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Editorial

INDUSTRY OF THE ALGAE PRODUCTION IN EUROPE: THE FUTURE AND POSSIBLE APPLICATION IN A CIRCULAR AND ECO-FRIENDLY BIOECONOMY

The algae production industry in Europe is undergoing a transformative phase, positioning itself as a critical player in the emerging circular and blue bioeconomy. With its versatile applications ranging from environmental remediation to sustainable aquaculture, algae offer immense potential to address some of the most pressing challenges of our time, including climate change, resource depletion, and environmental degradation.

Algae, particularly extremophilic species, are increasingly recognized as valuable assets in promoting sustainable growth across various sectors. Their adaptability to extreme environments, such as high temperatures or salinity, provides unique opportunities to develop eco-friendly solutions. The European algae sector, comprising both macro and microalgae production, has experienced substantial growth, with Spain, France, and Ireland leading in production (Araujo et al. 2021).

These are important parameters that inquired this organism in the objectives of the 2030 Agenda for sustainable cities and communities, responsible consumption and production and climate action.

A Circular Economy Enabler

One of the core strengths of algae production lies in its alignment with the principles of a circular economy. Algae can contribute to carbon sequestration, nutrient recycling, and renewable energy generation. This makes them ideal for integration into industrial processes, such as wastewater treatment and bioremediation, where they help mitigate pollution while producing valuable biomass. Moreover, algae-derived bioplastics and sustainable aquaculture feed are emerging as promising solutions to reduce reliance on fossil-based resources.

While the industry is experiencing significant growth, several barriers still impede its full potential. High production costs, limited scalability, and a fragmented regulatory landscape hinder broader adoption and market penetration. Addressing these challenges will require concerted efforts in innovation, investment, and regulatory harmonization across Europe.

As reported by Araujo et al. (2021), the European algae sector spans 23 countries and includes companies producing both macroalgae, microalgae, and the cyanobacteria Spirulina. The number of these companies, which was approximately 500 in 2021, has been steadily increasing, with a 150% rise in the number of new companies over the last decade. Some of these companies have been operating since before 1980, indicating long-term interest and stability in the sector.

Among macroalgae, some seaweed species collected along the European coasts such as *Laminaria digitata*, *Laminaria hyperborea*, *Ascophyllum nodosum*, and *Gelidium corneum* are used as feedstock for the extraction of food, and the hydrocolloids alginate and agar. Algae biomass finds diverse applications, serving as feed for aquaculture, and has been investigated for enhancing weight gain in cattle while mitigating enteric methane emissions.

Species like *Dunaliella* and *Chlamydomonas* have been extensively studied for their capacity to accumulate cadmium, lead, and mercury, significantly contributing to the reduction of environmental pollution. Others, like *Chlorella* and *Botryococcus*, can degrade hydrocarbons found in oil spills, aiding in the remediation of contaminated aquatic ecosystems. These algae also produce bioactive compounds with antimicrobial, antioxidant or anti-inflammatory properties, useful for pharmaceuticals, supplements and functional foods. Additionally, their enzymes, pigments, and biopolymers have applications in industrial processes, thanks to their ability to function under extreme conditions, making them an innovative resource for biotechnology.

Other algae species that are gaining importance in the global market include *Chlorella vulgaris*, *Arthrospira platensis*, *Haematococcus pluvialis*, which are source of proteins, carbohydrates, vitamins, minerals and fatty acids, furthermore, the last two are also source of astaxanthin and phycocyanin, very important products in the food, medical, nutraceutical and cosmetic world. Phycocyanin, a significant compound derived from microalgal and cyanobacterial cultures, is employed as a fluorescent marker in diagnostic histochemistry and finds applications as a dye in foods, cosmetics, and therapeutic agents. The global phycocyanin market is steadily increasing in value. With consumers gravitating toward natural food-grade substances, the market is expected to continue growing in the coming decades. Factors influencing the market value of microalgae biomass and the valuable extracted compounds include the production system, production costs (energy, labor), geographical origin, certification schemes (e.g., organic production), and the step of the value chain.

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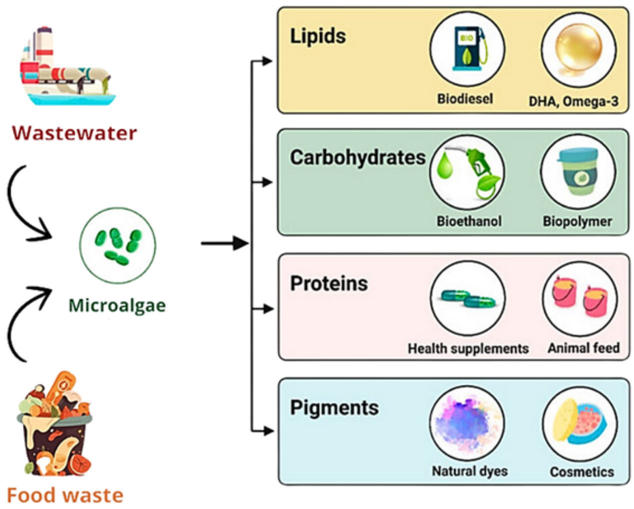

FIGURE 1: Possible applications in industry contexts. Modified from (Srimongkol et al, 2022).

Extremophiles: The Future of Sustainable Production

Extremophilic algae, such as *Galdieria sulphuraria*, are gaining particular attention due to their ability to thrive in harsh environments while providing valuable biochemical compounds. It is a member of the Cyanidiophyceae class which includes unicellular red algae thriving in extreme acidic geothermal settings with high temperatures and low pH. They showcase a unique metabolic versatility allowing for auto-, mixo-, and heterotrophic growth (Ciniglia et al., 2014). Notably, *Galdieria* exhibits remarkable tolerance to toxic metals, enabling its survival in metal-rich environments where other organisms struggle or fail to thrive (Iovinella et al., 2022). Innovative research on these extremophiles highlights their potential to overcome the limitations of conventional algae cultivation. Their resistance to contamination and ability to grow under varied conditions make them excellent candidates for large-scale industrial applications. Additionally, their use in carbon capture and utilization technologies could further solidify their role in the transition to a carbon-neutral Europe.

G. sulphuraria stands out as having commercial potential for remediating challenging wastewaters. Studies (di Cicco et al., 2022) have shown that *G. sulphuraria* is highly efficient in removing nutrients from municipal wastewaters, achieving impressive removal rates for ammoniacal nitrogen (88.3%) and phosphate (95.5%) in large-scale outdoor bioreactors. This extremophile alga emerges as a preferred strain for energy-efficient nutrient removal from urban wastewaters, surpassing other strains in terms of removal efficiencies and rates.

Galdieria cells have shown significant efficacy in recovering various crucial elements, including Rare earth elements (REEs), simplifying the extraction process (Iovinella et al., 2022). REEs, also known as lanthanides, possess unique magnetic and catalytic properties crucial for numerous technologies, including wind turbines, solar panels, batteries, fluorescent lamps, and electronic displays, among others. Traditional methods of extracting lanthanides from ores, such as pyrometallurgy and hydrometallurgy, are not only environmentally damaging but also expensive (Figure 1).

Conclusions

The future of algae production in Europe is undeniably bright. As technological advancements continue to drive efficiency and scalability, the algae industry is ready to become a cornerstone of Europe's sustainable bioeconomy.

However, achieving this vision will require overcoming existing challenges related to production costs, regulatory frameworks, and market acceptance. Collaboration between industry stakeholders, policymakers, and researchers is essential to unlock the full potential of algae in contributing to Europe's ecological and economic goals.

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