgae cultivation in the Baltic Sea and its potential role in nutrient removal, this section presents a large-scale scenario analysis. By evaluating the impact of substantial cultivation areas, the benefits and constraints of large-scale operations can be identified. However, it must be acknowledged that, in practice, environmental and spatial limitations would restrict the full implementation of these scenarios.

The analysis considers three levels of macroalgae farm coverage: 0.1% (377 km²), 0.5% (1,885 km²), and 1% (3,770 km²) of the Baltic Sea. Given the region's environmental conditions, floating farm systems, particularly the line cultivation method ([89]), are considered the most suitable. The low tidal activity in the Baltic Sea limits the effectiveness of fixed farm systems that rely on tidal movement.

Two of the three species selected in the previous section are included in this analysis, as the cultivation of *S. latissima* is restricted by decreasing salinity east of Kiel Bight, which limits its potential expansion ([90]). To quantify the nutrient removal potential of macroalgae farming at the selected scales, the publicly available Operational Decision Support System (ODSS), developed by the University of Tartu, was used. This tool illustrates the nutrient removal capacity for *U. intestinalis* (Figure 2) and *F. vesiculosus* (Figure 3) in units of kg per 5 ha. However, for subsequent calculations of removed N and P in Table 8, these rates are adjusted to kg per km².

([88]) Kalvaitienė et al. (2024). Diverse sources of fecal contamination in macroalgae wrack-affected environment adjacent to river outflow along the Baltic Sea coast. *Environmental Pollution*. https://doi.org/10.1016/j.envpol.2024.124429
([89]) Macroalgae Production Manual. Available here.
([90]) See footnote 89.

Table 8 – Quantitative ODSS estimates of macroalgae growth and nutrient removal

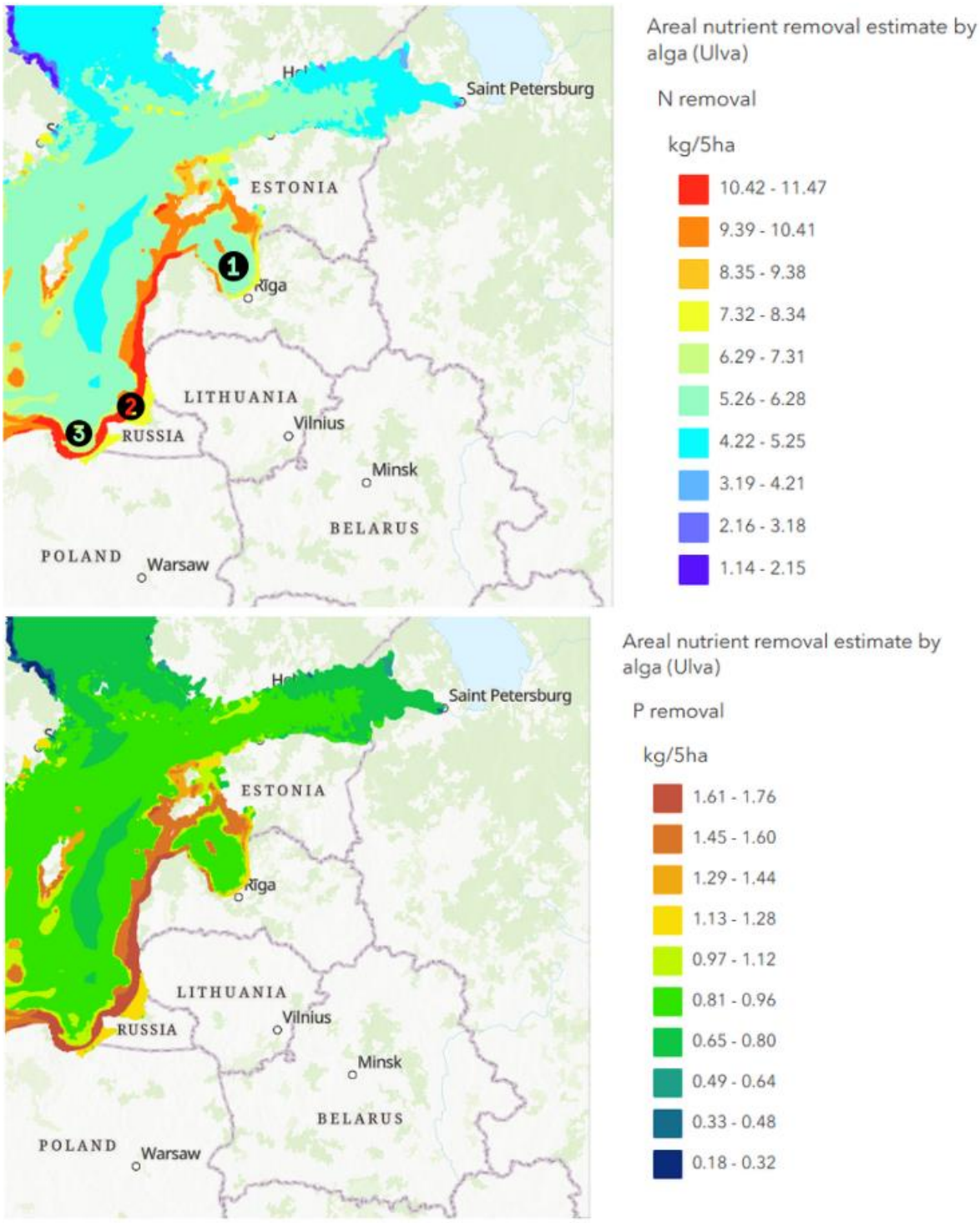
Eutrophic areas of the Baltic Sea	Growth rate and nutrient removal	Average rate	Yield for 1% of the Baltic Sea, t	Yield for 0,5% of the Baltic Sea, t	Yield for 0,1% of the Baltic Sea, t
Gulf of Riga	N removal by *Fucus* (kg/km^2)	100	377	189	38
	P removal by *Fucus* (kg/km^2)	20	74	37	7.4
	N removal by *Ulva* (kg/km^2)	120	452	226	45
	P removal by *Ulva* (kg/km^2)	20	75	38	7.5
Curonian Lagoon	N removal by *Fucus* (kg/km^2)	90	-	170	34
	P removal by *Fucus* (kg/km^2)	12	-	22	4.4
	N removal by *Ulva* (kg/km^2)	150	-	283	57
	P removal by *Ulva* (kg/km^2)	24	-	45	9.0
Gulf of Gdansk	N removal by *Fucus* (kg/km^2)	390	1470	735	147
	P removal by *Fucus* (kg/km^2)	80	302	151	30
	N removal by *Ulva* (kg/km^2)	150	566	283	57
	P removal by *Ulva* (kg/km^2)	23	87	44	8.7

These macroalgae farms were virtually deployed in the most eutrophic areas of the Baltic Sea – the Gulf of Riga, Curonian Lagoon, and Gulf of Gdańsk (Figure 2), where nutrient concentrations are high due to river outflows and limited water exchange. Due to the limited area of the Curonian Lagoon, the 1% scenario was not considered in this case.

The removal of N and P varies across different sub-basins of the Baltic Sea. The scenario results extracted from the ODSS model and presented in Table 8 indicate that even the smallest coverage scenario of 0.1% of the Baltic Sea could achieve substantial nutrient removal. In the Gulf of Riga, the modelled estimates suggest that *Fucus vesiculosus* could remove over 370 tonnes of nitrogen and 70 tonnes of phosphorus if cultivated across 1% of the Baltic Sea area. *Ulva intestinalis* also demonstrated strong potential in the Gulf of Riga, with estimated removals of approximately 450 tonnes of nitrogen and 75 tonnes of phosphorus

under the same scenario. Similar patterns were observed in the Curonian Lagoon and Gulf of Gdańsk. *Fucus vesiculosus* was predicted to contribute more to nitrogen removal in higher-salinity areas such as the Gulf of Gdańsk, while *Ulva intestinalis* showed greater efficiency in the lower-salinity environments of the Gulf of Riga and Curonian Lagoon. These modelled estimates suggest that scaling up macroalgae cultivation could support eutrophication mitigation efforts in the Baltic Sea. However, further empirical research is necessary to validate these projections under real-world conditions.

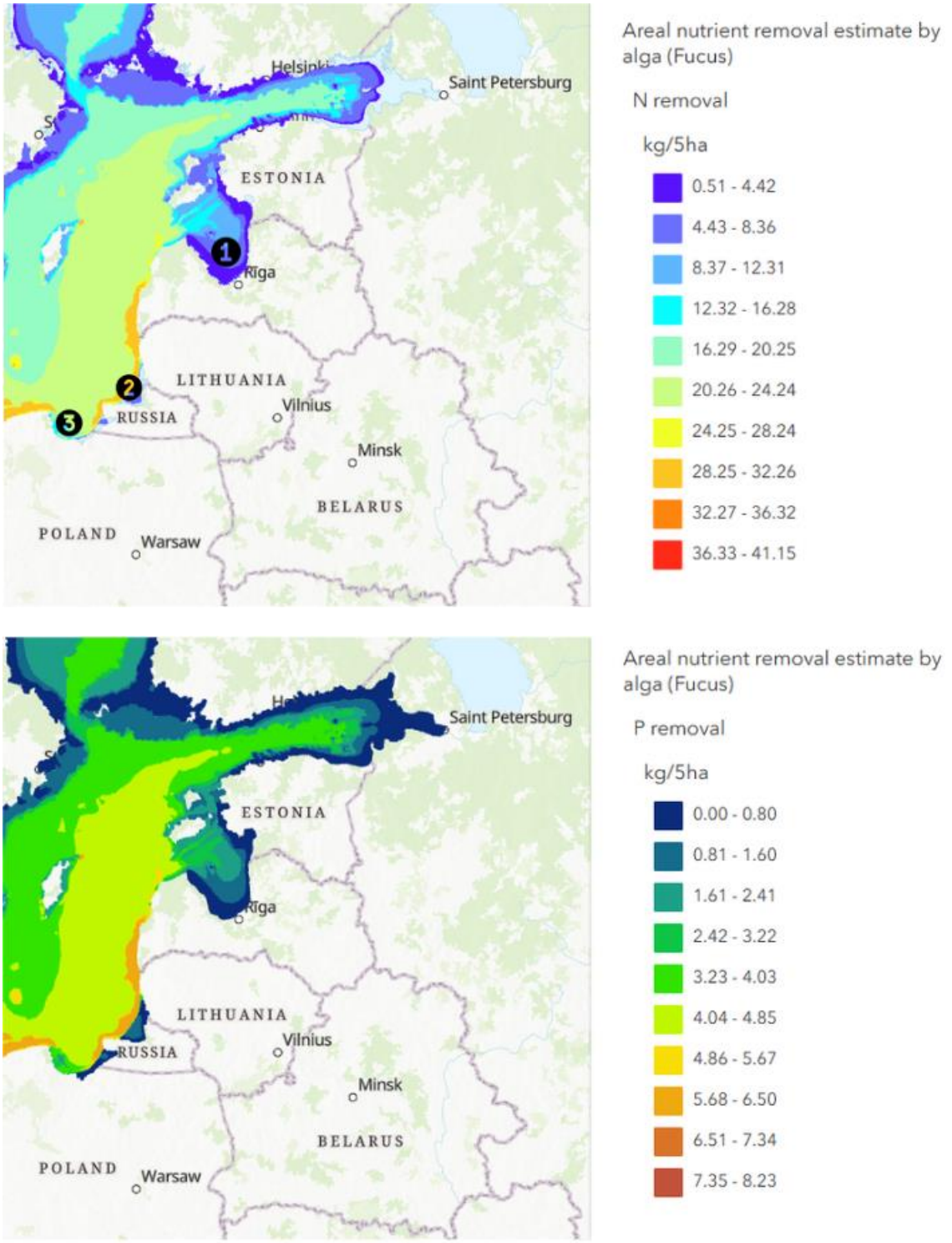
Figure 2 – Nutrient removal rate by *U. intestinalis* in the Baltic Sea



Source: https://gis.sea.ee/odss

1 – Gulf of Riga, 2 – Curonian Lagoon, 3 – Gulf of Gdańsk

Figure 3 – Nutrient removal rate map of *F. vesiculosus* in the Baltic Sea



Source: https://gis.sea.ee/odss

1 – Gulf of Riga, 2 – Curonian Lagoon, 3 – Gulf of Gdańsk.

2.4. Current practices for macroalgae aquaculture in the Baltic Sea

Over the past two decades, European macroalgae production has fluctuated between 0.23 Mt and 0.38 Mt, accounting for less than 1.5% of global supply. The dominant production method remains wild harvesting, with Norway, France, and Ireland leading biomass output in Europe ([91]). In the Baltic Sea region, seaweed aquaculture research and development are primarily driven by Denmark, Estonia, Finland, Germany, and Sweden ([92]). Notably, Estonia is the leading country in licensing the commercial harvesting of red macroalgae, permitting collection of up to 2,000 tonnes annually from wild stocks, thereby significantly contributing to regional biomass supply ([93]). Denmark is the leader in seaweed farming, with seven registered cultivation plants ([94]), including one land-based facility ([95]).

The highest reported specific production comes from experimental multi-trophic aquaculture systems – farms that co-cultivate different species to optimise resource use – reaching yields of up to 7 tonnes of wet weight per hectare in the region ([96]). However, this figure represents an exceptional case, as such yields are substantially higher than those typically achieved in standard commercial kelp farming.

Notable efforts include the establishment of a multi-trophic aquaculture pilot located in the North Sea, 80 km off Sylt, operated by the R&D Centre at Kiel University of Applied Sciences ([97]). In Finland, a biorefining company, Origin by Ocean, is advancing research into *Fucus vesiculosus* aquaculture while also using beach-cast biomass to develop high-value products. In Estonia, macroalgae farming initiatives focus on both attached and detached forms of *Furcellaria lumbricalis*, exploring their potential for nutrient removal and biorefining in the cold waters of the Baltic Sea ([98]).

