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# Microalgae and circular economy: unlocking waste to resource pathways for sustainable development

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## ABSTRACT

The growing environmental crises demands an urgent transition from a linear to a circular economy. Microalgae are photosynthetic microorganisms that offer exceptional potential due to their rapid growth, high CO<sub>2</sub> fixation capacity, and ability to remove nutrients and pollutants from wastewater, producing both clean water and valuable biomass. Such characteristics have attracted interest in developing circular systems that transform wastes into resources such as biomaterials, biofertilisers, biofuels and bioactive compounds. However, various challenges hinder their industrial application, including technical, economic, environmental, commercial and political barriers. Technical limitations such as inefficient culture systems, low productivity and contamination risks, can be addressed by using genetic engineering tools to develop superior strains, and by developing bioreactors coupled with emerging technologies (AI, Digital Twin). Additionally, it was found that studies using wastewater for microalgae cultivation and a biorefinery approach to recover low and high value bioproducts were found to be energetically, environmentally and economically viable. Several projects and studies demonstrating microalgae-based circular economy models were highlighted. Finally, the implementation of clear regulations and guidelines for wastewater composition in microalgae systems is recommended to facilitate market acceptance and consumer trust in microalgae-derived products.

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## 1. Introduction

### 1.1. Circular economy and key concepts

Living in modern society means living in a world where population growth and overconsumption stimulate a linear take-make-use-waste pattern without taking into consideration the limited resources that nature provides us. The most recent data indicates that 92.8% of the world's economy remains linear, relying mainly on virgin materials (Fraser, Conde, and Haigh 2024). Since 1970, global resource extraction has tripled, and statistics expect that it increases more 70% by 2050. A similar increase is expected for residue generation (United Nations Environment Programme 2021). As a result, concern has grown in the past decades about the depletion of natural resources, the accumulation of waste and pollution, the loss of biodiversity, climate change and other environmental impacts.

In 2024, humanity depleted natural resources on August 1, also known as Earth Overshoot Day, meaning that since then, until the end of the year, the world has been living in debt, compromising the needs of future generations (Kristensen and Mosgaard 2020; Lamba, Kumar, and Dhir 2023). Therefore, the linear economy has become an unsustainable practice, and the circular economy has been gaining momentum as a potential answer (Velenturf and Purnell 2021).

Circular economy is considered as an umbrella concept since it encompasses a multiplicity of concepts (Corvellec,

Stowell, and Johansson 2022). By analysing the term, Fogarassy and Finger (2020) clarified that the term 'circular' does not refer to increasing recycling, as many researchers believe, but rather to an environmental cycle that reflects the natural function of an ecosystem, and so, the economy should function accordingly. The most commonly used definition, proposed by the Ellen MacArthur Foundation in 2013 is as follows: 'The circular economy refers to an industrial economy that is restorative by intention; aims to rely on renewable energy; minimises, tracks, and eliminates the use of toxic chemicals; and eradicates waste through careful design' (MacArthur 2013). Nevertheless, Kirchherr et al. (2023) notes that there are hundreds of definitions of circular economy, and it is predicted to constantly evolve alongside technology, economy, politics, social behaviour and environmental health. The core principles are where these definitions diverge the most. For instance, many authors omit some Rs principles such as reduce or recover, others focus on improving recycling rates rather than calling for a paradigm shift, and even exclude technical and biological cycles, which are of highly relevant in the Ellen MacArthur Foundation's framework. Divergences in purpose strongly influence how the circular economy is viewed as contributing to sustainability, environment and economy. Finally, there was no concordance on who should be responsible for achieving this model. Businesses and consumers were the main focus, but more recently policymakers and academia

also shared responsibility. The need for new business models and a strong technological component were rarely mentioned despite their emerging relevance (Kirchherr et al. 2023).

Kirchherr, Reike, and Hekkert (2017) drafted a meta-definition, after analysing these various definitions which is as follows: ‘The circular economy is a regenerative economic system which necessitates a paradigm shift to replace the “end of life” concept with reducing, alternatively reusing, recycling, and recovering materials throughout the supply chain, with the aim to promote value maintenance and sustainable development, creating environmental quality, economic development, and social equity, to the benefit of current and future generations. It is allowed by an alliance of stakeholders (industry, consumers, policymakers, academia) and their technological innovations and capabilities’.

The main goal of the circular economy is to maximise economic growth while minimising resource consumption. This is achieved by following three principles: eliminating waste and pollution generation, extending the life of materials or products for as long as feasible, and regenerating nature. To uphold these principles, stakeholders should rethink products’ design and adopt ‘R’ principles, among them, the use of renewable resources and regenerative practices (Kristensen and Mosgaard 2020; Lamba, Kumar, and Dhir 2023). The implementation of these principles relies not only on practices and strategies, but also on policies and technologies. The European Commission has encouraged the implementation of the circular economy through the Circular Economy Action Plan, first announced in December 2015 (European Commission n.d.). This report focuses on the transition towards a circular economy and identifies different actions, prioritising critical topics such as plastics, food waste, feedstock, construction and demolition, biomass, and bio-based products (Rodriguez-Anton et al. 2019). In March 2020, a new Circular Economy Action Plan was adopted with the main objective of reducing the demand for natural resources and fostering jobs and sustainable growth. The action plan focuses on the entire life cycle of a product, from design to sustainable processing, encouraging conscious consumption, circular use of resources, and waste prevention (European Commission Directorate General for Communication 2020).

As efforts to move towards a circular economy increase, implications in terms of sustainability need to be addressed to understand the role that circular practices can play in achieving sustainable objectives.

### 1.2. Circular economy and sustainability

The United Nations Brundtland Commission of 1987 defined sustainability as ‘meeting the needs of the present without compromising the ability of future generations to meet their own needs’. Sustainable development is an essential practice that preserves a balance between economic growth, environmental protection, and society. In 2015, the United Nations established a list of 17 Sustainable Development Goals (SDGs) to promote sustainable development. These goals are to be achieved within 15 years and serve as a call to action for all members to provide peace, prosperity, and health for both the

current and future generations (Olabi et al. 2023; United Nations 2015).

Many experts suggest that the concept of circular economy is closely linked to that of sustainability, although there is no consensus on the exact nature of this relationship. Circular economy shares many of the same objectives as sustainability and is a key strategy for achieving it. This is accomplished by reducing waste and pollution, conserving resources, regenerating nature, promoting sustainable growth, and reducing Green House Gas (GHG) emissions. Moreover, it cannot be denied that the circular economy is significantly correlated with most of the SDGs, and is essential for achieving them (Rodriguez-Anton et al. 2019; United Nations 2015).

However, as the circular economy lacks a clear definition, the two concepts have recently been considered desegregated (Velenturf and Purnell 2021). Kristensen and Mosgaard (2020) recognises that a circular economy can promote a healthier earth and improve the quality of life for people. However, it is important to note that a circular economy often prioritises economic growth over environmental and social aspects. It is crucial to equalise these factors to better align with sustainable development, which means improving environmental and social matters. A better understanding of the inconsistencies between theoretical ideals and practical realities can lead to accurate and viable models for the whole circular economy paradigm.

### 1.3. Contentious issues within the circular economy

In addition to the vague concept of circular economy and its uncertain relationship to sustainability, there are other controversial topics surrounding its implementation that require further study and debate.

One of the main criticisms of the circular economy is that it disregards Lavoisier’s law, which states that, ‘nothing is neither created nor destroyed, but only converted and dissipated’. This means that the circular economy suggests an impossible scenario, since a closed material loop creates dissipation and entropy, which are associated with physical losses or by-products and loss of quality. Therefore, it is necessary to supply the loop with energy and new materials in order to overcome these losses, and, thus, an economy 100% circular is, in fact, impossible (Corvellec, Stowell, and Johansson 2022).