To date, the most commercially cultivated species in the Baltic Sea remains *Saccharina latissima*, with the highest yields reported near Horsens Fjord, Denmark. There, a 1 km² farm, initially launched as a pilot project, has scaled up to achieve annual production of up to 10 tonnes ([99]). In areas where low salinity permits *S. latissima* cultivation, fast-growing green macroalgae such as *Ulva*

([91]) FAO (2018). The state of world fisheries and aquaculture 2018. Available here.
([92]) Weinberger et al. (2019). Seaweed resources of the Baltic Sea, Kattegat and German and Danish North Sea costas. *Botanica Marina*. https://doi.org/10.1515/bot-2019-0019
([93]) Guide to macroalgae cultivation and use in the Baltic Sea Region. Available here.
([94]) Thomsen et al. (2016). The circular economy of seaweed as nutrient management instrument for biobased production. Available here.
([95]) EMODnet Map viewer. Available here.
([96]) Søndergaard Schmedes et al. (2016). Nutrient compensation as management tool– Sugar kelp production in sustainable aquaculture. Available here.
([97]) UltFarms (2024). FINO 3 pilot update – March 2024. Available here.
([98]) Macroalgae Production Manual. Available here.
([99]) See footnote 92.

intestinalis, known for high nutrient uptake rates, are feasible for nutrient removal. However, in nutrient-limited coastal ecosystems, these species are less resilient than slower-growing *F. vesiculosus*, which can store nutrients over time. Moreover, despite their high uptake capacity, green macroalgae typically have lower market value compared to other commercially farmed species. Other species considered suitable for aquaculture in European maritime regions include *Undaria pinnatifida* ([100]), and red macroalgae such as *Furcellaria lumbricalis* and *Ceramium tenuicorne* ([101]).

Recommendations for advancing macroalgae aquacultures in the Baltic Sea

- **Improving cultivation methods and infrastructure**. One of the first steps requires the development of site-specific guidelines that optimise farm location selection by considering salinity gradients, nutrient availability, and hydrodynamic conditions. Additionally, encouraging multi-use initiatives by integrating macroalgae farming with existing offshore wind energy projects, similar to the UNITED and OLAMUR projects, could enhance both economic and environmental benefits. Approximately 462 km² of offshore wind farm area in the North Sea ([102]) and over 2000 km² in the Baltic Sea, based on 20 newly identified areas still in the planning phase ([103]), could potentially be available for multi-use purposes, such as macroalgae aquacultures.
- **Enhancing monitoring and data collection**. This step involves establishing a standardised monitoring framework for assessing nutrient assimilation efficiency and the long-term ecosystem impacts of macroalgae farms. Strengthening cross-border collaboration in nutrient flow modelling, particularly within HELCOM and OSPAR frameworks, would refine estimates of macroalgae-driven nutrient removal. Moreover, improving remote sensing and GIS tools for real-time tracking of farm performance and eutrophication levels in priority areas will contribute to effective resource management.
- **Expanding market opportunities and product diversification**. This step can be achieved by strengthening regional value chains and promoting Baltic Sea macroalgae-derived products. Additionally, industry-academia partnerships can facilitate scaling up pilot projects and attract investment into sustainable macroalgae aquacultures.

([100]) Campbell et al. (2019). The Environmental Risks Associated With the Development of Seaweed Farming in Europe - Prioritizing Key Knowledge Gaps. *Frontiers in Marine Science.* https://doi.org/10.3389/fmars.2019.00107
([101]) Guide to macroalgae cultivation and use in the Baltic Sea Region. Available here.
([102]) Hornsea 2, the world's largest windfarm, enters full operation. Available here.
([103]) New potential of the Baltic Sea: 33 GW of capacity and 20 new offshore wind farm areas. Available here.

- **Regulatory and policy barriers can be reduced by facilitating access to marine space and licensing for macroalgae farms**. Aligning farming strategies with EU policies, like the European Green Deal, the EU Algae Initiative, and the Circular Economy Action Plan, can help secure funding and support.

2.5. Available technologies for the collection and processing of macroalgae into products

Macroalgae collection and processing methods vary according to species-specific characteristics, but best practices generally prioritise environmental sustainability. Passive harvesting in coastal accumulation zones and mechanical removal using specialised vessels are commonly employed to minimise environmental impact ([104]). However, overharvesting wild macroalgae can lead to unintended ecological consequences. Research indicates that excessive harvesting may reduce seaweed density, alter population structures, and increase the prevalence of undesirable species, potentially affecting the quality of biomass available for cultivation ([105]).

Offshore collection often involves mechanical harvesting using agricultural equipment such as front loaders, providing a cost-effective solution for large-scale biomass retrieval ([106]). Additionally, roll press technology is utilised to reduce the weight of harvested biomass, thereby improving transportation and storage efficiency.

Once harvested, the macroalgae biomass is typically processed prior to commercialisation. In recent years, technological advancements in processing methods, particularly biorefinery approaches, have enabled the extraction of high-value compounds such as proteins, polysaccharides, and bioactive metabolites for applications in food, pharmaceuticals, and biostimulants ([107]). The residual biomass can then be converted into biofuels or bioenergy, further enhancing the economic viability of macroalgae ([108]). Processing technologies such as hydrothermal treatment, enzymatic hydrolysis, and fermentation are central to the production of biofuels, bioplastics, and biostimulants. Meanwhile,

([104]) Paoli et al. (2023). Off-Shore and On-Shore Macroalgae Cultivation and Wild Harvesting: an LCA-Based Evaluation from Baltic Sea Region Case Studies. *Environmental and Climate Technologies*. https://doi.org/10.2478/rtuect-2023-0045
([105]) Mac Monagail et al. (2017). Sustainable harvesting of wild seaweed resources. *European Journal of Phycology.* https://doi.org/10.1080/09670262.2017.1365273
([106]) Wilding, C., Tillin, H., Corrigan, S.E. et al. (2021). Seaweed aquaculture and mechanical harvesting: an evidence review to support sustainable management (NECR378). Available here.
([107]) Farghali et al. (2023). Seaweed for climate mitigation, wastewater treatment, bioenergy, bioplastic, biochar, food, pharmaceuticals, and cosmetics: a review. *Environmental Chemistry Letters*. https://doi.org/10.1007/s10311-022-01520-y
([108]) Gao et al. (2020). Using macroalgae as biofuel: current opportunities and challenges. *Botanica Marina.* https://doi.org/10.1515/bot-2019-0065

less expensive techniques like drying and milling remain common for fertiliser production, which has historically been the primary use of macroalgae biomass in Europe.

Recent European projects have focused on the large-scale processing of macroalgae, exploring their potential in sectors such as food, feed, biostimulants, cosmetics, and pharmaceuticals. These initiatives aim to develop sustainable and economically viable markets for macroalgal biomass while unlocking its wide range of applications.

One notable example is the KELP-EU project, led by OCEANIUM, that focused on the sustainable production of macroalgae, particularly kelp, for multiple sectors, including food, cosmetics, pharmaceuticals, and materials. Similarly, other European initiatives, such as GENIALG, focused on large-scale processing of *Ulva spp*. for applications in cosmetics, pharmaceuticals, food, and feed ingredients. Similarly, Algaia produces ingredients for various industries, including agriculture, food, cosmetics, and pharmaceuticals. The company focuses on utilising brown macroalgae to develop alginates, biostimulants, and functional extracts.

In the Baltic Sea region, several companies are advancing the sustainable utilisation of macroalgae for various industrial applications. For example, UnderYtan is developing innovative solutions for macroalgae farming and processing, particularly focused on biorefining and biostimulants for agricultural use. Danish Seaweed cultivates *Saccharina latissima* for applications in food products, biostimulants, and cosmetics, and is actively engaged in research on algae-based products for wider commercial purposes. Vetik, an Estonian-based company, specialises in *Furcellaria lumbricalis*, which is converted into products for biostimulants and cosmetics.

As illustrated, biostimulants are among the primary products currently derived from macroalgae biomass. To estimate the potential production of biostimulants from macroalgae cultivated in the Baltic Sea, some conservative assumptions are made, given that biomass and biostimulant yields vary depending on species, processing methods, cultivation techniques, and location:

- Productivity: 0.1 tonne seaweed/ha ([109]),
- Area used: 40,000 ha (0.1% of the Baltic Sea area), and
- Biostimulant yield: 270 kg biostimulant/tonne algae ([110]).

([109]) Weinberger et al. (2019). Seaweed resources of the Baltic Sea, Kattegat and German and Danish North Sea costas. *Botanica Marina*. https://doi.org/10.1515/bot-2019-0019
([110]) Arias et al. (2024). Macroalgae as a sustainable biostimulant for crop production according to techno-economic and environmental criteria. *Sustainable Production and Consumption*. https://doi.org/10.1016/j.spc.2024.05.019

Therefore, in the Baltic Sea, a minimum of 1,080 tonnes of biostimulant per year could be produced. For a comparison, the global estimated production was 817,560 tonnes in 2023 ([111]), so the Baltic Sea could supply 0.1% of the world's production of biostimulants.

([111]) Transparency Market Research (2022). Biostimulants Market. Available here.

3. Algae potential to be used as fertilising products

The EU Green Deal aims to make Europe the first climate-neutral continent by 2050. At the centre of this strategy lies the Farm to Fork strategy, which focuses on creating a sustainable and resilient food system. However, land application of nitrogen, an important nutrient for increased agricultural productivity, is a significant emitter of GHG, regardless of whether it originates from manure or the Haber-Bosch process ([112]), and therefore, its use should be modified ([113]). Using algae-derived fertilising products in agriculture can potentially aid in achieving the goals of the Farm to Fork strategy.

Microalgae may serve as a suitable nutrient source for use as a slow-release fertiliser, potentially reducing nutrient losses that contribute to eutrophication. Macroalgae also offer potential as a nutrient source to replace mineral fertilisers. Furthermore, both macro- and microalgae can be used to produce biostimulants, enhancing plant resilience to stress, such as those induced by climate change, and improving nutrient use efficiency, thereby reducing fertiliser requirements.

The use of algae extracts as biostimulants, particularly from macroalgae ([114]), is well established, with several products already on the market. On the other hand, the use of algae as a fertilising product remains considerably less developed. Furthermore, its sustainability credentials still require further validation. For illustration, Table 9 presents a non-exhaustive list of companies in Europe commercialising algae-based fertilising products, most of which focus on biostimulants.

([112]) IEA. Ammonia Technology Roadmap - Towards more sustainable nitrogen fertiliser production. Available here.
([113]) Gao and Serrenho (2023). Greenhouse gas emissions from nitrogen fertilizers could be reduced by up to one-fifth of current levels by 2050 with combined interventions. *Nature Food*. https://doi.org/10.1038/s43016-023-00698-w
([114]) The Bio4Safe project developed a database of biostimulants currently in the market that contains 64 seaweed-based extracts. Available here.

Table 9 – Non-exhaustive list of companies commercialising algae-based fertilising products in Europe

Company	Country	Type of algae fertilising product	Website
Acadian Kelp	Ireland	Soil improver from macroalgae	https://acadiankelpmeal.com/
Agrocean	France	Biostimulants from macroalgae	https://www.agrocean.com/
AlgaEnergy	USA with presence in Europe	Biostimulants from microalgae	https://ag.algaenergy.com/
Algaia	France	Biostimulants from macroalgae	https://www.algaia.com/
Allmicroalgae	Portugal	Biostimulants from microalgae	https://www.allmicroalgae.com/
Biorizon Biotech S.L.	Spain	Biostimulants from microalgae	https://www.biorizon.es/
Donegal Seaweed	Ireland	Biostimulants from macroalgae	https://www.donegalseaweed.com/
Ficosterra	Spain	Biostimulants and fertilisers from macroalgae	https://www.ficosterra.com/
Olmix	France	Biostimulants from macroalgae	https://olmix.com/
Vetik	Estonia	Biostimulants from macroalgae	https://vetik.eu/

3.1. Microalgae biomass in fertilisation practices

Over the past decade, several studies have explored the use of microalgae as a nutrient source for plant production ([115]). However, only a limited number have examined this application in depth under real-world conditions, with the majority conducted at laboratory scale. Furthermore, many studies lack sufficient detail on materials and methods, making it difficult to accurately assess the agronomic value of the algal biomass used. Lastly, very few of these studies have been carried out in Europe ([116]).

For a comprehensive review on the use of microalgae as fertilisers, we recommend the published paper *"Algaeculture for Agriculture: From Past to*

([115]) Only one study using seaweed as fertilisers was found, with negative results (https://doi.org/10.1007/s10705-017-9881-7). However, in Europe, it is reported that farmers incorporate seaweed into the soil as natural fertiliser/compost.
([116]) The Horizon Europe Walnut project is currently conducting a field trial with microalgae fertilisers and results are expected to be made public in 2026 on the project website.

Future" ([117]). Below are some illustrative examples highlighting the potential benefits and drawbacks of using microalgae as a fertiliser.

Chinese cabbage treated with microalgae-based fertilisers (a mixture of *Chlorella* sp. and *Anabaena* sp.) exhibited increased plant height, leaf number, and fresh and dry weight compared to controls treated with conventional fertilisers ([118]). However, cabbages fertilised exclusively with microalgae demonstrated lower protein and pigment content than those receiving conventional fertilisers. The most notable improvements were recorded when microalgae were combined with organic fertilisers, resulting in enhanced crop yield and nutritional quality.

Similarly, barley fertilised with *Chlorella sorokiniana* displayed productivity comparable to that achieved with inorganic fertilisers ([119]). Nevertheless, the total protein content (N content) was lower in barley treated with algae compared to inorganic nitrogen treatment, as seen in the cabbage trial. This difference is attributed to the slow mineralisation rate of algal biomass, where nitrogen is predominantly in organic form and requires mineralisation to nitrate before plant uptake can occur.

Nannochloropsis oculata biomass was classified as a slow-release fertiliser as only 31% of its total N was mineralised after 95 days of soil incubation in the absence of plants ([120]), confirming the assumption of the trials using barley ([121]). In a subsequent pot experiment with tomatoes, no significant difference was found in the number of fruits between treatments; however, the algal treatment yielded a lower total fruit weight. Despite this, the algae-treated plants produced fruits of superior quality. The study concluded that to optimise both fruit yield and quality, microalgae-based fertilisers should be combined with conventional fertilisers.

Further confirmation of the slow-release properties of microalgae fertilisers was obtained in an experiment with tomato plants. Applying *Acutodesmus dimorphus* biomass to the soil 22 days before seedling transplantation led to significant improvements in both plant growth and fruit production, as soil microbiota were able to mineralise some of the organic nitrogen, making it available to the

([117]) Ferreira et al. (2023). Algaeculture for agriculture: from past to future. *Frontiers in Agronomy.* https://doi.org/10.3389/fagro.2023.1064041
([118]) Zhang et al. (2024). Using microalgae to reduce the use of conventional fertilizers in hydroponics and soil-based cultivation. *Science of The Total Environment*. https://doi.org/10.1016/j.scitotenv.2023.169424
([119]) Suleiman et al. (2020). From toilet to agriculture: Fertilization with microalgal biomass from wastewater impacts the soil and rhizosphere active microbiomes, greenhouse gas emissions and plant growth. *Resources, Conservation and Recycling*. https://doi.org/10.1016/j.resconrec.2020.104924
([120]) Coppens et al. (2015). The use of microalgae as a high-value organic slow-release fertilizer results in tomatoes with increased carotenoid and sugar levels. *Journal of Applied Phycology.* https://doi.org/10.1007/s10811-015-0775-2
([121]) The slow-release characteristic of a microalgae fertilizer was further confirmed by the Horizon Europe Walnut project (internal communication), which will publish this result in 2026 (deliverable 4.4) on its website.

seedlings ([122]). Given that fertilisers are typically applied before sowing, the slow-release nature of algae-based fertilisers is expected to be advantageous in field conditions, ensuring nutrient availability aligns with plant demand.

Regarding nutrient leaching, the use of *Chlorella vulgaris* has been shown to reduce nitrogen and phosphorus leaching while enhancing soil fertility ([123]). The study reported a 90% reduction in nitrogen leaching by the fourth week in soils treated with algae fertiliser, whereas a similar reduction was only observed by the tenth week in control samples receiving conventional fertilisers. In contrast, *C. vulgaris* had no significant effect on reducing phosphate leaching. Potassium leaching occurred in both groups, but the addition of microalgae reduced potassium losses in sandy soils. However, soils treated with algae exhibited increased sulphate leaching, which was attributed to sulphate release during microalgal decomposition.

Despite these positive outcomes, two independent studies reported increased emissions of N_2O and CO_2 following the application of microalgae fertiliser. This rise in emissions was linked to the high carbon content of the biomass, which stimulated microbial activity in the soil ([124];[125]).

In addition to elevated emissions, using microalgae as a sole fertiliser proved economically prohibitive, with costs approximately 20 times higher than conventional fertilisers ([126]). Overall, the literature suggests that fully replacing mineral fertilisers with microalgae-based products is not advisable. Instead, substituting less than 20% of mineral fertiliser with microalgae is recommended to capitalise on the stimulatory effects of algae while mitigating issues related to lower nutrient bioavailability and higher costs ([127];[128]).

Finally, the production volume required to fully substitute the nutrient requirement of European crops is also not feasible in the medium term. In 2022, the EU

([122]) Garcia-Gonzalez and Sommerfeld (2015). Biofertilizer and biostimulant properties of the microalga Acutodesmus dimorphus. *Journal of Applied Phycology.* https://doi.org/10.1007/s10811-015-0625-2
([123]) Garbowski (2024). The Effect of Chlorella vulgaris (Chlorellales: Chlorellaceae) on the Fertility of Sandy Soils and on the Composition of Soil Leachates. *Journal of Soil Science and Plant Nutrition*. https://doi.org/10.1007/s42729-024-01984-7
([124]) Suleiman et al. (2020). From toilet to agriculture: Fertilization with microalgal biomass from wastewater impacts the soil and rhizosphere active microbiomes, greenhouse gas emissions and plant growth. *Resources, Conservation and Recycling*. https://doi.org/10.1016/j.resconrec.2020.104924
([125]) Siqueira Castro et al. (2017). Microalgae biofilm in soil: Greenhouse gas emissions, ammonia volatilization and plant growth. *Science of The Total Environment*. https://doi.org/10.1016/j.scitotenv.2016.08.205
([126]) Coppens et al. (2015). The use of microalgae as a high-value organic slow-release fertilizer results in tomatoes with increased carotenoid and sugar levels. *Journal of Applied Phycology.* https://doi.org/10.1007/s10811-015-0775-2
([127]) See footnote 126.
([128]) Siqueira Castro et al. (2020). Algal biomass from wastewater: soil phosphorus bioavailability and plants productivity. *Science of The Total Environment*. https://doi.org/10.1016/j.scitotenv.2019.135088

imported 8.9 million tonnes of nitrogen-based fertilisers ([129]). With an average nitrogen content of 26%, this represents 2.3 million tonnes of nitrogen. Considering a nitrogen content of 7% in microalgae and an inclusion rate of 10% of N from algae-based fertilisers, this would result in the need for 3 million tonnes of microalgae fertilisers. The current microalgae (excluding cyanobacteria) production in Europe is estimated to be around 5 tonnes per year ([130]).

3.2. Algae extract as plant biostimulants

The use of macroalgae extracts holds significant biostimulant potential in agriculture, enhancing plant growth ([131]), improving nutrient absorption, and increasing crop yield, while also aiding recovery from abiotic stresses ([132]). Macroalgae-based biostimulants are well-established products in the market, as shown in Table 9; readers are encouraged to consult the cited reviews for further details ([133];[134]).

Compared to macroalgae, the potential of microalgae to be used as plant biostimulants has been less extensively studied, although some products are already available on the market (Table 9). Several studies report that microalgae extracts can significantly enhance plant growth, nutrient uptake, and crop yield ([135]). Additionally, microalgae improve root development, as extracts from *Scenedesmus quadricauda* or *Chlorella vulgaris* improved root length, root surface area, and the number of root tips in sugar beet ([136]). Studies have shown

([129]) Eurostat. (2024). Use of fertilisers in EU agriculture down 10% in 2022. Available here.
([130]) Vazquez Calderon and Sanchez Lopez (2022). An overview of the algae industry in Europe – Producers, production systems, species, biomass uses, other steps in the value chain and socio-economic data. Available here.
([131]) The stimulation of plant growth is a grey zone within the EU legal framework. Plant growth may also be the result of the use of a plant growth regulator, clearly covered by the scope of the Plant Protection Products Regulation and excluded by the Fertilising Product Regulation, which is the main legal framework used in this document.
([132]) Deolu-Ajayi et al. (2022). The power of seaweeds as plant biostimulants to boost crop production under abiotic stress. *Plant, Cell & Environment.* https://doi.org/10.1111/pce.14391
([133]) See footnote 132.
([134]) Shekhar Sharma et al. (2014). Plant biostimulants: a review on the processing of macroalgae and use of extracts for crop management to reduce abiotic and biotic stresses. *Journal of Applied Phycology.* https://doi.org/10.1007/s10811-013-0101-9
([135]) Kapoore et al. (2021). Algae biostimulants: A critical look at microalgal biostimulants for sustainable agricultural practices. *Biotechnology Advances*. https://doi.org/10.1016/j.biotechadv.2021.107754
([136]) Barone et al. (2017). Root morphological and molecular responses induced by microalgae extracts in sugar beet (Beta vulgaris L.). *Journal of Applied Phycology.* https://doi.org/10.1007/s10811-017-1283-3

that applications of microalgae extracts – such as from *A. dimorphus* – can also improve germination ([137]). Microalgae also improve stress tolerance in crops ([138]).

The effectiveness of microalgal biostimulants depends on species selection, application method, extraction method, and synergistic interactions ([139]). Therefore, it is nearly impossible to make generalisations between different products, as their effectiveness must be evaluated on a case-by-case basis. Overall, microalgae contain biostimulant molecules within their composition, and a biostimulant effect can be expected when an appropriate processing method is employed to recover or release these molecules for interaction with the target plant.

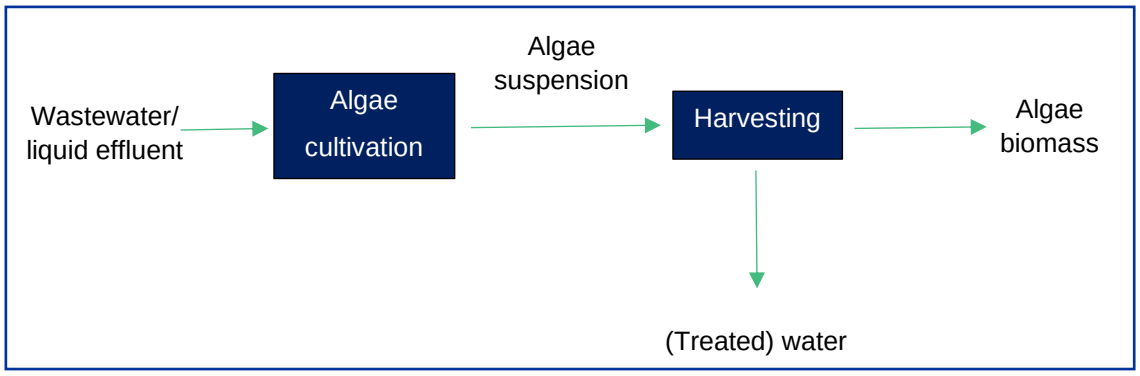
([137]) Garcia-Gonzalez and Sommerfeld (2015). Biofertilizer and biostimulant properties of the microalga Acutodesmus dimorphus. *Journal of Applied Phycology.* https://doi.org/10.1007/s10811-015-0625-2
([138]) Sánchez-Quintero et al. (2023). Overview of microalgae and cyanobacteria-based biostimulants produced from wastewater and CO2 streams towards sustainable agriculture: A review. *Microbiological Research*. https://doi.org/10.1016/j.micres.2023.127505
([139]) See footnote 138.

4. Legal requirements for producing algae-based fertilisers/biostimulants in wastewater and policy recommendations

4.1. Boundaries of this study

This study focuses on algae grown on land using the wastewater and liquid effluents highlighted in Section 1.1 and does not include beach-cast macroalgae ([140]) or algae harvested from natural environments. Moreover, the algae considered in this study refers to the biomass obtained after the harvesting step. This step separates the solid biomass from the water – in the case of macroalgae – or concentrates the biomass by approximately 100 times for microalgae, following the process illustrated in Figure 4. Consequently, the (treated) effluent would mostly be recovered as a separate stream, distinct from the produced biomass.

Figure 4 – Process of algae cultivation in wastewater/effluents to obtain an algae biomass to be used in fertilising products.



The separated water can be considered treated if it meets the national dischargeable limits. If not, it may still require some extra treatments to remove contaminants further.

When analysing the use of manure-based digestate for fertilisation, it is important to consider that the Nitrates Directive limits the amount of (processed) manure

([140]) Although beach-cast macroalgae are outside of the scope of this study, it seems this stream can be used as a fertilising product under the Fertilising Products Regulation. Question 8.22 of the FAQ mentions that CMC 2 does not explicitly exclude waste if the waste contains pure plants (and follows the processes listed in this CMC). Therefore, it is expected that beach-cast algae would meet this requirement and be allowed as input for CMC 2. However, wastes are not allowed as an input for CMC 1, which leads to an inconsistency where you would be able to directly apply beach-cast algae to the land but would not be able to make an extract of this material and use it in a fertilising product. This is the same for other plant wastes. We would recommend DG GROW to evaluate the wording on both CMCs to remove this inconsistency.

that can be applied to land in designated Nitrate Vulnerable Zones. This is a legally complex area, and the Directive is currently under evaluation by the European Commission to determine whether it remains fit for purpose ([141]). Moreover, the Directive does not regulate the types of materials that qualify as fertilising products; rather, it sets limits on the land application of certain materials. Therefore, a detailed analysis falls outside the scope of this document. Nonetheless, given that algae biomass is biochemically distinct from manure, it would be beneficial for the Commission to assess the potential of algae cultivation on processed manure as a permissible transformation process. This could produce a material that no longer qualifies as "manure" and, consequently, would not be subject to the 170 kg N/ha limit imposed by the Nitrates Directive.

4.2. Legal background for using algae as fertilising products in the European market

The Fertilising Product Regulation (FPR) establishes rules for placing EU fertilising products on the EU market. However, products that do not comply with the FPR can still be marketed within national markets under the respective national legislation and circulate among Member States by virtue of the principle of mutual recognition. To encourage the use of algae biomass as a component of fertilising products, it is essential to establish whether these materials meet the FPR requirements, thereby enabling the commercialisation of standardised products across the single market.

The FPR defines a fertilising product as "*a substance, mixture, micro-organism or any other material, applied or intended to be applied on plants or their rhizosphere or on mushrooms or their mycosphere, or intended to constitute the rhizosphere or mycosphere, either on its own or mixed with another material, for the purpose of providing the plants or mushrooms with nutrient or improving their nutrition efficiency*" ([142]). Furthermore, the preamble to the FPR emphasises that fertilising products "*should be placed on the market only if they are sufficiently effective*".

Therefore, the first prerequisite for using algae as a component in fertilising products is demonstrating their proven effectiveness. Once effectiveness has been established, a product must satisfy two main criteria to gain approval under the FPR:

- it must fall under one of the Product Function Categories (PFC) defined in the Regulation, each of which is subject to specific safety and quality requirements (further details in Section 4.2.1); and

([141]) Commission consults citizens and stakeholders on evaluation of the Nitrates Directive. Available here.
([142]) Article 2(1) of Regulation (EU) 2019/1009

- it must meet the requirements specified by the FPR for the relevant component material category or categories (CMC; further details in Section 4.2.2).

Finally, the product must be assessed for compliance with all relevant requirements according to the procedures set out in Annex IV and labelled in accordance with the requirements of Annex III of the FPR.

4.2.1. Product Function Categories (PFC)

For algae products ([143]), four PFCs are most relevant, as defined in the FPR:

- 1.A.I. solid organic fertiliser;
- 1.A.II. liquid organic fertiliser;
- 3.A. organic soil improver; and
- 6.B. non-microbial plant biostimulant.