From another perspective, there are controversies associated with the material properties of a given product and its manufacturing process. In practical terms, dissipation, contamination, and material wear can limit the closure of the loop in the circular economy. One limitation is associated with the concept of using waste as a resource, and the necessary decontamination process, which requires a significant supply of energy or the addition of more components, going against the sustainable circular economy principles (Johansson, Velis, and Corvellec 2020). At the policy implementation level, there is a lack of flexibility in the waste sector, which limits the possibility to change circumstances to improve waste management due to economic losses and resistance to legislative changes. For companies, there are obstacles to the adoption of circular practices, including lack of technical support, high initial costs, uncertain returns and social obstacles such as

inflexibility of consumer behaviour (Corvellec, Stowell, and Johansson 2022). In this context, there is a need for more coherence in the concept, practices, and implementation of the circular economy, to prevent it from going beyond sustainability.

#### 1.4. Environmental challenges and potential circular solutions

Unsustainable resource extraction and processing are responsible for more than 90% of biodiversity loss, half of the total GHG emissions and the current water scarcity. In addition, the overshoot of 5 out of 9 planetary boundaries resulting from the linear economy is concerning due to its major impact on environmental health. These include: climate change, chemical pollution and release of novel entities, biogeochemical flows (nitrogen and phosphorus), land-system change and, lastly, biodiversity loss (Fraser, Haigh, and Soria 2023). Human activities, such as the excessive usage of fossil fuels that release GHG into the atmosphere (CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>2</sub>), industrial waste discharges containing pollutants and toxic components (Persistent Organic Pollutants (POPs), Polycyclic Aromatic Hydrocarbons (PAHs), heavy metals), the use of pesticides, fertilisers and antibiotics in agricultural activities, and the overconsumption of plastic have led to overstepping of environmental boundaries (Ukaogo, Ewuzie, and Onwuka 2020).

To address these environmental challenges, a multidisciplinary approach is crucial, where science, technology, governments, industry, and citizens must team up and take action. It is essential to implement sustainable waste management solutions, pollution mitigation technologies, alternative green energy sources, and the application of strict policies and regulations regarding waste discharge and pollution.

Nowadays, circular business models already include a waste-to-resource philosophy, where waste from one industry is then repurposed as a resource for another, reducing waste disposal and adding value to waste. For example, rice biowaste can be converted into biofuels through the use of microbial cultures (Gupte et al. 2022). Remediation methods to mitigate air, water and land pollution are also being developed and applied. Different chemical, physical and biological methods are used to remove pollutants from the environment. Bioremediation is particularly aligned with the concept of a sustainable circular economy, as it allows for the valorisation of the resulting biomass as an input for various industrial applications. For instance, bacteria, plants, algae, microalgae or consortia have the potential to effectively remove phosphates, nitrates, toxic heavy metals like Hg, Cd, Pb, Cr, and antibiotics from wastewater (Amaral et al. 2023). They can also eliminate organic contaminants like pharmaceuticals, endocrine disruptors, surfactants, gasoline additives, organometallic compounds, brominated flame retardants and organophosphates, as well as plastics and microplastics (Amaral et al. 2023; Kumari et al. 2020; Sodhi et al. 2022). These bioremediation strategies are also promising to mitigate air pollution, focusing on the reduction of carbon dioxide and monoxide, sulphur oxides, nitrogen oxides, volatile organic compounds (VOCs) and PAHs. Microalgae are advantageous for performing bioremediation

within a sustainable circular economy framework due to the potential for the removal of a wide range of pollutants and bioproduct recovery in a biorefinery approach. This allows the entire biomass to be used for recovering low- and high-value resources with the aim of achieving zero-waste, making the process economically and environmentally viable (Abdelfattah et al. 2023).

#### 1.5. Research gap

Solving the emergent environmental crisis demands innovative and systemic solutions. This review article intends to understand in depth the concept of circular economy, its theoretical foundations and practical applications, but also how microalgae can contribute to a transition from a linear economy to a circular and sustainable economy. Based on recent scientific literature, market evaluation and current policies, it aims to identify barriers and limitations from a holistic perspective that prevent the achievement of full circularity. By exploring these multiple concepts and factors, this study analyses practical strategies for using wastes as inputs for microalgae cultivation and for the production of renewable resources, while also addressing current limitations, policy gaps, environmental analysis and finally providing recommendations to promote circularity.

## 2. Methods

To do so, bibliographical research was performed with the data extraction of selected articles variables from reliable databases to minimise possible bias. These comprehensive databases were Google Scholar, Scopus, Web of Science, Science Database and PubMed. The bibliographic search was performed using relevant key words strongly linked to the subject under review, including [circular economy], [circular strategies], [microalgae], [sustainability], [wastewater], [wastes], [bioremediation], [waste-to-resource], [bioproducts], [biofuel], etc. The research papers analysed were selected by excluding those in languages other than English or other than between 2017 and 2025, and by screening for significant titles and abstracts. Then, the selected articles were read in full and carefully analysed as they were found the most relevant for the different topics under discussion. Additionally, relevant websites, reports and documents from governmental and international organisations were included to provide broader context.

## 3. Circular economy strategies

According to the Circularity Gap Report (2023), the circular economy represents merely 7.2% of the global economy. This indicates that the global economy relies heavily on virgin materials and produces far too much waste (Geisendorf and Pietrulla 2018; MacArthur 2013).

To stimulate the implementation of circular strategies, it is important to consider all the stakeholders and their interests. Well-defined circular business models, environmental and technological strategies (such as R's framework, industry 4.0 and 5.0, and waste-to-resource systems), circular innovations,

changes in consumer behaviour, social acceptance and new policies should be implemented, as will be discussed in the following sections (European Commission Directorate General for Communication 2020).

### 3.1. Circular business models

From a business point of view, circular business models seem to be the most viable option for ensuring an economic stability in the face of impending resource scarcity. Creating value and capturing material and energy flows in a closed material loop are essential components of a circular business. However, it is not possible to create a fully circular system in a single business model. Therefore, social relationships between companies are essential to create closed-loop supply chains (Fogarassy and Finger 2020).

Industrial symbiosis is a collective concept of circular models, which consists of using under-utilised wastes from other industries, such as materials, energy, by-products, water and others, as inputs, contributing with economic profit and environmental benefits as a win-win situation. This is promising approach to maintain a sustainable waste management and reduce the use of virgin materials and create circularity. By adopting this practice, the link between the bioremediation process and the vast potential downstream markets is facilitated between different organisations (Fehrer and Wieland 2021; Li, Ge, and Xiao 2021). This is a model supported by many researches studying microalgae systems, as it promotes economic viability and long-term sustainability of the process (Li, Ge, and Xiao 2021; Mahmud et al. 2025). The term urban-industrial symbiosis is also often used as a similar strategy, but involves the cooperation between urban facilities and industries to recover the value of wastes (Pechsiri et al. 2023).

### 3.2. Environmental and technological strategies

The current circular economy concept aims to optimise the use of virgin materials through eco-design. The objective is to maintain the product for as long as possible, making it easy to reuse, repair or refurbish. Once the product is no longer functional, it should be recycled to generate new products. Waste reduction is a key concern at all stages of production (Khaw-Ngern et al. 2021).

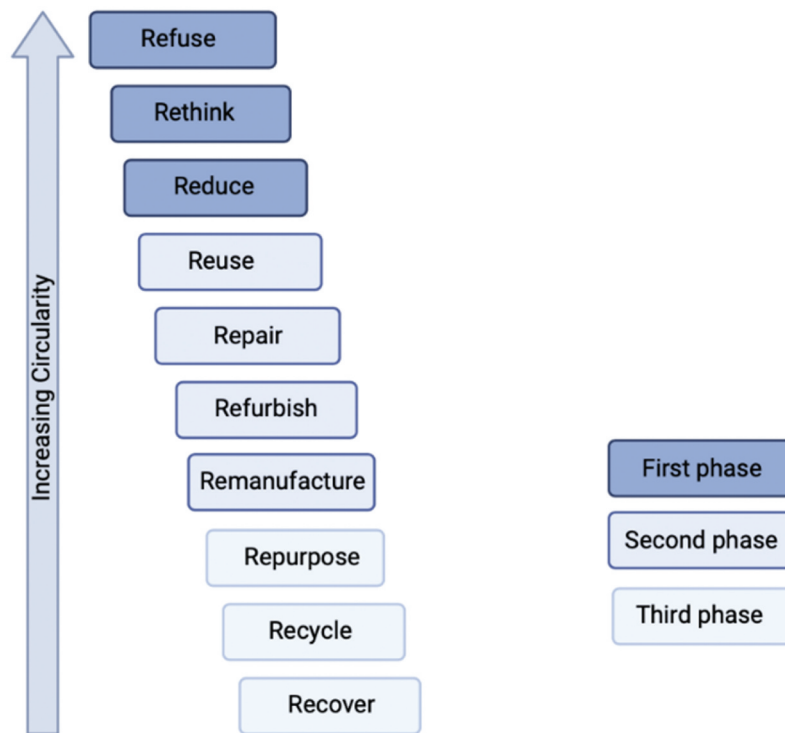
The R's principles have been used for a long time and are described as practical circular economy actions and activities that can be applied in companies to create economic value, environmental protection, and a positive social impact. This framework is commonly used to describe the waste hierarchy and promote circular economy practices. However, the number of R's (3 R's, 4 R's or 6 R's), and their meanings vary depending on the context. The 3 R's were originally known as Reduce, Reuse and Recycle, and gradually, different 'R' principles have been defined by researchers and practitioners according to different areas of study. To better conceptualise, several authors reorganised the 3 R's principles into a 10 R's hierarchy. The most emphasised principles are refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover, which are organised into three phases respectively related to design (first phase), use (second phase) and end-of-life (third phase) (Figure 1) (Kirchherr, Reike, and Hekkert 2017; Uvarova et al. 2023). Microalgae