Regarding their effectiveness, a review of the current knowledge on these potential applications was conducted, with the main findings presented in Chapter 3. Overall, there is a broad consensus on the effectiveness of algae-based plant biostimulants, particularly those derived from macroalgae, with several companies already commercialising such products. Conversely, the use of microalgae as a fertilising product – whether as a fertiliser or biostimulant – would benefit from further research, especially through field-scale, long-term trials. As for organic soil improvers, macroalgae are primarily employed for this purpose; however, since they also supply nutrients, they are more commonly classified as organic fertilisers when applied to land

PFC 1.A. Organic fertilisers

PFC 1 is defined as a fertilising product intended to provide nutrients to plants or mushrooms. Algae-based fertilisers may fall under PFC 1A, which covers organic fertilisers ([144]), provided they contain organic carbon (>15% for solids and >5% for liquids), nutrients of solely biological origin, and comply with all relevant requirements set out in the FPR.

([143]) In Section 4.2.1, a theoretical pure algae product is compared against the legal requirements for the various Product Function Categories (PFCs) presented here. However, it is important to note that most fertilising products comprise more than one material, often including technical additives such as anti-caking or anti-dusting agents. It is the final formulation (algae plus technical additives) that must comply with the legal requirements outlined for the relevant PFCs.
([144]) Organic fertilisers in the FPR are defined as fertilisers with organic carbon and nutrients of solely biological origin. They are not to be mistaken for fertilisers suitable for organic farming according to Regulation (EU) 2018/848.

PFC 1.A.I Solid organic fertiliser

The FPR defines solid form as "*the form characterized by structural rigidity and resistance to changes of shape or volume and in which the atoms are tightly bound to each other, either in a regular geometric lattice (crystalline solids) or in an irregular manner (an amorphous solid)*" ([145]). Therefore, untreated macroalgae could be classified under the provisions for solid organic fertilisers, whereas microalgae must first be concentrated and dried to meet the FPR's definition of solid fertilisers. If microalgae are only concentrated into a paste, the resulting EU fertilising product should be classified as a liquid organic fertiliser (PFC 1.A.II, see below). Depending on the processing methods, macroalgae can also be processed into a paste, thus fitting within the liquid organic fertiliser category as well.

A solid organic fertiliser must contain at least one primary nutrient declared as N, P_2O_5, or K_2O. If only one primary nutrient is declared, its content must be at least (a) 2.5% by mass of total nitrogen (N), (b) 2% by mass of total phosphorus pentoxide (P_2O_5), or (c) 2% by mass of total potassium oxide (K_2O). If more than one primary nutrient is declared, the sum of nutrient contents must be at least 4% by mass, with each individual nutrient present at a minimum of (a) 1% by mass total N, (b) 1% by mass total P_2O_5, or (c) 1% by mass total K_2O.

The elemental composition of macroalgae (on a dry weight (DW) basis) can vary between 1.2–4.0% N, 0.07–0.24% P, and 1.5–8.5% K ([146]). This indicates that macroalgae cannot be considered a phosphorus fertiliser but, depending on their origin, could be marketed as a source of nitrogen, potassium, or as an NPK mixture. Microalgae generally contain (dry weight) between 3.8 and 9.7% N, 0.7 to 1.5% P, and 0.7 to 2.4% K ([147]). These concentrations allow microalgae to be commercialised as either individual or combined sources of these three macronutrients, depending on the species and cultivation conditions ([148]). Nevertheless, due to their high-water content, legal requirements would typically only be met after a drying step for both macro- and microalgae.

PFC 1.A.II Liquid organic fertiliser

According to the FPR, the liquid form is defined as "*a suspension or a solution, where a suspension is a two-phase dispersion in which solid particles are maintained in suspension in the liquid phase, and a solution is a liquid that is free*

([145]) Article 2(7) of Regulation (EU) 2019/1009.
([146]) Olsson et al. (2020). Biochemical composition of red, green and brown seaweeds on the Swedish west coast. *Journal of Applied Phycology.* https://doi.org/10.1007/s10811-020-02145-w
([147]) Tibbetts et al. (2014). Chemical composition and nutritional properties of freshwater and marine microalgal biomass cultured in photobioreactors. *Journal of Applied Phycology.* https://doi.org/10.1007/s10811-014-0428-x
([148]) This was further confirmed by the LIFEALGAECAN project, as can be seen in their layman's report. Available here.

of solid particles, or a gel and includes pastes" ([149]). Therefore, an algae paste could be a liquid fertiliser.

A liquid organic fertiliser must contain at least one primary nutrient such as N, P_2O_5, or K_2O. If it contains only one primary nutrient, this content must be at least (a) 2% by mass of total N, (b) 1% by mass of total P_2O_5, or (c) 2% by mass of total K_2O. If it contains more than one declared nutrient, the sum of the nutrient content must be at least 3% by mass, and the individual nutrient contents must be at least (a) 1% by mass of total N, (b) 1% by mass of total P_2O_5, or (c) 1% by mass of total K_2O.

As previously presented, microalgae generally contain (DW) 3.8–9.7% N, 0.7–1.5% P, and 0.7–2.4% K, which corresponds to a composition of 0.76–1.94% N, 0.32–0.69% P_2O_5, and 0.17–0.56% K_2O for an algae paste with 20% dry matter (DM). Therefore, either a nitrogen-based liquid microalgae fertiliser or an NPK mixture could be commercialised. To meet the necessary nutrient contents, it must be composed of algal biomass at the higher end of the typical reported range of NPK contents and have a high dry matter content (≥20%).

Macroalgae generally contain (DW) 1.2–4.0% N, 0.07–0.24% P, and 1.5–8.5% K, which corresponds to a composition of 0.24–0.80% N, 0.03–0.11% P_2O_5, and 0.36–2.05% K_2O for an algae paste with 20% dry matter (DM). Therefore, it is more likely that a potassium-based liquid macroalgae fertiliser could be commercialised. To reach the 2% K content, the fertiliser must be composed of algal biomass with potassium content at the higher end of the typical range and a high dry matter content (≥20%). A mixed N-K fertiliser might also be possible under these conditions.

PFC 3.A. Organic soil improver

According to the FPR, "*a soil improver shall be an EU fertilising product the function of which is to maintain, improve or protect the physical or chemical properties, the structure or the biological activity of the soil to which it is added*" ([150]). Moreover, an organic soil improver must comprise at least 95% materials of solely biological origin, contain 20% or more dry matter, and have an organic carbon content of at least 7.5% by mass. Since algae are entirely of biological origin and possess a high carbon content, they can be classified as organic soil improvers once dried to meet the required dry matter content.

([149]) Article 2(6) of Regulation (EU) 2019/1009
([150]) Part II of Annex I of Regulation (EU) 2019/1009

The average C_{org} content for macroalgae is usually between 28-41% ([151]), with some reports indicating values as high as 60% ([152]). For microalgae, the average C_{org} content is 50% ([153]). Therefore, all algae can satisfy the minimum 7.5% carbon content criterion once dried to exceed the >20% dry matter threshold.

PFC 6.B. Non-microbial plant biostimulant

According to the FPR, a plant biostimulant is defined as an EU fertilising product that stimulates plant nutrition processes independently of the product's nutrient content, with the sole aim of improving one or more of the following characteristics of the plant or its rhizosphere: (a) nutrient use efficiency, (b) tolerance to abiotic stress, (c) quality traits, or (d) availability of confined nutrients in the soil or rhizosphere. Furthermore, Annex I specifies that all plant biostimulants must demonstrate the effects claimed on their labels for the designated plants. As noted previously, a review of the biostimulant capacity of algae-based products is provided in Chapter 3.

A non-microbial plant biostimulant is defined as a plant biostimulant other than a microbial one; in other words, it does not consist of a micro-organism or a consortium of micro-organisms. While there is a CMC dedicated to micro-organisms, microalgae are currently not included in this category but are classified under the plant category (CMC 2), alongside macroalgae and plants. Further details on CMCs are discussed in Section 4.2.2.

Legal limit values for contaminants in algal fertilising products

All EU fertilising products must comply with the limit values outlined in Annex I of the FPR concerning certain contaminants and pathogens (Table 10).

([151]) Olsson et al. (2020). Biochemical composition of red, green and brown seaweeds on the Swedish west coast. *Journal of Applied Phycology.* https://doi.org/10.1007/s10811-020-02145-w
([152]) Alexander (2021). An evaluation of the organic carbon content found in Fucus vesiculosus and Ascophyllum nodosum from Skutulsfjörður and Eyjafjörður, Iceland. Available here.
([153]) Derakhshandeh et al. (2021). Evaluation of Wild-Type Microalgae Species Biomass as Carbon Dioxide Sink and Renewable Energy Resource. *Waste and Biomass Valorization.* https://doi.org/10.1007/s12649-020-00969-8

Table 10 – Limit values for the highlighted PFCs

Contaminants	Organic fertilisers	Soil improvers	Biostimulants	Unit
Cadmium (Cd)	1.5	2	1.5	mg/kg dry matter
Hexavalent chromium (Cr VI)	2	2	2	mg/kg dry matter
Mercury (Hg)	1	1	1	mg/kg dry matter
Nickel (Ni)	50	50	50	mg/kg dry matter
Lead (Pb)	120	120	120	mg/kg dry matter
Inorganic arsenic (As)	40	40	40	mg/kg dry matter
Copper (Cu)	300	300	600	mg/kg dry matter
Zinc (Zn)	800	800	1500	mg/kg dry matter
Biuret (C2H5N3O2)	Must not be present	No requirement	No requirement	
Pathogens				
Micro-organisms to be tested	Sampling plans			Limit
	n	**c**	**m**	**M**
Salmonella spp.	5	0	0	Absence in 25 g or 25 ml
Escherichia coli or enterococci	5	5	0	1000 in 1 g or 1 ml
Where (i) **n** is the number of samples to be tested; (ii) **c** is the number of samples where the number of bacteria expressed in colony forming units (CFU) is between m and M; (iii) **m** is the threshold value for the number of bacteria expressed in CFU that is considered satisfactory, and (iv) **M** is the maximum value of the number of bacteria expressed in CFU.				

4.2.2. Component Material Categories (CMC)

For algae-based products, the following CMCs are mainly applicable, with the first two (CMC 1 and CMC 2) being the most relevant for biostimulants and fertilisers, respectively:

- CMC 1 Virgin material substances and mixtures;
- CMC 2 Plants, plant parts, or plant extracts;
- CMC 3 Compost;
- CMC 5 Digestate other than fresh crop digestate;
- CMC 13 Thermal oxidation materials and derivates, and
- CMC 14 Pyrolysis and gasification materials.

CMC 12 (precipitated phosphate salts and derivatives) and CMC 15 (recovered high purity materials) could potentially be included in this list, however including them would require numerous processing steps to extract such materials from

algae, processes that are not yet established at a high TRL, and therefore are not considered relevant in the near future.

According to the definition of CMC 2 of the FPR ([154]), "*an EU fertilising product may contain plants, plant parts or plant extracts having undergone no other processing than cutting, grinding, milling, sieving, sifting, centrifugation, pressing, drying, frost treatment, freeze-drying or extraction with water or supercritical CO_2 extraction. For the purpose of this point, plants include mushrooms and algae and exclude blue-green algae (cyanobacteria)*".

Therefore, fresh and dried algae are specifically included in CMC 2 (Plants, plant parts or plant extracts), with the exception of cyanobacteria ([155]). This classification also applies to microalgae, which are currently not considered microorganisms (CMC 7) for the purposes of the FPR ([156]). Nonetheless, the inclusion of microalgae and cyanobacteria could be considered under CMC 7 in a future revision of the FPR.

If the algae undergo a processing step not covered by this definition, they must either be classified under a different CMC or cannot be used in the formulation of an EU fertilising product. For example, if enzymatic hydrolysis or ethanolic or acid extraction is performed—processes commonly used to produce biostimulants from algae—the resulting algae or extract would fall under CMC 1 (Virgin material substances and mixtures) and be subject to REACH regulation ([157]). The same applies to composting (CMC 3), anaerobic digestion (CMCs 4 and 5), thermal oxidation (CMC 13), and pyrolysis/gasification (CMC 14), each subject to their own specific requirements.

CMC 2 does not distinguish between algae cultivated in synthetic media or wastewater and those harvested from natural environments. However, this classification appears valid only as long as the legal status of the algae remains unchanged, which may not necessarily be the case for certain effluents, as discussed in the legal analysis presented in Section 4.4 below.

([154]) Part II of Annex II of Regulation (EU) 2019/1009; further clarified in question 8.20 of the Frequently Asked Questions of FPR.
([155]) This exclusion is currently being assessed by DG GROW following the proposal by the EU Algae Initiative. A non-exhaustive list of potential cyanobacteria that are harmless and should be allowed to be included in fertilising products is presented further below. Even though cyanobacteria are excluded from CMC 2, their extract can be used under CMC 1 according to the Frequently Asked Questions of FPR (see question 8.23). It is unclear from the FPR or its FAQ if cyanobacteria processed by composting (CMC 3) or thermal processes (CMC 13 and 14) would be eligible for use in a fertilising product, but they are also specifically excluded from CMC 5 (anaerobic digestion).
([156]) See question 8.20 of the Frequently Asked Questions of FPR.
([157]) See question 8.3 of the Frequently Asked Questions of FPR.

Inclusion of cyanobacteria in the FPR

Cyanobacteria can fix nitrogen and, therefore, can be added to soil to reduce the need for nitrogen fertilisation. Moreover, several species have demonstrated growth-promoting effects when applied to the rhizosphere of certain plants, such as rice ([158]). Additionally, cyanobacterial biomass is rich in nutrients and could be applied directly as a fertiliser to soil or processed into biostimulants using the same methods employed for microalgae (see Chapter 3 for more information on the use of algae as fertilisers and biostimulants). Therefore, there is value in including cyanobacteria within the scope of the FPR.

However, as outlined in the previous section, cyanobacteria are currently almost entirely excluded from the FPR, except under CMC 1, where processed cyanobacteria and their extracts may potentially be included. This is due to the stringent requirements of CMC 1, which necessitate rigorous analyses and registration pursuant to Regulation (EC) 1097/2006 including a dossier containing information and a chemical safety report as specified in the FPR, thereby mitigating any risks associated with the use of cyanobacteria.

This exclusion is mainly attributed to the production of toxins by several cyanobacterial species ([159]). Indeed, several species tested for soil application are known to produce toxins, such as Anabaena, Nostoc, Oscillatoria, Calothrix, Synechococcus, Phormidium, and Microcoleus.

However, some cyanobacteria are approved for human consumption under the Novel Food Regulation: *Aphanizomenon flos-aquae*, *Arthrospira platensis*, *Limnospira fusiformis*, *Limnospira indica*, *Limnospira maxima*, and *Spirulina major*. Therefore, if direct consumption is permitted, it is reasonable to expect that the application of such biomass to soil would also pose no risk regarding toxin content. Besides these species, the genera *Aulosira*, *Tolypothrix*, and *Aphanothece* have also been shown to have positive effects on plant growth and are considered non-toxic ([160]).

Based on this information, a first approach to adding cyanobacteria to the FPR could be to enable the use of species allowed for human consumption under the Novel Food status catalogue. Depending on the intended application, cyanobacteria could fall under CMC 2 if used as a fertiliser or non-microbial plant biostimulant, or under CMC 7 if intended for application to soil as a microbial plant biostimulant.

([158]) Nawaz et al. (2024). Harnessing the potential of nitrogen-fixing cyanobacteria: A rich bio-resource for sustainable soil fertility and enhanced crop productivity. *Environmental Technology & Innovation*. https://doi.org/10.1016/j.eti.2024.103886
([159]) WHO (2021). Toxic cyanobacteria in water - Second edition. Available here.
([160]) See footnotes 158 and 159.

A technical study is currently underway to assess the safety and agronomic efficacy of selected cyanobacteria, with the aim of amending the FPR requirements, if deemed appropriate.

4.3. Algae cultivated in the selected effluents – current legal status and policy recommendations for use in EU fertilising products

This section provides a summary legal analysis of the key regulations and directives relevant to the selected wastewaters and liquid effluents. For a more comprehensive review, readers are encouraged to consult the legal study prepared by Mr Barry Love, commissioned by the European Sustainable Phosphorus Platform (ESPP) ([161]).

To better understand how algae can be integrated into the sectors discussed below, please refer to Chapter 1.

4.3.1. Algae grown on urban wastewater

Current legal status

The Urban Wastewater Treatment Directive (UWWTD) regulates the treatment and discharge of water resulting from domestic and industrial activities, as well as urban run-off. It does not prescribe specific treatment technologies, remaining technology-neutral, and instead imposes threshold values for certain discharge parameters. Consequently, the UWWTD permits the integration of algae cultivation within urban wastewater treatment processes. This may occur in one of two ways: (i) through the use of algal ponds to remove COD, nitrogen, and phosphorus as part of a combined secondary and tertiary treatment, typically in symbiosis with bacteria; or (ii) as a tertiary treatment stage focused specifically on the removal of nitrogen and phosphorus.

Algae-based secondary and tertiary treatment

Algae grown on urban wastewater fits the legal definition of sludge, as stated in Article 2 of the UWWTD: "*sludge means organic and inorganic residue resulting from the treatment of urban wastewater from an urban wastewater treatment*

([161]) Environmental Law Chambers Ltd. (2024). Legal Opinion on the Waste/Animal By Product (ABP) status of waste-derived algae with particular reference to the Animal Feeds Regulation. Available here.

plant, excluding grit, grease, other debris and any other screenings and residues from the pre-treatment step".

Once algae are classified as "sewage sludge", their eligibility for inclusion under the Fertilising Products Regulation (FPR) is altered. Specifically, it is likely that they would no longer qualify under CMC 2 (plants), as they would no longer be legally recognised as “algae”. The same rationale would apply to CMC 5 (digestate). Furthermore, CMC 3 (compost) and CMC 14 (pyrolysis and gasification materials) explicitly exclude sewage sludge, while CMC 1 (virgin material substances and mixtures) excludes waste – a category under which sewage sludge is expected to fall. As a result, only CMC 13 (thermal oxidation materials and derivates) and CMC 15 (recovered high purity materials) currently permit the use of sewage sludge as an input. Therefore, algae cultivated in urban wastewater could only be incorporated into EU fertilising products if processed through one of these two pathways.

Article 20 of the UWWTD stipulates that sludge from wastewater treatment shall be reused whenever appropriate. This principle is implemented through the Sewage Sludge Directive (SSD), which regulates the use of sewage sludge in agriculture. As algae cultivated in urban wastewater meet the definition of sewage sludge, they may benefit from the provisions of this Directive and be applied to land as a fertiliser, provided that national legislation permits the use of sewage sludge for such purposes ([162]). However, while the SSD explicitly addresses land application, it does not make specific reference to biostimulants. Moreover, the definition of “use” in Article 2 of the SSD is restricted to “the spreading of sludge on the soil or any other application of sludge on and in the soil.” Consequently, the use of algae grown on urban wastewater as foliar-applied biostimulants is not currently encompassed within the scope of this legislation.

Sewage sludge intended for agricultural use must comply with the limit values established in Annex I of the SSD, which are also presented in Table 11. Notably, the permissible limits for contaminants in sewage sludge under the SSD are significantly higher than those set out in the FPR for EU fertilising products, as shown in Table 10.

([162]) Certain countries do not permit the use of sewage sludge in agriculture, including Belgium (except Wallonia), Slovakia, the Netherlands, and specific regions of Austria. The current status of this Directive’s implementation can be accessed here.

Table 11 – Limit values for the use of sewage sludge in agriculture

Parameters	Limit values in sludge (mg/kg DM)	Limit values for annual application (kg/ha/yr)	Limit values in soil (mg/kg DM within pH 6-7)
Cadmium (Cd)	20-40	0.15	1-3
Copper (Cu)	1000-1750	12	50-140[1]
Nickel (Ni)	300-400	3	30-75[1]
Lead (Pb)	750-1200	15	50-300
Zinc (Zn)	2500-4000	30	150-300[1]
Mercury (Hg)	16-25	0.1	1-1.5
Chromium (Cr)[2]	-	-	-

[1] Member States may allow the established limit values for these parameters to be exceeded on soils with a consistently high pH (above 7). However, the maximum authorised concentrations of these heavy metals must not exceed the specified values by more than 50%. Member States must also ensure that such exceedances do not pose a risk to human health, the environment, or groundwater.

[2] Although the Directive does not establish limit values for this metal, national authorities have set such limits independently. These limits vary across Member States.

Algae-based tertiary treatment

One possible means of avoiding the classification of algae cultivated on urban wastewater as sewage sludge could be to grow it in an already treated water stream, solely for the purpose of removing nitrogen and phosphorus in a polishing (tertiary treatment) step. This process could occur either within the urban wastewater treatment facility itself or at a separate installation receiving the treated effluent and dedicated to algae cultivation. Although such options are not explicitly authorised under current legislation, they are supported by a legal foundation provided by the Water Reuse Regulation.

The Water Reuse Regulation establishes minimum requirements for water quality and monitoring, primarily aimed at enabling the reuse of water for agricultural irrigation. However, Paragraph 29 explicitly states that "*the indication of specific uses within this Regulation should not preclude Member States from allowing the use of reclaimed water for other purposes, including industrial, amenity-related and environmental purposes, as considered necessary in the light of national circumstances and needs, provided a high level of protection of the environment and of human and animal health is ensured*".

Accordingly, Member States may individually permit the use of reclaimed water for alternative applications – such as algae cultivation – provided appropriate safeguards are maintained. Recommendations on how this may be achieved are outlined below. For instance, as an example of non-agricultural applications, the AWARE project is assessing the use of reclaimed water in the production of fish intended for human consumption.

Policy recommendations (DG ENV/DG GROW)

- **Maintain the classification of algae grown on untreated urban wastewater as "sewage sludge"**, given that urban wastewaters are a significant source of pollutants detrimental to human and environmental health. Like the microorganisms present in conventional sewage sludge, algae absorb and/or adsorb contaminants found in urban wastewater. Consequently, the risks associated with their subsequent use are comparable to those of traditional sewage sludge (further discussed in Chapter 5). In recent years, newly identified or previously unquantified contaminants – such as microplastics and perfluoroalkyl and polyfluoroalkyl substances (PFAS) – have emerged, and additional emerging contaminants may pose concerns in the future.
- **Assess whether the production process of biostimulants from algae sufficiently mitigates any risks associated with its cultivation on urban wastewaters.** If proven effective, leaf-applied biostimulants derived from this biomass could be incorporated into a revised version of the SSD to permit their use in national markets. This approach could subsequently be extended to the FPR at the European level, as has been achieved for precipitated phosphate salts from urban wastewater (CMC 12). However, since CMC 1, which covers chemical processing excluding aqueous extraction, prohibits the use of waste or materials recovered from waste, including materials derived from sewage sludge within this CMC appears unlikely in the near term. A viable alternative could be to integrate some of the processes currently encompassed by CMC 1 into the approved processes under CMC 2, provided they meet the criteria outlined in point 2 of CMC 1.
- Member States should consider employing the minimum quality requirements outlined in Section 2 of Annex I of the Water Reuse Regulation to guide decisions regarding **the use of reclaimed water for algae cultivation.** To produce fertilising products from algae grown in reclaimed water, it is recommended that all water quality classes (A–D, as per Table 2 of Annex I of the Water Reuse Regulation) may be utilised, provided that the final product's application is restricted to the specific crop categories indicated in Table 1 of Annex I. For example, algae cultivated with reclaimed water of quality class D should only be used for the cultivation of industrial, energy, and seed crops.
- **Add to CMC 2 (FPR) a positive list of approved growing media for algae cultivation,** including reclaimed water. This list should remain open to future amendments as new evidence emerges regarding suitable recycled nutrient sources for algae cultivation, as recommended in subsequent sections. Alternatively, a new CMC dedicated exclusively to algae could be established, listing all approved media. This approach would facilitate the expansion of approved processes and circumvent

challenges related to the exclusion of waste in CMC 1, which currently encompasses most extraction processes commonly used for algae products.

4.3.2. Algae grown on manure-derived digestate

Current legal status of manure-derived digestate used as fertilising products

The handling of manure, and consequently manure-based digestate, is regulated by the Animal By-product Regulation (ABPR). According to Article 9 of the ABPR, manure is a Category 2 material. Following Article 13, Category 2 materials can be "*used for the manufacturing of organic fertilisers or soil improvers to be placed on the market in accordance with Article 32 following processing by pressure sterilisation, when applicable, and permanent marking of the resulting material*". Article 32 also permits the use of digestate derived from these materials as organic fertiliser in national markets.

An animal by-product may only be incorporated into an EU fertilising product after achieving a specified endpoint in the manufacturing process in accordance with the ABPR. Specifically, with regard to manure-based digestate, as described under CMC 5 in the FPR: "*an EU fertilising product may contain digestate obtained through anaerobic digestion of Category 2 or Category 3 materials or derived products thereof […], provided that the end point in the manufacturing chain has been determined in accordance with the third subparagraph of Article 5(2) of Regulation (EC) No 1069/2009*". The Commission delegated Regulation (EU) 2023/1605 has established such an endpoint for processed manure, detailing the requirements for the digestion process.

Consequently, manure-based digestate can be utilised as a component material in EU fertilising products marketed both nationally and across the European Union.

Current legal status of algae cultivated in manure-based digestate

Article 13 of the ABPR establishes the proper disposal and use of Category 2 materials, which includes manure. According to this Regulation, manure may be (i) (co)incinerated, (ii) landfilled, (iii) used for producing organic fertilisers or soil improvers ([163]), (iv) composted or digested, (v) directly applied to land, (vi)

([163]) According to the ABPR, organic fertiliser and soil improver means "materials of animal origin used to maintain or improve plant nutrition and the physical and chemical properties and biological activities of soils"; therefore, they can only be land-applied and using them to fertilise water for the growth of algae is not covered by this legislation.

combusted, or (vii) used for producing derived products. Therefore, algae production is not explicitly listed among the approved processes for manure.

However, Article 16 of the ABPR allows for the use of alternative methods for animal by-products, which could potentially include algae cultivation. Under Article 20, an authorisation request for an alternative method can be submitted by the Commission, a Member State, or an interested party, with the latter required to apply to the competent authority in their Member State.

Once a permit to cultivate algae on manure-based digestate is granted ([164]), the next issue concerns the commercialisation of such algae as a fertilising product under the FPR. At present, algae biomass produced in this way is not explicitly covered by the FPR.

Nonetheless, considering that both manure-based digestate and algae are permitted for such use, it follows logically that algae grown on manure-based digestate should also be allowed to be marketed as a fertilising product under the FPR, as the cultivation process does not pose additional risks to human or environmental health (see Chapter 5 for further details). Additional recommendations on implementing this approach are provided in the following section.

This conclusion is further supported an informal communication with DG SANTE, following an enquiry from ESPP regarding whether manure could be used for algae cultivation for fertiliser production. DG SANTE responded: “considering that processed manure may be used as organic fertilisers or growing media, the use of processed manure as growing media for algae intended for production of fertilisers is allowed. However, the use of unprocessed manure for growing media is not allowed.” They emphasised that this is their technical opinion and that only the Court of Justice of the European Union has the authority to provide a definitive interpretation of EU law.

Policy recommendations (DG GROW)

- **Add to CMC 2 (FPR) a positive list of accepted growing media for algae cultivation,** including manure-based digestate produced in accordance with the requirements of CMC 5. This list should remain open to future amendments as new evidence emerges regarding suitable recycled nutrients for algae cultivation, as recommended in the following sections. Alternatively, a new CMC specifically for algae could be

([164]) In Flanders, Belgium, as an example, a permission request needs to be submitted to OVAM, the Public Waste Agency of Flanders, for a feedstock declaration (grondstofverklaring). The request must contain an analysis from an official authorised lab on the parameters of Vlarema annex 2.3.1. For the algae to be perceived as fertiliser and not as processed manure, OVAM highlighted that they might require additional analyses to guarantee that there are not significant amounts of original material (manure digestate) in the final product (algae biomass).

established, listing the approved media. This approach would facilitate the expansion of approved processes and help avoid complications arising from the exclusion of waste in CMC 1, which currently covers most extraction processes commonly used for algae products.

4.3.3. Algae grown on aquaculture and horticulture effluents

Current legal status

The discharge of aquaculture and horticulture effluents is not specifically addressed in the UWWTD ([165]) nor the Industrial Emissions Directive. Consequently, there is no dedicated EU-level regulation for these effluents, and individual Member States may impose their own legislative and permitting requirements for such facilities, provided they comply with overarching environmental objectives such as those in the Water Framework Directive and the Nitrates Directive, and any relevant national legislation. Therefore, there are no legal restrictions on the cultivation of algae on these effluents, so long as the Member State grants the appropriate permit for this activity.