processes align with these circular economy principles by recycling nutrients (N and P), consuming wastes, contaminants and CO<sub>2</sub> from other industries and using them to grow and generate valuable biomass. This process allows to recycle wastes into valuable, bio-based and renewable products, thus minimising the use of limited and fossil-based ones. It also produces clean water that can be reused for further microalgae cultivation or agricultural purposes.

From another perspective, it is unthinkable to discuss a full transition to a circular economy without mentioning Industry 4.0 (Tsolakis et al. 2023). It is a paradigm shift in manufacturing practices that includes circular economy principles through a digital transition that improves management, maintenance, and performance. Recent technologies, such as blockchain technology (BCT), big data (BD), artificial intelligence (AI), cloud, internet of things (IoT), additive manufacturing (AM) and industrial simulation, interconnect data and facilitate the transformation of traditional business models (S. A. R. Khan et al. 2021). Chong et al. (2024) investigated the application of machine learning and deep learning methods, in line with the principles of Industry 4.0, to microalgae technology. Their approach aims to integrate digital microscopy with AI algorithms to achieve rapid and precise microalgae classification at the species level while enabling real-time monitoring. This innovative methodology addresses limitations of conventional methods, which are often characterised by high costs, time-consuming processes, and susceptibility to human error. Other studies combine AI models to improve performance of microalgae cultivation, enhance yield and effectiveness of downstream processing (Imamoglu 2024). Furthermore, an upgrade to Industry 5.0 is already being adopted. It builds on the digital transformation of Industry 4.0 and circular economy practices for sustainable production, but with a human-centred approach. Industry 5.0 highlights how human-machine interactions and human-robot collaborations can elevate productivity and resource efficiency, while eliminating social concerns (Atif 2023). More recently, Digital Twin has raised interest in the microalgae field to enhance biomass production and improve the prediction of negative impacts (Sheik et al. 2024). Through microalgae pilot plants, a new model was developed for the production of advanced liquid fuels using CO<sub>2</sub> emission streams from industrial sectors. This was achieved using different innovative technologies such as Digital Twin (<https://itene.com/casos-de-exito/fuelgae-biocombustibles-microalgas-transporte/> accessed on 16 April 2025). Moreover, some authors are already forecasting a possible Sixth Industrial Revolution, in which the interconnection of humans, machines and nature will transform the way systems operate (Chourasia et al. 2022; Encarnação, Da Graça Campos, and Mateus 2023).

### 3.3. Waste-to-resource systems

Due to the diversity and value of wastes, the R's strategy alone cannot address all the waste disposal. Innovative waste-to-resource approaches aim to convert various types of waste materials into valuable resources, energy, or useful products, therefore contributing to the circular economy in a practical sense. This approach enables the recovery of all the valuable components and maximises its potential for up-cycling (You 2022).



**Figure 1.** The 10 R's hierarchy organised in three phases, the first phase includes refuse rethink and reduce; the second phase includes reuse, repair, refurbish and remanufacture; and the third phase includes repurpose, recycle and recover. Ordered from the more linear practice to the more circular one (adapted from Kirchherr, Reike, and Hekkert 2017).

There are various waste-to-resource designs, depending on the feedstock waste and its composition, the technology used to process the waste, and the type of end-product. Recent technologies, such as waste-to-energy, waste-to-biofuels, waste-to-biochar, and waste-to-product systems are recent technologies that convert biowaste into energy and value-added chemicals, contributing to carbon mitigation and to the circular economy (Dini 2021; You 2022).

Microalgae can be integrated into waste-to-resource systems to treat and bioremediate wastewaters, producing valuable biomass for multiple applications (Figure 2). Microalgae can play a significant role in closing the gap in the circular economy, supporting sustainable resource usage, and having a positive environmental impact (Moreira et al. 2021).

## 4. Microalgae and circular economy

### 4.1. Microalgae and biotechnological potential

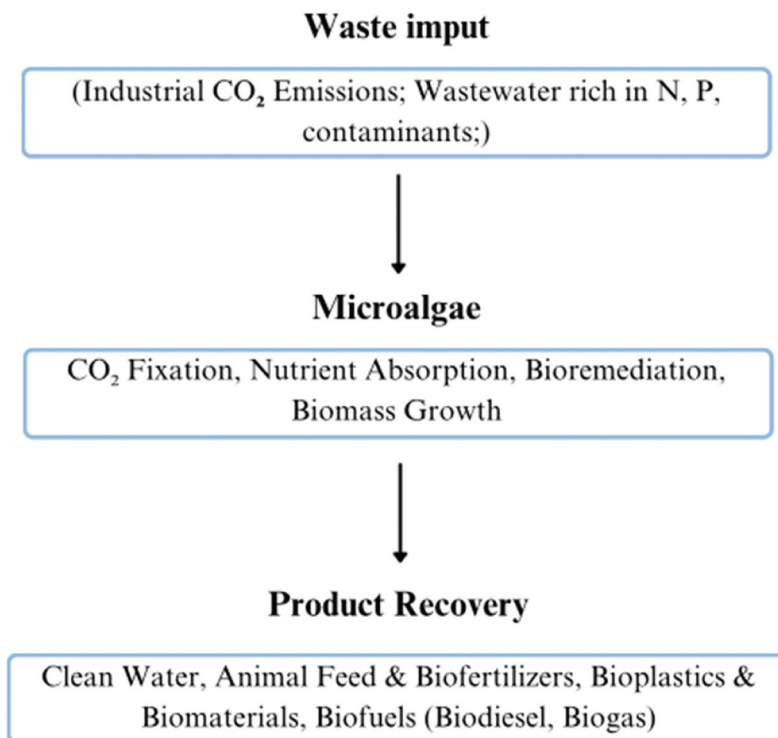
Microalgae are photosynthetic autotrophic microorganisms. Some have the ability to shift their metabolism to grow under heterotrophic or mixotrophic conditions (eg.: *Chlamydomonas* genus). They are characterised as ubiquitous since they can be found in all types of habitats, including aquatic, terrestrial and aerial. These organisms usually adopt a unicellular or simple multicellular structure, which allows them to survive in less favourable conditions to their development, having a great tolerance to a wide range of conditions like pH, temperature, light intensity, and salinity (Kholssi et al. 2021). They fix CO<sub>2</sub> from the air and, in the presence of water and light, generate oxygen and

carbohydrates (Bhatt et al. 2022). In fact, microalgae are responsible for producing about 50% of the atmospheric oxygen (Abdelfattah et al. 2023).

Microalgae have a major biotechnological interest due to their outstanding diversity. It is estimated that there are between 200,000–800,000 species of microalgae, although only 50,000 species have been described and studied. This diversity characterises microalgae as an important source of different valuable bio-products, such as vitamins, pigments, antioxidants, fatty acids, proteins and carbohydrates leading to interest from several industries including pharmaceuticals, nutraceuticals, agriculture, bioenergy, cosmetics, food and feed (Kholssi et al. 2021; Udayan et al. 2021; Yin et al. 2020). Table 1 summarises relevant species with industrial applications, in addition to their pros and cons.