Under a strict interpretation, algae grown on such effluents might be classified as waste, which would significantly limit their potential uses and require an end-of-waste determination before they could be utilised under the FPR. Alternatively, if the use of these effluents for algae cultivation is certain, algae cultivation could be considered an additional process step (subject to permit approvals; see, for example, the case in Flanders, Belgium, in footnote 164), thereby allowing the algae to be classified as a secondary product of the facility. For commercialisation, the algae produced must comply with the relevant legislation applicable to their intended use, which in this case is the FPR.

Policy recommendations (DG GROW)

- **Add to CMC 2 (FPR) a positive list of accepted growing media for algae cultivation,** encompassing aquaculture and horticulture effluents. This list should remain open to future amendments as new evidence emerges regarding suitable recycled nutrient sources for algae cultivation, as recommended in the following sections. Alternatively, a new CMC specifically for algae could be established, listing the approved media. This

([165]) Horticulture and aquaculture effluents can, however, fall within the scope of the UWWTD as non-domestic wastewater when mixed with domestic wastewater and urban runoff in urban agglomerations. According to Article 2 of the UWWTD, “non-domestic wastewater” means “wastewater, other than domestic wastewater and urban runoff, which is discharged from premises used for the exercise of a trade or industrial or economic activities.” Once mixed with urban wastewater and treated at an urban wastewater treatment facility, the resulting algae would be subject to the analysis set out in Section 4.3.1 of this document.

approach would facilitate the expansion of approved processes and help avoid complications arising from the exclusion of waste under CMC 1, which currently covers most extraction processes commonly used for algae products.

5. Identification and quantification of contaminants when growing algae in wastewaters

5.1. Quantification of contaminants listed in the Fertilising Product Regulation

According to the FPR, algae may be commercialised in the European Market as organic fertilisers (PFC 1.A), soil improvers (PFC 3.A), and non-microbial biostimulants (PFC 6.B) (further discussed in Chapter 4). To comply with this regulation, the algae material must satisfy specific quality requirements, including legal limits for contaminants and pathogens, which are detailed in Table 12.

The FPR states that, if analyses are conducted using CEN standards published in the Official Journal of the European Union (OJEU), the results are presumed to comply with the legislation. Consequently, following the publication of the FPR, CEN was tasked with drafting harmonised standards for the parameters specified in the regulation. Table 12 lists the CEN standards already published and, where these are not yet available, the corresponding relevant ISO standards for the highlighted contaminants.

Currently, most of the CEN standards referenced in Table 12 have not yet been published in the OJEU, as they were developed recently following the publication of the FPR and are still undergoing evaluation.

At the time of writing this report (April 2025), CEN Technical Committee 455 on Plant Biostimulants has published 33 European standards. Other Technical Committees, such as TC 260 (Fertilisers and Liming Materials) and TC 223 (Soil Improvers and Growing Media), have released several CEN Technical Specifications (CEN/TSs) and a limited number of European standards, with the remainder expected to be published by 2027. Relevant links to access the standards, once published, are provided in the footnotes of Table 12.

Besides the specific Technical Committees for the relevant product function categories (PFCs) covered by the FPR, CEN also has an Algae Technical Committee developing standards for this biomass, though not necessarily within the scope of the FPR. In principle, the methods included in Table 12 are specific for certain PFCs and component materials. Therefore, it remains unclear whether these methods will also be applicable to algae biomass. Validation of these methods for algae biomass is advisable, unless it is explicitly stated that this particular type of biomass was tested.

Table 12 – Limit values for the relevant PFCs according to the FPR and standardised methods for their quantification

	Organic fertilisers[a]		Organic soil improvers[b]		Biostimulants[c]	
	Limit	Methods	Limit	Methods	Limit	Methods
Cadmium (Cd) (mg/kg dry matter)	1.5	CEN/TS 17777:2022	2	ISO 17318:2015	1.5	EN 17701-1:2024 EN 17701-2:2024
Hexavalent chromium (Cr VI) (mg/kg dry matter)	2	CEN/TS 17778:2022	2	ISO 17318:2015	2	EN 17701-1:2024 EN 17701-2:2024 EN 17703:2024
Mercury (Hg) (mg/kg dry matter)	1	CEN/TS 17777:2022	1	ISO 17318:2015	1	EN 17701-1:2024 EN 17701-3:2024
Nickel (Ni) (mg/kg dry matter)	50	CEN/TS 17777:2022	50	-	50	EN 17701-1:2024 EN 17701-2:2024
Lead (Pb) (mg/kg dry matter)	120	CEN/TS 17777:2022	120	ISO 17318:2015	120	EN 17701-1:2024 EN 17701-2:2024
Inorganic arsenic (As) (mg/kg dry matter)	40	CEN/TS 17777:2022	40	ISO 17318:2015	40	EN 17701-1:2024 EN 17701-2:2024 EN 17706:2024
Copper (Cu) (mg/kg dry matter)	300	CEN/TS 17777:2022	300	CEN/TS 17733:2022 CEN/TS 17729:2022	600	EN 17701-1:2024 EN 17701-2:2024
Zinc (Zn) (mg/kg dry matter)	800	CEN/TS 17777:2022	800	CEN/TS 17733:2022 CEN/TS 17729:2022	1500	EN 17701-1:2024 EN 17701-2:2024
Biuret ($C_2H_5N_3O_2$)	Absence	CEN/TS 17765:2022	No requirement		No requirement	

	Organic fertilisers[a]		Organic soil improvers[b]		Biostimulants[c]	
	Limit	**Methods**	**Limit**	**Methods**	**Limit**	**Methods**
***Salmonella* spp.**	Absence in 25 g or 25 ml	CEN/TS 17803:2022	Absence in 25 g or 25 ml	-	Absence in 25 g or 25 ml	EN 17708:2024 EN 17717:2024
***Escherichia coli* or enterococci**	1000 in 1 g or 1 ml	CEN/TS 17803:2022	1000 in 1 g or 1 ml	-	1000 in 1 g or 1 ml	EN 17708:2024 EN 17716:2024 EN 17720:2024

When a hyphen is present, it means that no standardised method was found for the determination of this contaminant in that specific matrix.

[a] All CEN standards for organic fertilisers already published can be found here.

[b] All CEN standards for soil improvers already published can be found here.

[c] All CEN standards for plant biostimulants already published can be found here.

5.2. Potential contaminants present in the selected wastewaters/effluents and their quantification

In Chapter 1, four wastewaters and effluents were identified as the most promising for algae cultivation aimed at producing fertilising products: urban wastewater (microalgae), horticulture (hydroponics) effluent (microalgae), aquaculture effluent (micro- and macroalgae), and manure-based digestate (microalgae). The following subsections examine the potential contaminants that may be present in the biomass produced from cultivation on each of these streams, beyond those currently covered by the FPR, and suggest standardised analytical methods for their quantification. For further details on algae growth using these effluents, please refer to Chapter 1.

5.2.1. Urban wastewater

As analysed in Chapter 4, algae grown on untreated urban wastewater would be classified as sewage sludge and, therefore, would not be compatible with the FPR unless treated via thermal oxidation. Consequently, their use as fertilisers is more likely to fall under the Sewage Sludge Directive (SSD). Currently, this Directive only mandates heavy metal analysis; however, sewage sludge is expected to contain several emerging contaminants (see Section 5.2.4), in addition to antibiotics – which are of growing concern (see Section 5.2.3) – as well as hormones and pharmaceuticals. Therefore, following the publication of the new UWWTD and the increased controls for such contaminants during wastewater treatment, it is recommended that the SSD be revised to include more stringent limits on the return of such substances to the soil.

Algae grown on urban wastewater have been characterised for potential contaminants, with results supporting their use as fertilisers ([166]). The heavy metal contents were all below the legal thresholds set by the SSD and generally complied with the stricter limits of the FPR. Pathogen levels were also below the legal limits established by the FPR. However, only a homogenised sample was evaluated, and fluctuations in heavy metal content over different months were not recorded. Notably, while 26 emerging contaminants were detected in the input wastewater, only three were found at significant levels in the produced algal biomass, and these did not appear to be directly transferred to plants grown using the algae fertiliser.

([166]) Álvarez-González et al. (2023). The potential of wastewater grown microalgae for agricultural purposes: Contaminants of emerging concern, heavy metals and pathogens assessment. *Environmental Pollution.* https://doi.org/10.1016/j.envpol.2023.121399

The PRODIGIO project analysed pathogens in algal biomass produced during wastewater treatment, finding only three pathogenic species in the biomass compared to eighteen in the inlet. This indicates that the algae cultivation step promoted partial hygienisation of the wastewater ([167]). These results are promising for the land application of algae grown on wastewater; however, further studies are needed using wastewater from various locations and over longer periods of algae production to confirm the reduced risk of using algae grown on such streams as fertilising products.

With the more stringent limits of the new UWWTD on N and P, the use of algae cultivation for tertiary treatment of urban wastewater is likely to increase. Therefore, it is recommended that a European study be commissioned to evaluate the feasibility of using the produced algal biomass as a fertilising product and to assess the associated risks. If the risks are found to be low and the biomass can be safely land-applied, this would provide a significant incentive for wastewater treatment plants to incorporate algae-based tertiary treatment to meet the new N and P targets while commercialising the produced algal biomass as fertilising products.

5.2.2. Horticulture effluents

The main contaminants of concern in horticulture effluents, not currently addressed by the FPR, are pesticides. These are commonly used in such systems to prevent production losses and are therefore present in the effluent utilised for microalgae cultivation.

The cultivation of various microalgae is considered a potential method for removing pesticides from wastewater. While some algae can degrade pesticides, bioaccumulation is often cited as the primary removal mechanism ([168];[169]), meaning the resulting biomass is likely to contain the pesticides or their degradation products.

Regarding algae-based EU fertilising products, the mere presence of pesticides is not inherently problematic under the FPR. Paragraph 3 of Part I of Annex III of the FPR states: "*Where the EU fertilising product contains a component material which, if placed on the market as food or feed, would have been subject to […] maximum residue levels set in accordance with Regulation (EC) No 396/2005 of*

([167]) Clagnan et al. (2022). Profiling microalgal cultures growing on municipal wastewater and fertilizer media in raceway photobioreactors. *Bioresource Technology.* https://doi.org/10.1016/j.biortech.2022.127619
([168]) Morais et al. (2022). Chapter 4 - Microalgae for bioremediation of pesticides: Overview, challenges, and future trends. In *Algal Biotechnology*. https://doi.org/10.1016/B978-0-323-90476-6.00010-8
([169]) Fayaz et al. (2024). Harnessing the potential of microalgae-based systems for mitigating pesticide pollution and its impact on their metabolism. *Journal of Environmental Management*. https://doi.org/10.1016/j.jenvman.2024.120723

the European Parliament and of the Council […] and that component material contains a substance in exceedance of (one of) the corresponding limit value(s), the maximum concentration of that substance in the EU fertilising product shall be indicated, together with a warning that the EU fertilising product must not be used in such a manner as to risk leading to the exceedance of that limit in food or feed."

Algae are therefore subject to maximum residue levels (MRLs) of pesticides as outlined in Regulation (EC) No 396/2005. If algae used in an EU fertilising product contain pesticide residues exceeding these MRLs, the concentration of the exceeding pesticide(s) must be indicated on the final product label.

Currently, there are no specific CEN methodologies for determining pesticides in algal biomass. However, since the FPR explicitly references Regulation 396/2005, which relates to food and feed, it is expected that the CEN standards applicable to food samples (CEN/TC 275) would also apply. Relevant standards for pesticide determination include CEN/TR 15641:2007, CEN/TR 16468:2013, CEN/TR 16699:2014, CEN/TS 17061:2019, and CEN/TS 17743:2022.

Horticulture effluents are produced under controlled conditions, making their monitoring relatively straightforward. To minimise analytical efforts and costs, only pesticides applied within the horticulture system should be analysed in the resulting biomass.

5.2.3. Aquaculture effluents

The main contaminants of concern in aquaculture effluents not covered by the FPR are antibiotics, which are frequently used in such systems to maintain fish health and are therefore present in the effluent used for microalgae cultivation. Some pesticides may also be applied in aquaculture to control the growth of certain aquatic plants or insects that could harm production. These are more common in pond and raceway systems and less likely to be used in Recirculating Aquaculture Systems. Consequently, the recommendations in section 5.2.2 on horticulture effluents may also be relevant for aquaculture effluents.

Several microalgae have demonstrated the ability to adsorb antibiotics onto their cell walls, thereby removing these compounds from the cultivation medium ([170]). Hence, if antibiotics are present in the aquaculture effluent, they are expected to accumulate in the resultant microalgal biomass. This phenomenon has yet to be studied for macroalgae; however, one study showed that powdered macroalgal

([170]) Frascaroli et al. (2024). Removal efficiencies of seven frequently detected antibiotics and related physiological responses in three microalgae species. *Environmental Science and Pollution Research*. https://doi.org/10.1007/s11356-024-32026-5

biomass could serve as an adsorbent for antibiotics ([171]), suggesting that their cell walls may similarly interact with and accumulate antibiotics in the biomass produced.

As with pesticides, the presence of antibiotics is not currently regulated under the FPR and is only subject to the labelling requirements outlined in section 5.2.2, pursuant to Paragraph 3 of Part I of Annex III of the FPR. In this context, the relevant legislation for antibiotic residues in foodstuffs is Regulation (EC) No 470/2009. While algae are explicitly mentioned in Regulation (EC) No 396/2005 concerning pesticides, they are not referenced in Regulation (EC) No 470/2009, as antibiotics are expected only in products of animal origin. Consequently, an amendment to Paragraph 3 of Part I of Annex III of the FPR is necessary to clarify that it also covers algal products cultivated in animal-derived effluents such as manure-based digestate and aquaculture effluents. Alternatively, Regulation (EU) 2024/1229, which establishes specific maximum levels for cross-contamination of antimicrobial active substances in non-target feed, may be used as a reference for determining acceptable limits for algae.

Currently, there are no standardised methods for determining antibiotics in algal biomass. Nevertheless, in 2024, the JRC published a method for detecting 24 antibiotics at trace levels in animal feed by high-performance liquid chromatography ([172]), which should be applicable to algal biomass. Regulation (EU) 2024/1229 also mentions acceptable analytical methods for each antibiotic. As with horticulture effluents, aquaculture effluents are produced under controlled conditions, facilitating monitoring. To minimise analytical effort and costs, only antibiotics used in the aquaculture system should be analysed in the produced biomass.

Finally, selenium may be added to fish feed to improve algae health, and algae have been shown to bioaccumulate this element when cultivated in selenium-rich aquaculture effluent ([173]). Selenium can have beneficial effects on plant production when dosed correctly; however, excessive amounts may be harmful to crops. Therefore, it is important that selenium content is clearly disclosed on the fertiliser product label. Selenium is already mentioned in the FPR but only regarding CMC 15 (high-purity materials). An amendment to Paragraph 7b of Part I of Annex III should clarify that selenium content must also be indicated on the label if the EU fertilising product contains algae cultivated in aquaculture effluent from fish fed with selenium (CMC 2).

([171]) Khamayseh and Kidak (2024). Biosorption of reactive amoxicillin antibiotic on Pithophora macroalgae in aqueous solution: Equilibrium and kinetic studies. *Desalination and Water Treatment.* https://doi.org/10.1016/j.dwt.2024.100669
([172]) Vincent et al. (2024). Determination of 24 antibiotics at trace levels in animal feed by high performance liquid chromatography. Available here.
([173]) Han et al. (2020). Bioremediation of Aquaculture Wastewater with Algal-Bacterial Biofilm Combined with the Production of Selenium Rich Biofertilizer. *Water.* https://doi.org/10.3390/w12072071

Although there are currently no CEN standards for selenium analysis in fertilisers, commonly used elemental analysis methods may be applicable for determining selenium, provided the user verifies their suitability. Relevant CEN Technical Specifications include CEN/TS 17768:2022 and CEN/TS 17770:2022. Additionally, ISO standards exist for selenium analysis in other matrices such as soil, treated biowaste, sludge, and waste – namely ISO 16729:2013, ISO 54321:2020, and ISO 22036:2024. These methods can therefore serve as a foundation for developing a standardised method for selenium detection in fertilising products, including both high-purity materials and algae.

5.2.4. Manure-based digestate

Both processed manure and manure-based digestate are accepted as CMCs in the FPR. Therefore, as argued in Chapter 4, microalgae grown on manure-based digestate should also be accepted as a CMC (within CMC 2), since the cultivation of algae in this stream is not expected to produce biomass with an increased risk compared to the original feedstock.

Microalgae can accumulate certain compounds, such as antibiotics, which, as mentioned above, may be present in both manure and digestates ([174]). Consequently, if antibiotics are used during the animal husbandry activities of a farm supplying manure for algae cultivation, it is recommended to analyse the algal biomass for residues of these antibiotics, as advised in section 5.2.3.

5.2.5. Organic pollutants and pathogens pertinent to all effluents

Besides the contaminants specific to each effluent, a key overall concern when using such streams for algae cultivation is the presence of pathogens. Within the FPR, only *Salmonella* spp., *Escherichia coli*, and enterococci have defined limits, while several of the proposed water sources are known to harbour other pathogens of concern. Therefore, it is recommended to always install a disinfection system – such as ozonation, chlorination, UV radiation, or pressure sterilisation, among other technologies – before feeding the effluents into the algae system to reduce any risk of pathogen propagation.

Finally, the emerging contaminants listed below are expected to be present in all effluents, as they have been detected in water, soil, and air samples from various locations. Although not directly regulated by the FPR, they should also be monitored, since Paragraph 3 of Part I of Annex III of the FPR indicates that

([174]) Spielmeyer (2018). Occurrence and fate of antibiotics in manure during manure treatments: A short review. *Sustainable Chemistry and Pharmacy*. https://doi.org/10.1016/j.scp.2018.06.004

contaminants relevant to food and feed according to Regulation (EU) 2023/915 should also be mentioned in the labelling of EU fertilising products.

Dioxins and PCBs

Land-based aquaculture systems seem to result in lower concentrations of dioxins in farmed fish than in wild-caught fish ([175]), indicating that aquaculture – and possibly horticulture systems – might result in low levels of dioxin in the produced algae. Conversely, the presence of such contaminants in sewage sludge has been confirmed by various studies, and thus they are expected to be found in algae grown on untreated urban wastewater. Nevertheless, a JRC study ([176]) indicated that there was no environmental threat from dioxin accumulation when sewage sludge and manure were applied to fields over 39 years, suggesting these compounds were mainly deposited from the air. Therefore, dioxins might not pose significant concern for the land application of algae biomass grown on such streams.

Dioxin-like substances are already addressed in the FPR for thermal oxidation materials (CMC 13), pyrolysis and gasification materials (CMC 14), and high-purity materials (CMC 15). For all these CMCs, the maximum acceptable level is 20 ng WHO toxicity equivalents per kg dry matter of polychlorinated dibenzo-para-dioxins and dibenzofurans.

Currently, no CEN standard is in force for measuring dioxins in food, feed, or fertilisers. However, an ISO standard exists for soil, treated biowaste, and sludge (ISO 13914:2023).

Perfluoroalkyl substances (PFAS)

PFAS are widespread throughout European waters ([177]) and, therefore, are expected to be found in the evaluated effluents. PFAS accumulation in algae is not well documented, but one study suggested that some PFAS might accumulate in the cells while others might be metabolised ([178]). Therefore, when grown in waters contaminated with PFAS, the end-product might also be contaminated. It is recommended that the presence of PFAS is evaluated in the influent water of aquaculture and horticulture effluents and, if present, a filter should be installed to remove the possibility of contaminating the produced

([175]) FAO/WHO background document on the risks and benefits of fish consumption. Available here.
([176]) Umlauf et al. (2011). PCDD/F and dioxin-like PCB profiles in soils amended with sewage sludge, compost, farmyard manure, and mineral fertilizer since 1962. *Environmental Science and Pollution Research*. https://doi.org/10.1007/s11356-010-0389-9
([177]) PFAS pollution in European waters. Available here.
([178]) Marchetto et al. (2021). Bioremediation of Per- and Poly-Fluoroalkyl Substances (PFAS) by Synechocystis sp. PCC 6803: A Chassis for a Synthetic Biology Approach. *Life.* https://doi.org/10.3390/life11121300

fish/crops, therefore eliminating the possibility of contamination of the algae production step.

Regarding urban wastewaters, the new Urban Wastewater Treatment Directive highlights PFAS as a source of concern. As noted, it remains unclear whether algae grown on untreated wastewater would accumulate PFAS, and further studies are needed on this subject. If algae are cultivated in treated urban wastewaters, then the use of filters to remove PFAS prior to feeding the algae system would ensure that no contamination is present in the biomass.

Finally, monitoring PFAs in manure also requires further effort; however, there is evidence suggesting that urban environments have higher contamination levels than rural ones, with animal manures showing a low presence of PFAS ([179]), indicating that PFAS might not be of concern when growing algae on manure-based digestate.

PFAS monitoring tools are still being developed. Currently, there is one CEN standard for the determination of PFAS on sediment, soil, sludge, and waste under development (CEN/TC 444) and an ISO for the quantification of PFAS in water (ISO 21675:2019).

Polycyclic aromatic hydrocarbons (PAHs)

PAHs are organic compounds of both natural and anthropogenic origin and are associated with incomplete combustion. They are considered recalcitrant, and many exhibit toxic properties. PAHs are already addressed in the FPR for compost (CMC 3), digestate other than fresh crop (CMC 5), processed manure (CMC 10), precipitated phosphate salts (CMC 12), thermal oxidation materials (CMC 13), pyrolysis and gasification materials (CMC 14), and high-purity materials (CMC 15). For all these CMCs, the maximum acceptable level is 6 mg/kg dry matter of PAH_{16}.

While PHAs can be accumulated in algae, there is strong evidence that they are mainly degraded into other compounds ([180]), which may result in lower final concentrations of PAHs in the produced algal biomass. This should be further verified and, if confirmed, monitoring such contaminants in algae fertilising products would not be necessary. However, if relevant concentrations of PAHs are detected, the 6 mg/kg dry matter limit of PAH16 should be extended to CMC 2 when algae products are considered.

([179]) Munoz et al. (2021). Target and Nontarget Screening of PFAS in Biosolids, Composts, and Other Organic Waste Products for Land Application in France. *Environmental Science & Technology*. https://doi.org/10.1021/acs.est.1c03697
([180]) Mou et al. (2023). Biodegradation mechanisms of polycyclic aromatic hydrocarbons: Combination of instrumental analysis and theoretical calculation. *Chemosphere.* https://doi.org/10.1016/j.chemosphere.2023.140017

Currently, a CEN standard is being drafted for the analysis of PAHs in sediment, soil, sludge, and waste (CEN/TC 444), which could also potentially be applied to algae samples intended for use as fertilising products.

Microplastics

Microplastics are ubiquitously present and represent a growing concern within the EU. However, there is currently no comprehensive EU legislation specifically regulating microplastics ([181]). Nevertheless, the FPR regulates plastic impurities larger than 2 mm, which can be considered microplastics (< 5 mm).

The interaction between algae and microplastics requires further study, but evidence suggests it depends on both the algae species and the type of plastic. Some macroalgae can adsorb and accumulate microplastics, while certain microalgae have been shown to aid in their degradation ([182]). For plastic impurities currently regulated by the FPR, a washing step for macroalgae and a separation step for microalgae could be performed if necessary. However, smaller plastic particles are also expected to be widely present, and these are more challenging to separate from microalgae when they are similar in size to individual cells.

At present, no legislation sets limits on such small microplastics that could serve as a basis for their inclusion in the FPR, so further research is generally required on these contaminants. For algae systems, it may be more practical to monitor and regulate the amount of microplastics entering the system (and to install filters for their removal if necessary), as quantifying microplastics in organic matrices is more complex than in aqueous samples. Regarding water samples, two CEN standards are currently under evaluation: prEN ISO 16094-2 and prEN ISO 16094-2, developed by CEN/TC 230.

([181]) European Commission (n.d.). Microplastics. Available here.
([182]) Jiang et al. (2024). The role of algae in regulating the fate of microplastics: A review for processes, mechanisms, and influencing factors. *Science of The Total Environment*. https://doi.org/10.1016/j.scitotenv.2024.175227

6. Roadmap for simultaneous wastewater treatment and fertilisers/ biostimulants production from algae

6.1. Objectives

This roadmap aims to guide stakeholders interested in producing algae-based fertilising products from wastewaters/effluents or from macroalgae grown on eutrophicated open waters. It presents the current situation for this technology, highlighting challenges and opportunities when combining the two approaches. It also summarises the main economic and environmental aspects of the technology, and brings research gaps that need to be addressed to support its further development.

Finally, it also presents a summary of the main policy recommendations outlined in the previous chapters, along with a summary table (Table 13) with recommended species, their nutrient removal potential from the target effluents, and the main challenges when producing fertiliser from the algal biomass grown on such effluents/waters.

6.2. Situation analysis

As shown in this study, algae have potential for integration with effluent-generating industries, promoting nutrient recovery and biomass generation for the Blue Bioeconomy. However, the system volumes and land requirements needed to effectively treat these effluents are often substantial, which will entail significant capital and operational costs.

Moreover, creating value from the produced algae is an essential condition for the implementation of these technologies. When using effluents for algae cultivation, fertilising products present a viable option with fewer legal constraints. Nevertheless, the legal framework could be amended to further encourage such use.

Macroalgae growth on eutrophicated open waters could also contribute to nutrient recycling and the production of more sustainable fertilising products, but a lack of data and legal barriers present important challenges for further implementation.

These aspects and others are further presented as two SWOT analyses in Figure 5 and Figure 6 to better illustrate the current potential and challenges of growing algae on wastewater/effluents/eutrophicated waters for obtaining fertilising products.

Figure 5 – SWOT analysis for growing algae in wastewater/effluents and processing the biomass into algae-based fertilising products