Microalgae are often considered functional foods, mainly because of the high quantities of omega-3 and omega-6, and other polyunsaturated fatty acids (PUFA), along with their protein content, diversity of vitamins (A, B1, B6, B12, C, biotin, riboflavin, folic acid) and minerals. Hence, microalgae constitute a promising alternative source of nutrients relevant to human and animal nutrition (Diao et al. 2024).

Microalgae have been extensively studied in the bioenergy industry due to their potential to produce affordable and clean energy (Khan et al. 2023). The high carbohydrate content of microalgae makes them a valuable carbon source for bioethanol production. Additionally, from the microalgae lipids' transesterification, biodiesel can be produced and used as a renewable substitute for fossil fuels, thereby reducing their hazardous impact on the environment. Lastly, in the context of green energy, the production of biogas and biohydrogen can



**Figure 2.** Microalgae role in waste minimisation and product recovery.

**Table 1.** Relevant microalgae and cyanobacteria bioproducts and industrial applications.

Microalgae species	Bioproducts	Industrial application	Pros	Cons	Reference
<i>Anthrospira</i> sp. (Spirulina)	Source of protein, vitamins, phycocyanin, phycobiliproteins,	Food and Feed industries, Pharmaceutical and Cosmetic industries	High protein content, tolerance to contamination	Low lipid content, needs controlled conditions	Oleskin and Boyang (2022)
<i>Chlorella</i> sp.	Vitamins, β-1,3-glucan and other polysaccharides, Fatty acids	Cosmetic and Feed industries, Bioremediation	Fast growth rate, tolerance to wastewater and high CO <sub>2</sub>	Thick cell wall, difficulty in extraction of compounds	Oleskin and Boyang (2022)
<i>Haematococcus pluvialis</i>	Source of astaxanthin, β-carotene	Food and Feed industries, Pharmaceutical and Cosmetic industries	Produces astaxanthin (high-value antioxidant)	Slow growth, sensitive to contamination, controlled conditions required	Gamal and Shreadah (2024)
<i>Nannochloropsis</i> sp.	Source of lipids, omega-3 fatty acids	Bioenergy, Cosmetic industry, Bioremediation	Small size with fast growth, grows in saline water	Hard cell wall, requires controlled salinity conditions	Oleskin and Boyang (2022)
<i>Scenedesmus</i> sp.	Source of lipids, biogas, bioethanol	Biodiesel, Bioremediation	Robust in wastewater environments	Difficulty in harvest and extraction	Gamal and Shreadah (2024)
<i>Chlamydomonas reinhardtii</i>	Source of PHB, antioxidants, therapeutic proteins, industrial chemicals	Bioplastics, Bioenergy, Pharmaceutical and Cosmetic, industry, Bioremediation	Model organism, well-characterised, easy to modify genetically	Low productivity, sensitive to stress	Bellido-Pedraza, Torres, and Llamas (2024)

also be achieved through microalgae processes (Khan et al. 2023; Olabi et al. 2023).

In the cosmetic industry, the use of natural microalgae antioxidants and pigments such as carotenoids, instead of chemical alternatives, meets people's demand for safety, security, and environmental protection. Additionally, some microalgae species have beneficial properties for the skin, as they can regenerate and adapt to adverse conditions by protecting cells from damage and preventing the formation of free radicals (Udayan et al. 2021). The main microalgae pigments used in cosmetics are carotenoids, chlorophylls and phycobiliproteins. For instance, Spirulina is a common source of the blue dye phycocyanin for cosmetics purposes (Yu, Zhao et al. 2024).

On the other hand, the active peptides, polysaccharides, vitamins, and carotenoids extracted from microalgae have an active role in the pharmaceutical industry. Numerous studies have shown anti-inflammatory, anti-viral, antioxidant, anti-cancer, anti-diabetic and neuroprotective properties, thus helping to prevent, cure and improve common diseases (Zhuang et al. 2022). Additionally, microalgae have the potential to work as cell-factories to express recombinant proteins with pharmaceutical purposes (Kholssi et al. 2021).

Microalgae biomass can be used as biofertiliser in the agriculture industry, replacing chemical fertilisers that contribute to soil pollution. They improve nutrient consumption and enrich the soil with vital nutrients. Furthermore, polysaccharides, plant

growth hormones, antibacterial substances and other metabolites that stimulate plant growth can be synthesised by microalgae (Braun and Colla 2023). Other emerging bioproducts include the biopolymers such as polyhydroxycanoates (intracellular PHB, PHBV, etc.), polylactic acid (PLA) and cellulose (for novel biomedical applications), which can be produced by microalgae as sustainable alternatives to fossil-based plastics (Pacheco et al. 2025; Windhagauer et al. 2022; Zanchetta et al. 2021).

Beyond all the industrial and commercial potential microalgae applications, it is also worth noting that Olabi et al. (2023) found that microalgae effectively contribute to each SDG, either directly or indirectly (Figure 3). The microalgae's ability to treat water, to reduce CO<sub>2</sub> from the atmosphere, to remediate nutrients from water, and to improve soil quality, directly address SDGs 6, 13, 14 and 15, respectively. Additionally, their potential to produce renewable and sustainable energy sources is essential in achieving the clean energy goal (SDG 7). Furthermore, they can potentially create more jobs, including jobs for women, and encourage microalgae education, which is closely linked to the goals 1, 4 and 5, respectively. Microalgae have valuable compounds that can be extracted for nutritional, nutraceutical, or pharmaceutical purposes, contributing to SDG 2 (Zero Hunger) and SDG 3 (Good Health and Well-being). Additionally, their potential to boost innovation, increase the economy, and promote sustainable practices, tackles SDGs 8,9, 10, 11 and 12. Lastly, microalgae indirectly contribute to achieving peace, justice, and strong institutions and partnerships (SDGs 16 and 17) by addressing driver violence-related concerns such as poverty, unemployment and food insecurity and by promoting

collaboration between industries, globalisation and the implementation of international policies (Olabi et al. 2023). In conclusion, microalgae have a substantial impact on the circular economy and sustainable development.

#### 4.2. Advantages and limitations

Advantages associated with the use of microalgae for different purposes span from their high photosynthetic efficiency, fast growth rates, high biomass productivity, rapid accumulation of compounds of interest, and the ability to survive under extreme conditions. Additionally, microalgae can fixate CO<sub>2</sub>, resulting in a low carbon footprint and eco-friendly and sustainable biomass production that can be converted into valuable products. One important benefit of microalgae cultivation is that it does not compete with arable land required for agricultural purposes. Moreover, using wastewater or seawater as culture medium can significantly reduce operational costs and promote the circular economy (Udayan et al. 2021).

However, microalgae production also has some drawbacks that limit their industrial application and scalability. One limiting factor is the existence of harmful microalgae such as dinoflagellates (eg.: *Karenia* spp., *Karlodinium* spp.), raphidophytes (*Chattonella* spp.), diatoms (*Skeletonema* spp. and *Chaetoceros* spp.), and cyanobacteria (*Trichodesmium* spp.), which toxicity must be addressed in order to verify their safety for commercial use (Kholssi et al. 2021; San Diego-McGlone et al. 2024). At the industrial level, the major issue is related to the high cost and high energy demand of the downstream processing which includes harvesting, drying, extraction and purification, in addition to the high costs of PBRs. This is one



Figure 3. Microalgae contribution to each of the united nations sustainable development goals.

of the most highlighted limitations for the upscaling of microalgae systems. Other technical challenges involve difficulties in product recovery, susceptibility to contamination in open ponds and costly media (Cheirsilp et al. 2023).

From a commercial perspective, there are also limitations associated with licences to market microalgae-related products, small market demand, and high process costs that increase the final product's commercial price, limiting its potential to compete with well-established markets (Xu et al. 2023).

### 4.3. Microalgae in waste-to-resource systems

Industrialization and urbanisation generate daily discharges of contaminants to the environment, leading to water contamination. This contamination consists of the release of pharmaceutical products, micro and nanoplastics, polyaromatic hydrocarbons, dyes, heavy metals, pesticides, and other toxic components that pose a threat to human health. For that reason, biological methods have gained momentum for wastewater treatment due to their alignment with the circular economy principles and environmental demands.

Microalgae can be used to perform biological processes for the synthesis of bioproducts from organic residues as raw materials, providing a double advantage: removing waste and producing value, sustainably. Thus, microalgae can be integrated into waste-to-resource systems in several contexts and contribute to the circular economy. For instance, a typical approach to upcycling waste is the valorisation of food waste, lignocellulosic waste, and agricultural waste as potential nutrient sources for microalgae cultivation. Similarly, Nwoba and Moheimani (2022) studied the use of fire extinguisher powder waste, as a sustainable alternative source of phosphorus and nitrogen for microalgae production.

Microalgae can be cultivated in various wastewaters including those from households, municipalities, chemical, pharmaceutical, food, and aquaculture industries. They serve multiple purposes such as mitigating atmospheric CO<sub>2</sub> along with other GHG like SO<sub>x</sub> and NO<sub>x</sub> which contributes to carbon neutralisation. Additionally, they consume excess nutrients from the water like phosphorus (P) and nitrogen (N) and remove organic and inorganic pollutants. Depending on the microalgae species, biological oxygen demand (BOD) removal can reach up to 92% and chemical oxygen demand (COD) removal values can reach 89%. Moreover, P and N can be completely (100%) removed from wastewater by certain microalgae (Abdelfattah et al. 2023; D. Yu et al. 2024). The biomass resulting from the treatment can be processed in a biorefinery approach into multiple products economically valuable, with reduced residual components, therefore, helping to close the loop (Costa et al. 2023). A recent report focusing on a circular economy-based approach addresses the environmental concerns related to wastewater from the ophthalmic spectacle lens industry; the study focuses on the integration of solid waste materials into polymeric and cement matrices and the use of wastewater for microalgae cultivation. The approach aims to transform environmental pollutants from wastewater into valuable organic products using a circular economy model (Encarnaç o et al. 2023).

Compared to conventional biological treatments (such as activated sludge systems and membrane bioreactors), microalgae-based treatment offers a superior removal efficiency of nutrients such as N and P. Moreover, conventional treatment involves high energy demands and the emission of GHG as downside, while microalgae treatments help mitigating these limitations (Abdelfattah et al. 2023; Song et al. 2022).

## 5. Technico-economic analysis and energy balance

Assessing the techno-economic feasibility and the energy balance of a microalgae-based circular process is critical to ensure process reproducibility, feasibility and viable scale-up. In this review techno-economic analysis (TEA) were analysed for different microalgae-based products.

There are various reports of TEAs of biomass conversion into value-added products, including biodiesel, biofertiliser, high-value pigments, and others, to determine the economic feasibility of microalgae processes. A great variation in net profit values is reported in the literature, depending on capital investment and operating costs of facilities and processes, as well as the revenue from the bioproducts. In waste-to-resource systems, the use of wastewater and flue gases to cultivate microalgae significantly reduces operating costs, which is a limiting factor for industrial scale up (Mahmod et al. 2025). In this context, the production costs of a bioproduct vary depending on location, cultivation systems, microalgae species, and downstream processing techniques (Wan Mahari et al. 2022). A positive net was calculated to produce biofertiliser from microalgae biomass grown in open ponds using agro-industrial wastewater. In the same study, the production of biodiesel using the same upstream process was found to be economically unviable due to higher costs related to energy requirements for downstream processing and equipment acquisition, in addition to a lower selling price of the final product (Castro et al. 2023). Other biomass valorisation systems demonstrated that biorefinery approaches can improve economic viability of microalgae biomass utilisation by producing multiple products (including high-value products) while supporting circular economy (Chen et al. 2018; Wan Mahari et al. 2022). Silkina et al. (2024) estimated the cost-benefit for growing a microalgae using brewery CO<sub>2</sub> waste gas. The analysis showed that growing *Limnospira maxima* in a 1000 L raceway pond may generate a net financial gain, considering protein production and phycocyanin valorisation (high-value bioproduct) from microalgae, resulting in a cost of 1225 GBP/year and benefit of 1999 GBP/year.

Another approach to optimise the microalgae wastewater treatment while reducing economic costs and overcoming technical issues, is to use microalgae-bacteria consortia. The interactions between the microalgae and bacteria result in higher efficiency and faster nutrient removal from the wastewater. Besides, this interaction enhances lipid and carbohydrate accumulation and facilitates downstream processing, such as flocculation and cell disruption (Chia et al. 2023).

The energy balance for the production of microalgae-based bioproducts is estimated taking into account the energy required to obtain the final product and the energy output obtained from that bioproduct. The aim is to determine

whether the process is energy efficient/viable. Different researchers calculate the energy balance using different approaches depending on the context, including net energy ratio (NER), energy return on energy invested (EROEI), fuel energy ratio (FER). In the context of microalgae systems, ratio values greater than 1 are desirable, meaning that the energy invested to produce the microalgae-based fuel is less than the energy produced by this bioproduct (Fozer et al. 2017; Milledge and Heaven 2017; L. Xu et al. 2011). Table 2 shows energy balance values for different microalgae bioproducts.

In terms of energy balance, the energy-based bioproducts produced by microalgae typically reach values lower than the NER of fossil fuels (around 5) (Saranya and Ramachandra 2020). Despite the lower energy input, the production of biofuels is still relevant as its value extends to slowing down the use of fossil fuels, which are limited and facing a decline in availability.

## 6. Applications and case studies

Circular practices are being explored to make microalgae products commercially viable and competitive in the open market. These practices include cascade extraction of valuable products, coupling biofuel production with the extraction of other value-added products (high-volume low-value and low-volume high-value products), and the development of new bioreactors and downstream processing technologies (Roy Chowdhury and Das 2023; Sarma et al. 2021). Moreover, the aforementioned industrial symbiosis models are being applied to create circular systems for microalgae cultivation. These include the valorisation of CO<sub>2</sub> emissions and/or other flue gases from industries, which are used as input for microalgae

biomass production. The biomass can be subsequently transformed into biofuel, bioplastics and other bioproducts. Other approaches use material byproducts or wastes from agriculture/food/beverage industries, (eg.: glycerol or brewery wastes) as nutrient uptake for microalgae, generating biomass rich in oils, proteins and pigments (Mahmod et al. 2025).

Laboratory and pilot-scale case studies have been conducted to demonstrate the feasibility of waste-to-resource approaches using microalgal water bioremediation for biomass valorisation, and some were already scaled up and industrialised. Several collaborative international, European and national projects are focused on developing innovative and sustainable microalgae-based technologies for waste valorisation (Table 3).

One such initiative is INCOVER, a European project that studied microalgae for a resource recovery-based wastewater treatment (<https://incover-project.eu/case-study/case-study-1/>), which involved collaboration between various universities and companies. In this project, three horizontal semi-closed photobioreactors fed with agricultural and urban wastewater were designed. A feast and famine strategy was developed in order to select cyanobacteria capable of accumulating polyhydroxyalkanoates (PHA), which are bioplastics. Part of the harvested biomass can be used to recover energy in the form of biomethane and other bioproducts such as biofertiliser, recovered nutrients and irrigation water (Figure 4). This approach can help to reduce the global operation and maintenance costs of wastewater treatment (Uggetti et al. 2018). The process was successfully validated in continuous operation in a pilot unit over a relevant period of time, achieving a technology readiness level (TRL) of 7, however, there are no reports that commercial viability has been achieved.