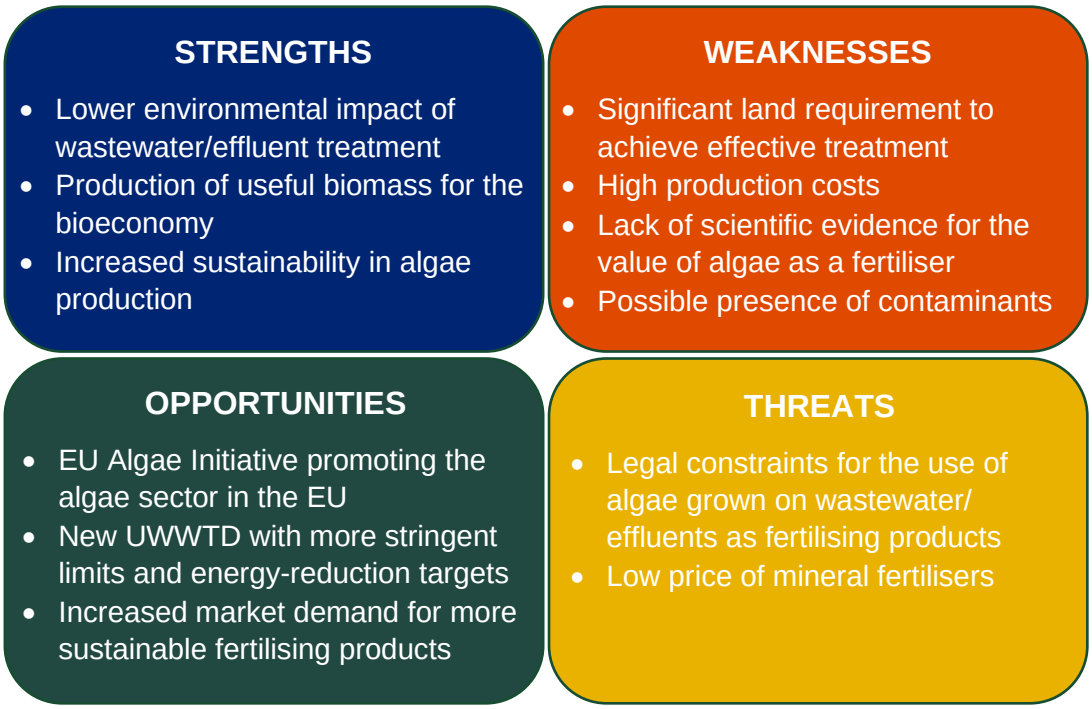
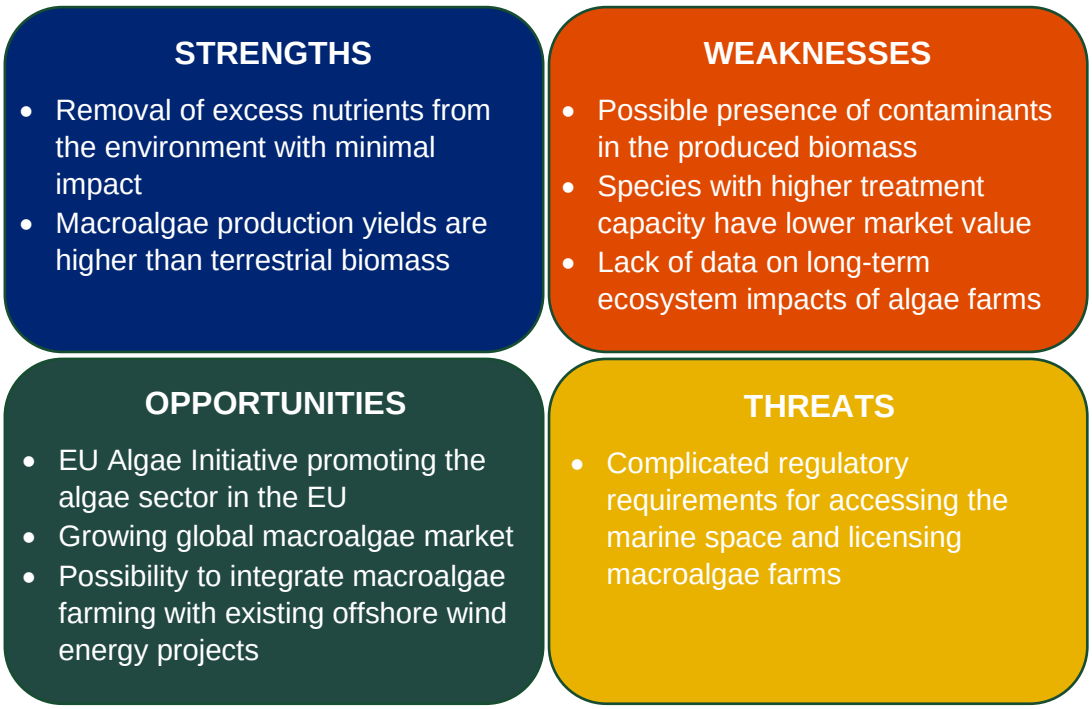


Figure 6 – SWOT analysis for growing macroalgae in eutrophicated open waters



6.3. Business case and economic assessment

For the integration of algae production and effluent treatment, two scenarios are possible: (i) the algae system is installed in-house by the effluent generator, or (ii) an algae facility run by a third party is installed near the effluent generator and receives their effluent for treatment with their algae system.

When option (ii) is considered, different business models can be applied:

1. The “effluent generator” pays a gate fee to the algae facility for treating its effluent – this fee should be lower than the current cost of effluent treatment, while also generating revenue for the algae facility;
2. The “effluent generator” supplies the nutrient-rich stream free of charge, thereby avoiding treatment obligations;
3. The “effluent generator” charges the algae facility a fee for the nutrient stream – this fee should remain below the cost of commercial mineral media used in algae cultivation.

The choice between the various scenarios will depend on the economic feasibility of the algae production process, which will be highly dependent on the market value of the produced biomass. Scenario 1 is more likely if the cost of algae production is not compensated by its market value, while scenario 3 would be implemented if the algae product is highly profitable, and the source of nutrients is highly desirable for the algae system.

The use of an algae system for the treatment of the effluents highlighted in this report (enumerated in Table 13) is still under development and, therefore, reliable economic assessments for this technology are not currently available. However, the integration of algae with urban wastewater systems has been more thoroughly investigated and implemented at more relevant scales, and a few preliminary conclusions on its economic feasibility are presented in section 1.5 of this report and summarized here:

- Algae-based treatment is currently more expensive than conventional treatments due to its early development stage;
- Algae-based treatment requires much more land, which will also have an impact on its cost;
- For small agglomerations (200–15,000 p.e.y.), algae-based treatment can be more competitive than the conventional treatment due to reduced CAPEX/OPEX, simpler operation, and reduced energy use compared to small-scale conventional plants;
- Raceway ponds are more suitable for wastewater treatment due to their lower CAPEX and OPEX;

- Biomass valorisation is key to offsetting the costs of algae-based treatments.

Regarding fertilising production, the use of algae as biostimulants appears to be the most attractive option, as the yield of biostimulants per mass of algae is more favourable than that of fertilisers, and such products command a higher market price.

Finally, the economic viability of a macroalgae farm for treating eutrophicated open waters cannot be currently ascertain due to lack of relevant data and the difficulty in assigning a cost to the nutrient removal from such waters. Nevertheless, as for the treatment of wastewaters/effluents, the financial viability of such an endeavour will highly depend on the quality of the produced biomass and its market value. The production of biostimulants appears as an interesting possibility from this biomass due to the growing market demand for such products.

6.4. Environmental assessment

As for the economic analysis, the low maturity of algae systems for treating effluents results in the lack of reliable environmental assessments. Nevertheless, more robust data exists for the urban wastewater treatment scenario, and some conclusions can already be made from the existing data (further analysed in section 1.5):

- Well-optimised algal treatment systems can reduce net energy consumption and emissions compared to conventional treatment plants;
- The integration of algae into treatment processes can significantly reduce nutrient levels in the discharged effluent, reducing eutrophication risks;
- If the algal biomass is used as a slow-release fertiliser, it can substitute for synthetic alternatives, which are produced in highly energy-intensive and polluting processes. By displacing a portion of them, the algae-based system can earn an environmental credit;
- Land occupation is a significant bottleneck for algae-based treatment systems, and it may be considered within impact categories such as “land use change” or biodiversity impact.

Regarding the use of algae biomass as a fertiliser, some conflicting results are presented in the few studies conducted at a relevant scale (further analysed in Chapter 3):

- Microalgae fertilisers have slow-release properties, potentially reducing the risk of eutrophication and groundwater pollution, as they have been shown to reduce nitrogen and phosphorus leaching while enhancing soil fertility;
- However, increased emissions of N_2O and CO_2 following the application of microalgae fertiliser have been recorded due to soil microbial activity during the decomposition of organic matter, particularly under conditions of high moisture and temperature.

Finally, as highlighted in Figure 6, there is a lack of data on the environmental impact of establishing off-shore macroalgae farms. On the one hand, the nutrient removal from eutrophicated waters is an obvious gain but the long-term ecosystem impacts are not known and could potentially offset the benefits.

6.5. Research and innovation priorities

As presented in the previous sections, data availability is scarce at a relevant scale to truly assess the potential economic and environmental gains of using algae for wastewater/effluent use and applying the produced biomass as fertilising products. Therefore, the following research and innovation priorities are recommended:

1. **Pilot/full-scale studies on growing algae on effluents**
   (a) Key parameters regarding algae cultivation at higher TRL (enumerated below) should be clearly reported when conducting these experiments.
      — Algae productivity in g/L/d
      — N and P uptake in g/g_{algae} or g/L/d
      — Area footprint of the used reactor in m^2/L
   (b) Algae biomass should be characterized for contaminants to provide relevant data for making decisions on their suitability for different applications.
2. **Developing/optimising novel types of microalgae reactors**. One key outcome was the significant land requirement of algae-based effluent treatment, primarily due to the need for large surface areas to capture sufficient sunlight for photosynthesis - unlike traditional wastewater treatments that rely on compact, enclosed systems, so the development of novel reactors with a lower area footprint would improve the adoption of this technology.

3. **Assessing the suitability of algae as a fertiliser in field trials.** These should focus not only on their nutrient replacement value when compared to mineral fertilisers, but also on the technical feasibility of their application (as powders are not compatible with the current existing machinery) and their economic feasibility.

4. **Expanding the reference data on nutrient uptake across different environments and region-specific macroalgae species**. This is especially important for nutrient-rich (eutrophicated) coastal regions, where macroalgae cultivation could serve a dual role in both biomass production and nutrient removal, although current assessments still rely largely on modelling estimates. In addition to fertiliser use, future research should explore other processing options to enable broader applications of macroalgae grown on eutrophicated waters.

5. **Studying the potential ecosystem impact when establishing large-scale macroalgae farms in open waters.**

6.6. Policy recommendations

Recommendations for better integrating the production of **algae-based fertilising products and wastewater treatment** include:

1. Introducing tax incentives and/or allocating funding at the Member State level to support the development of industrial symbiosis initiatives, thereby promoting greater sustainability and accelerating the growth of the European algae industry.

2. Ensuring the proper adoption of algae grown on wastewaters in the legal framework of the EU via the existing or creation of a new interservice group with representatives from the JRC, DG RTD, DG ENV, DG MARE, DG AGRI and DG GROW (and possibly others depending on the target end-use of the produced algae). This service could look at opportunities to further integrate the growth of algae in wastewaters into the existing legislation, using the recommendations below as a starting point, and highlight the research needs that should be prioritised to assess the potential risks of this inclusion.

3. Conducting an evaluation on whether the production process of biostimulants from microalgae can mitigate the risks associated with their cultivation on urban wastewaters. If that is the case, leaf-applied biostimulants from this biomass could be included in an amended version of the Sewage Sludge Directive to enable such application in national markets. This could eventually be expanded to the Fertilising Product Regulation (European market).

4. Regarding algae grown on treated urban wastewater, Member States could consider using the minimum requirements described in Section 2 of Annex I of the Water Reuse Regulation to inform their decisions to allow the use of reclaimed water for algae cultivation.

5. The Fertilising Product Regulation could be amended to add to CMC 2 a list of accepted growing media for algae cultivation, including treated urban wastewater (reclaimed water), aquaculture effluent, horticulture effluent, and digestate (following the requirements of CMCs 4 and 5). The list should be open for further amendments upon new evidence of suitable recycled nutrients for algae cultivation. Moreover, a clarification in the FAQ of the Fertilising Product Regulation could be included that such biomass is also eligible as input for CMC 1. Alternatively, a new CMC could be created for algae, including all the abovementioned requirements and clarifications.

6. Cyanobacteria species allowed for human consumption under the Novel Food status catalogue should be considered for inclusion in the Fertilising Product Regulation.

Recommendations for advancing **macroalgae aquaculture** in the Baltic Sea include:

1. Improving macroalgae cultivation methods and infrastructure. This requires the development of site-specific guidelines that optimise farm location selection by considering salinity gradients, nutrient availability, and hydrodynamic conditions.

2. Establishing a standardised monitoring framework for assessing nutrient assimilation efficiency and the long-term ecosystem impacts of macroalgae farms.

3. Strengthening regional value chains and promoting macroalgae-derived products. Additionally, industry-academia partnerships can facilitate scaling up pilot projects and attract investment into sustainable macroalgae aquacultures.

4. Regulatory and policy barriers could be reduced by facilitating access to marine space and licensing for macroalgae farms.

Table 13 – Summary of main information contained in the previous chapters

Effluent	Algae	Implementation	Estimated nutrient recovery potential		Potential contaminants[f]	Legal constraints
Horticulture	*Chlorella*[a], *Scenedesmacea*[b]	Possible to implement in the hydroponics facility	0.05	gN/L/d	Pesticides, pathogens[g]	Unclear status in the FPR
			0.005	gP/L/d[d]		
			0.8	gCO_2/L/d[e]		
Aquaculture	*Chlorella*[a], *Scenedesmacea*[b] *Isochrysis galbana*	Large volumes required, best to implement as industrial symbiosis with an external algae producer	0.05	gN/L/d	Antibiotics, pathogens[g]	Unclear status in the FPR
			0.005	gP/L/d[d]		
			0.8	gCO_2/L/d[e]		
	Ulva sp.		0.8	$gN/m^2/d$		
			0.03	$gP/m^2/d$[d]		
			30	$gCO_2/m^2/d$		
Manure-based digestate	*Chlorella*[a], *Scenedesmacea*[b]	Large volumes required, best to implement as industrial symbiosis with an external algae producer	0.04	gN/L/d	Antibiotics, pathogens[g]	Unclear status in the FPR
			0.004	gP/L/d[d]		
			0.7	gCO_2/L/d[e]		
Urban wastewater	(*Chlorella*[a], *Scenedesmacea*[b])[c]	Currently better-suited for locations with smaller populations and adequate weather; only economic if biomass can be sold as a product	0.02	gN/L/d	Heavy metals, antibiotics, hormones, pharmaceuticals, pathogens[g]	Algae grown in untreated wastewater falls under sewage sludge; it is unclear if using treated wastewater would change this
			0.002	gP/L/d[d]		
			0.4	gCO_2/L/d[e]		
Eutrophicated waters	*Saccharina latissimi, Ulva intestinali, Fucus vesiculosus*	Economic and environmental potential exists, especially when associated with other species in IMTAs	150	kgN/km^2	None	Bureaucratic licensing and permitting for large-scale farms
			30	kgP/km^2		
			11	$tonCO_2/km^2$		
Chapters with more information	Chapter 1; Chapter 2 (eutrophicated waters)				Chapter 5	Chapter 4

[a] The most commonly used species are *Chlorella vulgaris* and *Chlorella sorokiniana*; [b] The most commonly used genera are *Scenedesmus* and *Tetradesmus*; [c] These species are frequently used in studies. However, communications with Aqualia, a company implementing this technology in Spain, indicated that local permits only allow the cultivation of indigenous algae from the locality; [d] P may need to be added to the effluents to balance the N/P ratio in the medium so that, if managed correctly, all P will be removed by the end of the process; [e] It is important to note that many current algae systems are net CO_2 emitters due to their high energy demand; [f] This excludes emerging ones; [g] To reduce risks with pathogens, a disinfection step before the algae cultivation is recommended for all effluents.

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