Another example is the national project NABIA (<https://sciproj.ptcris.pt/160713PRJ>). The lab-scale project aimed to

**Table 2.** Energy balance values for different microalgae bioproducts produced under different conditions.

Bioproducts	Microalgae species	Conditions	Energy balance	Reference
Biodiesel, biogas and glycerol	Mixture of species	Aquaculture wastewater input, pilot scale bioreactor, transesterification from dry biomass using biocatalyst	NER = 18.8	Saranya and Ramachandra (2020)
Upgraded bio-oil, biogases, bio-char solids	–	Cultivation in an helical tubular photobioreactor and conversion of wet biomass to biofuel through hydrothermal liquefaction (HTL)	NER = 1.137	Diao et al. (2024)
Biofuel	<i>Chlorella Vulgaris</i>	Biofuel conversion from dry/wet biomass	FER = 1.37/1.50	Pechsiri et al. (2023)
Biodiesel	<i>Nannochloropsis oculata</i>	Raceway pond, wet paste extraction with hexane, alkaline transesterification	NER = 0.88	Collet et al. (2014)
Biodiesel, glycerol	Phototrophic microalgae	Open pond, dry biomass, chloroform and methanol lipid extraction, transesterification	NER = 2.03	Zhang et al. (2013)

**Table 3.** Non-exhaustive list of international, European and national projects focused on integrating microalgae into waste-to-resource systems. Information related to funded projects can be found on <https://cordis.europa.eu>, <https://sciproj.ptcris.pt/160713PRJ>, and <https://www.energy.gov/eere/>.

Acronyme	Project title	Programme	Date	Total Cost
AzCATI	Direct Air Capture Integration with Algae Carbon Biocatalysis	DOE: Office of Energy Efficiency and Renewable Energy (EERE)	2021–2023	\$3,200,000
E4WATER	Economically and Ecologically Efficient Water Management in the European Chemical Industry	FP7-NMP	2012–2016	€ 17031,405.40
GREEN DUNE	Projecto Iceland, Liechtenstein, Norway Grants, Blue Growth, Innovation and SME	Blue Growth Innovation and SMEs	2021–2024	€409,180
INCOVER	Innovative Eco-Technologies for Resource Recovery from Wastewater	H2020 EU	2016–2019	€ 8,432,456.43
ProEMiBIL	Microalgae and agricultural residues provide fermentation feedstock for biofuels	H2020 EU	2019–2021	€ 98507.52
NABIA	New Approach to Bioremediation using Algae	FCT	2021–2024	€ 239,739.90
SABANA	Sustainable Algae Biorefinery for Agriculture and Aquaculture	H2020 EU	2016–2021	€ 10 646 705.00

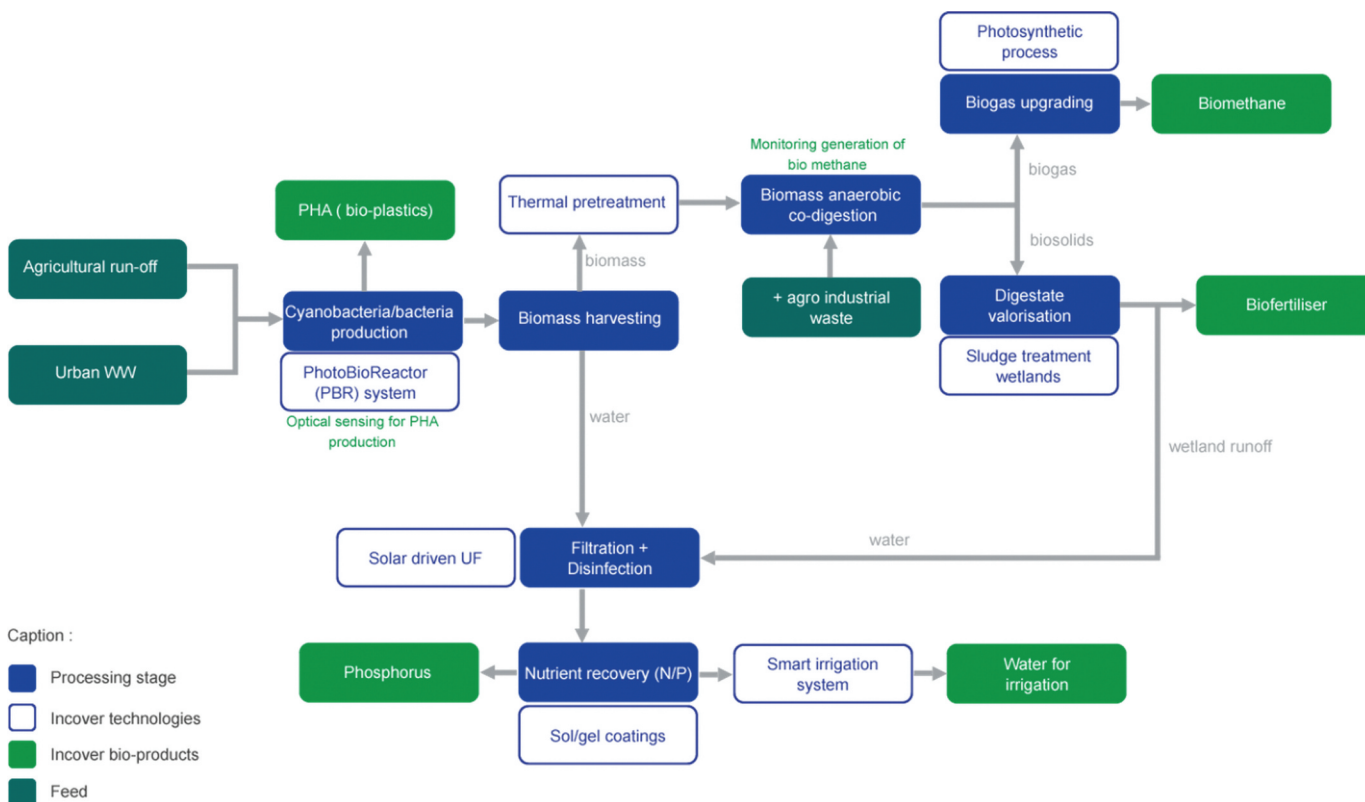


Figure 4. Process flow diagram of the case study 1 within the INCOVER project. Source: <https://incover-project.eu/case-study/case-study-1> (visited at 31/01/2025).

decontaminate wastewater from emerging pollutants using microalgae. It proposes potential solutions for the residual biomass and promotes the generation of enhanced environmentally friendly bioproducts, the capture CO<sub>2</sub> and other greenhouse gases in the process, and awareness about the conservation and sustainable use of ecosystems. NABIA project also encourages and suggests new policies and empowers policymakers to implement them (<https://nabiaproject.pt>).

Numerous case-studies in non-European countries are reported due to the expansion of microalgae cultivation in these regions. China, India, the United States, Brazil and Malaysia are the top 5 countries leading research on microalgae-based wastewater treatment and biomass valorisation mainly for biofuel production (Bandh and Malla 2023). For instance, Goswami, Mehariya, and Verma (2024) conducted an outdoor sub-pilot study in India, with the aim of developing sustainable eco-friendly microalgae-based wastewater treatment technologies to promote a circular economy, considering the semi-hot climate. A consortium of *Tetraselmis indica* and *Picochlorum* sp. was cultivated in a low-cost PBR and high

removal efficiencies were achieved for removing COD (92.49%), nitrate (94.16%), and phosphate (94.24%) removal. The consortium produced 2.65 g L<sup>-1</sup> of biomass with a lipid content of 40.67%. As another example, Leong et al. (2023) studied the feasibility of using *Chlorella vulgaris* for biodiesel production from wastewater resources in Malaysia. A pilot-scale photobioreactor was developed and used to grow the biomass, then it was dewatered and dried to extract lipids using solvents. High energy inputs were required to convert lipids into biofuels through transesterification, which was found the biggest limitation of this investigation.

Some companies have been able to develop a sustainable and scalable wastewater treatment business model using microalgae. Some examples of companies in the field are highlighted on Table 4. Some approaches are designed to remove the excess nutrients and other pollutants from municipal and industrial wastewater to originate a clean water stream. Such strategy also allows to produce valuable biomass and obtain revenue-producing biomass products. The biomass is sent to a wide range of partner companies that process it, and produce

Table 4. Non-exhaustive list of companies with circular economy model.

Companies	Products	Field	Websites
Algae Systems	Bio-oil, bio-char and fertilisers	Biomass feedstock	<a href="https://www.algaesystems.com">https://www.algaesystems.com</a> .
Algenist	Alguronic acid, vitamin C, oils	Cosmetics	<a href="https://www.algenist.com">https://www.algenist.com</a> .
Algenuity	Algal-cell ingredients	Biomass feedstock	<a href="https://www.algenuity.com">https://www.algenuity.com</a> .
BioPak	Bioplastics	Compostable food packaging	<a href="https://www.biopak.com/au/materials/pla-bioplastic">https://www.biopak.com/au/materials/pla-bioplastic</a> .
Bloom	Resin and thermoplastic rubber	Footwear	<a href="https://www.bloommaterials.com">https://www.bloommaterials.com</a> .
Checkerspot	Algae oils	Materials	<a href="https://checkerspot.com">https://checkerspot.com</a> .
LivingInk	Black ink	Pigments	<a href="https://livingink.co">https://livingink.co</a> .
Redono	Biomass, astaxanthin, vitamins	Animal feed and SuperFoods	<a href="https://www.redono.fi">https://www.redono.fi</a> .

different products, including running shoes, inks, fertilisers, cosmetics, fuels, animal feed ingredients, textiles, etc.

Some partnerships have emerged between industries, fomenting collaboration to implement microalgae products. For instance, Unilever has partnered with Algenuity to develop microalgae-based ingredients as sustainable protein sources. Algenuity, a biotechnology company with expertise in producing and developing innovative applications for *Chlorella* species, focuses on creating ingredients for food and beverages industry (<https://www.unilever.com/news/press-and-media/press-releases/2020/unilever-and-algenuity-partner-to-explore-use-of-microalgae-protein/>, accessed on 15 April 2025). On the other hand, Veramaris produces oil rich in omega-3 (EPA and DHA) from *Schizochytrium* sp. as an environmentally friendly alternative to fish oil. Mowi, the world's largest salmon farmer, collaborated with Veramaris to incorporate their oil into salmon feed, supporting sustainable aquaculture practices (<https://www.veramaris.com/media-resources-detail/veramaris-wins-f3-fish-oil-challenge>).

## 7. Challenges and barriers

Limitations associated with microalgae-based approaches in circular economy systems involve various key issues related to technical, economic and regulatory challenges throughout the entire process.

Technical problems related to the bioremediation process include possible contamination or variable composition of the effluent. These issues can affect the consistency in the biomass yield and composition, thus compromising the presence or quantity of a desired component for a specific application. In addition, a high concentration of contaminants can have a negative impact on microalgae. To mitigate the risk of contamination, some researchers have studied the co-cultivation of microalgae species with beneficial bacteria/ yeasts to promote microalgae growth and suppress the presence of harmful organisms affecting microalgae culture, such as rotifers (Fisher et al. 2019; Zhou et al. 2021). Additionally, the presence of pathogenic microorganisms (such as bacteria and viruses) poses a barrier to product development and requires strict control to ensure the safety of the bioproducts extracted from microalgae biomass (Udayan et al. 2021).

Another technical challenge is related to the downstream processing, which is in the early stages of development, as there is still no viable, energy-efficient and cost-effective methods developed for harvesting, dewatering and processing

biomass after the water treatment (Cheirsilp et al. 2023). There are also some economic barriers to the practical application of these circular systems, including cost competitiveness with traditional wastewater treatment methods. Investment in such facilities is costly and uncertain, resulting in few interested investors in implementing these processes. Besides, in the case of bio-based products, although microalgae cultivation in wastewater can lower the market prices, it still cannot compete with chemical-based products (Table 5). The volatility of the selling prices of microalgae products is representative of different production pathways, process technologies, productivities and inconsistencies in system boundaries (Quinn and Davis 2015).

To overcome this limitation, downstream technologies should be improved to reduce energy requirements, as some emerging technologies are being developed and applied. According to Min et al. (2022), electroflocculation is the most suitable technique for biomass recovery from an energy point of view. From an economic point of view, the use of microorganism-produced bioflocculants is a promising approach to concentrate microalgal biomass, but further research is needed to apply it to large-scale processes, as some interactions are not yet fully understood. Among the available dewatering processes, a belt filter system appears to be the most energy-efficient option, allowing continuous operation that can be scaled up. Drying methods are the most energy intensive of the harvesting processes. Using solar energy is the cheapest approach, but it is highly dependent on the weather and requires large areas of land, which may not be feasible on a large scale. Microwave drying can save energy compared to technologies such as freeze or spray drying and is considered the most efficient drying method.

Regarding legislation, there are some barriers to the possible applications of the microalgal biomass used in wastewater remediation, which will be discussed in the next section. Broadening the potential applications of this biomass is also essential to promote process viability (Su et al. 2023). Additionally, the successful market implementation of such products is greatly influenced by social acceptance. Well-defined standards and policies can ensure reliable and safe products that are accepted by the community (Su et al. 2023).

## 8. Environmental impact

Life cycle assessment (LCA) is often performed to evaluate energy and environmental impacts. LCA considers all stages

**Table 5.** Price of microalgae bioproducts calculated in different studies compared to the average market prices of the corresponding conventional products.

Product	Price of microalgae products	Price of conventional products (EUR/Kg)	References
Fertiliser	2.5–7.5 EUR/Kg	0.35–0.602 EUR/Kg	(Romero-García et al. 2022) (European commission- <a href="https://agridata.ec.europa.eu/extensions/DashboardFertiliser/FertiliserPrices-m.html">https://agridata.ec.europa.eu/extensions/DashboardFertiliser/FertiliserPrices-m.html</a> , accessed on 15 April 2025)
Plastics	4–135 EUR/Kg (PHB)	0.90 EUR/Kg (PP)	(Rueda et al. 2023) ( <a href="https://www.statista.com/statistics/1171084/price-polypropylene-forecast-globally/">https://www.statista.com/statistics/1171084/price-polypropylene-forecast-globally/</a> accessed on 15 April 2025)
Fuels	3.46–6.75 EUR/L	0.44–3.31 EUR/L	(Greene et al. 2025) ( <a href="https://www.statista.com/statistics/1266885/automotive-diesel-prices-by-country/">https://www.statista.com/statistics/1266885/automotive-diesel-prices-by-country/</a> accessed on 15 April 2025)

of the process, including upstream and downstream processes, from the microalgae-based remediation process to the final product.

Several variables are quantified to measure the environmental impact, including energy and resource requirements, atmospheric emissions, water consumption, and other releases. In addition, relevant impact categories are considered such as human and environmental health, biodiversity preservation, contribution to climate change and global warming, and fossil fuel depletion (Wimmerova et al. 2022). In the case of microalgae-based water treatment with by-product valorisation, the LCA is influenced by various factors, including algae strain, culture scale and conditions, source of inputs (nutrients and flue gas), harvesting methods and product processing methods. In most LCA studies, the use of fossil fuel as an energy source for cultivation and the process of harvesting is the primary cause of high carbon emissions, so replacing it with renewable energy, greatly reduces the impact on climate change. On the other hand, the nutrient source also has a large impact on LCA; therefore, using waste as an alternative to commercial culture medium is less harmful to the environment, and can even achieve negative carbon emissions (Arashiro et al. 2022; P. Xu et al. 2023).

One LCA study of microalgae-based biodiesel production reported a higher global warming potential (GWP100) than fossil-based fuels. Even in the most favourable scenario for microalgae biodiesel (using renewable energy), a value of  $1.48 \times 10^{-1}$  kg CO<sub>2</sub> eq MJ<sup>-1</sup> was obtained, which is 67% higher than the emissions from fossil diesel production ( $8.84 \times 10^{-2}$  kg CO<sub>2</sub> eq MJ<sup>-1</sup>) (Bradley et al. 2023). Another study revealed that using wastewater as input for microalgae cultivation resulted in the lowest GHG emissions of 0.85 kg CO<sub>2</sub> eq kg<sup>-1</sup> of biodiesel. This value was substantially lower than the GHG emission from fossil fuel (9.47 kg CO<sub>2</sub> eq kg<sup>-1</sup> of biodiesel) (Saranya and Ramachandra 2020). These two examples demonstrate that the environmental impact of the technology is dependent on the elementary input flow and of each specific case.

Besides, microalgae contribute significantly to the mitigation of water and land pollution. They have the ability to degrade or accumulate threatening pollutants such as POPs, PAHs, and endocrine disruptors and also to prevent water eutrophication by consuming excess nutrients. As a result, this contributes to human and animal health, reduces the negative impact of pollution on ecosystems, and preserves biodiversity. Likewise, the microalgae ability to consume CO<sub>2</sub> and other GHGs contributes significantly to the mitigation of global warming (Olabi et al. 2023).

Microalgae play an active role in achieving the challenging goal of carbon neutrality by 2050. They have a natural ability to effectively absorb CO<sub>2</sub> (180 tonnes of CO<sub>2</sub> per 100 tonnes of microalgae) to produce valuable biomass. This circular process is in line with the concept of carbon neutrality by reducing the atmospheric concentration of this gas, widely emitted by industries and transportation (Sadvakasova et al. 2023). This extraordinary characteristic makes them ideal to generate tradable credits in the carbon credit market. A credit represents one less tonne of carbon dioxide or another equivalent gas in the atmosphere. The

integration of microalgae technology into the carbon credit market is still in its early stages, however there are some players taking the first steps. For instance, a company located in Hong Kong is dedicated to farming microalgae for carbon capture, using genetically improved strains cultivated in novel PBRs. This company is applying for carbon credit certification on the international carbon transaction platform (<https://www.asiaresearchnews.com/content/alcarbo---farming-microalgae-carbon-capture-help-achieve-carbon-neutrality>). Similarly, some companies are investing in large-scale microalgae cultivation for carbon sequestration, in order to reduce emissions from various industries, including cement industry (<https://www.portal-energia.com/secil-sequestra-co2-producao-microalgas/>; <https://www.carbonworks.bio/en>).

All in all, there are many environmental benefits associated with the integration of microalgae into circular systems, making this a popular topic for further research. Optimising processes can make these systems viable, sustainable, and feasible.

## 9. Legislation and regulatory impositions

Biobased products derived from microalgae biomass used for water remediation should be carefully evaluated before stepping into the market, with special attention paid to the applicable regulations. While there has been much initiative and focus from the scientific community to transition to the use of wastes as culture medium to obtain valuable biomass, less attention has been paid to studying the toxicity of the final product and market opportunities in terms of regulations. Although policymakers and regulatory entities have not been able to keep pace, some legislation regarding the use of microalgae grown on wastewater is already in place. Therefore, an oriented selection of potential commercial applications is possible and recommended.

In the USA, a limited number of microalgae species are approved for human consumption by agencies like the Food and Drug Administration (FDA), which are Generally Recognized as Safe (GRAS). These include *Spirulina* sp., *Chlorella* sp., *Dunaliella* sp., *Haematococcus* sp., *Schizochytrium* sp., *Porphyridium cruentum* and *Cryptocodinium cohnii*. Oil from *Ulkenia* sp. and *Prototheca moriformis* as well as protein from *Chlamydomonas reinhardtii* also have this status (<https://www.fda.gov/food/food-ingredients-packaging/generally-recognized-safe-gras>, accessed on 14 April 2025). In the EU, New Novel Food Regulation (EC) 2015/2283 collects the species of microalgae considered as novel foods safe for human consumption. This list comprises 22 microalgae species, including *Chlamydomonas reinhardtii*, *Tetraselmis chuii*, *Haematococcus pluvialis* and *Arthrospira platensis* (<https://ec.europa.eu/food/food-feed-portal/screen/novel-food-catalogue/search>, accessed on 14 April 2025).

The use of microalgae grown in wastewater is not explicitly prohibited by a specific regulation, but it is not allowed under the current frameworks due to food and feed safety concerns. According to the FDA and EU regulations, regarding food and feed safety, the use of microalgae cultivated in wastewater raises health risk due to potential contamination of the biomass with pathogens, heavy metals and other contaminants in

a way that interferes directly with the human food chain (Commission Regulation (EC) No 1881/2006 on contaminants sets permitted levels of heavy metals for food; Commission Regulation (EC) No 2073/2005 concerns microbiological criteria for foods). However, microalgae produced from specific waste streams (excluding urban wastewaters) may be used as animal feed ingredients or extracts for cosmetics, if rigorous quality control for toxic compounds or hazardous microorganisms is performed (Moreira et al. 2021; Su et al. 2023).

The potential applications of microalgae are currently restricted to biofertilizers, pigments, biofuels, and bioplastics. The main industrial applications that are currently available in the market focus on new biomaterials for different purposes, including resins, coatings, binders, and bioplastics (Moreira et al. 2021; Su et al. 2023). For these, the applicable regulations and standards are the ones followed for similar biobased products but from other different sources. However, when wastes are used as a growth medium, legal limits should define the maximum contaminants and pathogens contents allowed to be present in the final product. For instance, EU Regulation 2019/1009, is the most recent legislation that recommends the use of recycled or organic materials as biofertilizers. It permits the use of microalgae and microalgae-derived products in fertilising products and establishes acceptable levels of some heavy metals, namely cadmium, mercury, arsenic, nickel, and others.

For other possible commercial applications, an assessment of prohibited and restricted ingredients should be performed. This is because certain microalgae are able to absorb harmful chemicals from wastewater, which cannot be present in the final product due to potential negative effects. For cosmetics, a list of these compounds is made available by the FDA (US) and the European Commission (EU) for consultation. The European Committee for Standardization (CEN) developing standards to uniformise methods and procedures for extracting and quantifying ingredients and contaminants from algae to ensure quality and safety. CEN/TR 17,611, CEN/TR 17,612 and CEN/TR 17,739 define EU standards for the use of algae and algae products in cosmetics, pharmaceuticals, and chemicals and biofuels, respectively.

In addition to these policies and regulations, microalgae-based technologies are being incentivised by policy makers. In 2022, the European commission initiative 'Towards a strong and sustainable EU algae sector' identified 23 actions to increase the algae sector in the European Union to address water pollution, healthier diets and lower CO<sub>2</sub> emissions. Key actions include assessing the market potential, efficiency and safety of algae-based materials when used in fertilising products; support the transfer of microalgae technology from research to market; funding pilot projects in the algae sector; developing standards for algae ingredients, contaminants, and algae biofuels; supporting research programmes to develop and improve algae processing systems, novel production methods and algae cultivation systems. This initiative contributes to the achievement the UN SDGs, the European Green Deal and the Farm to Fork strategy, among others (Kuech, Breuer, and Popescu 2023).

To ensure the production of safe and reliable products that are trusted and accepted by users, it is necessary to follow

established rules, guidelines, and relevant legislative requirements (European Commission Directorate General for Communication 2020).

## 10. Concluding remarks and recommendations

The world's urgent transition to a circular economy can be accelerated by the integration of microalgae into waste-to-resource systems. These organisms have unique characteristics that enable them to generate economic value, address environmental issues, and contribute to sustainable development simultaneously.

The gaps identified throughout this article limit the practical implementation of microalgae within circular systems, i.e. the integration of wastewater bioremediation with valuable product recovery. Hence, to overcome these barriers research and development investment through public funds could drive the development of energy-efficient downstream technologies, innovative PBRs designs, and strategic integration of microalgae in wastewater treatment plants. The exploration of different sources of waste streams and screening efficient microalgae species is crucial. Optimisation of strains using genetic and metabolic engineering to increase performance in pollutant assimilation, CO<sub>2</sub> fixation and tolerance and to enhance the productivity of targeted bioproducts is emerging and showing promising results. New applications for the valuable biomass and technologies to recover multiple bioproducts can ensure the economic and environmental viability of the process. Moreover, it is important to continuously innovate by incorporating Industry 4.0 and 5.0 into the system's processes in order to make the most of the advantages that the digital era allows us to benefit from.

To ensure the quality and safety of biomass-derived products, regulation entities should clarify laws and standards that limit and rigorously control contaminant and pathogen concentrations. In this context, the establishment of clear regulatory guidelines on the chemical characteristics and quality of wastewaters used for microalgae cultivation is recommended. Such measures would contribute to ensuring the safety of the resulting biomass and promote greater acceptance among downstream industries and final consumers.

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## Authors contribution

Bruna Santos- Original draft, Methodology, Investigation; Filomena Freitas- Supervision, Review and Editing; Abílio Sobral- Review and Editing; Telma Encarnação- Conceptualization, Supervision, Review and Editing. International Journal of Sustainable Engineering

## Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

## Generative artificial intelligence (AI)

Generative AI tools, including Chat GPT and DeepL, were used solely for grammatical correction and English improvement.

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