CURRENT STATE OF THE ALGAE PRODUCTION INDUSTRY IN EUROPE: AN EMERGING SECTOR OF THE BLUE BIOECONOMY

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ABSTRACT: The algae production industry in Europe is at a pivotal stage of development, poised for accelerated growth and innovation within the emerging blue bioeconomy. With ongoing technological advancements, supportive regulatory frameworks, and collaborative partnerships, the industry is well-positioned to capitalize on opportunities and address challenges to sustainably meet the demands of a rapidly evolving market landscape. Among algae, extremophilic ones represent a versatile and valuable resource in the blue bioeconomy, offering solutions for environmental remediation, renewable energy, health and nutrition, biotechnology, and aquaculture. Their unique adaptations to extreme environments enable them to address pressing challenges while contributing to sustainable economic development and resource utilization.

Keywords: algae, blue bioeconomy, extremophiles

1. INTRODUCTION

The algae production industry in Europe is experiencing significant growth, fueled by increasing awareness of the environmental and economic benefits of algae-based product, positioning itself as a prominent sector within the blue bioeconomy. Market analyses indicate a steady rise in demand for algae- derived products across multiple sectors, including food and beverages, pharmaceuticals, nutraceuticals, cosmetics, and biofuels. Emerging applications, such as algae-based bioplastics and sustainable aquaculture feed, are driving further market expansion and diversification.

Ongoing research and development efforts are focused on enhancing algae cultivation techniques to improve productivity, efficiency, and scalability. Innovations in photobioreactors, cultivation systems, and genetic engineering are optimizing algae strains for specific applications and environmental conditions. Integrated approaches, such as co-cultivation with other microorganisms or utilization of waste streams, are being explored to maximize resource efficiency and minimize environmental impact.

European regulatory bodies are actively engaged in shaping the regulatory framework for algae production and utilization, aiming to ensure safety, sustainability, and market competitiveness (EC, 2020). Standards and certification schemes are being developed to verify the quality, safety, and sustainability credentials of algae-derived products, enhancing consumer confidence and market acceptance. Policies promoting research, innovation, and investment in the algae sector, such as Horizon Europe funding programs and the European Green Deal, are driving momentum for industry growth and development.

2. THE IMPORTANCE OF ALGAE IN ECONOMY, ENVIRONMENT AND HEALTH

Algae production is increasingly recognized for its role in promoting sustainability and circular economy principles by mitigating greenhouse gas emissions, reducing dependence on finite resources, and promoting resource recycling. Integration with other sectors, such as wastewater treatment, carbon capture and utilization, and sustainable agriculture, is unlocking synergies and creating new business opportunities within the broader bioeconomy. Despite significant progress, challenges such as high production costs, technology scalability, regulatory complexity, and market competitiveness remain obstacles to overcome. Addressing these challenges presents opportunities for innovation, collaboration, and policy support to unlock the full potential of the algae production industry in Europe and realize its contributions to the blue bioeconomy. Algae, integral to marine ecosystems, offer numerous ecosystem services vital for addressing EU strategic priorities. They contribute significantly to global primary production, absorb nutrients, provide coastal defense, and potentially aid in carbon sequestration. Algae are used in several commercial applications. Already considered as a foodstuff in Asia, algae biomass is increasingly being included in western diets for human consumption or food applications (Peteiro, 2018), due to their nutritional and therapeutic properties and the search for more sustainable and natural food sources. *Spirulina* is a cyanobacteria traditionally used in Western human nutrition since the 1970s and currently referred to as a “super food” given its nutritional properties (Jung et al., 2019). Some microalgal species are up-to date important sources of bio-compounds such as antioxidants, pigments, oils, and vitamins (Niccolai et al., 2019). Among macroalgae, some seaweed species collected along the European coasts such as *Laminaria digitata*, *L. hyperborea*, *Ascophyllum nodosum*, and *Gelidium corneum* are used as feedstock for the extraction of food, and the hydrocolloids alginate and agar (Peteiro, 2018). 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 (Kinley et al., 2020). Despite its potential, there's limited understanding of the current state of the European algae industry, underscoring the need for comprehensive data to steer informed decisions towards its sustainable development.

2.1 The algae production in Europe

As reported by Araujo et al. (2021), the European algae sector consists of 225 companies producing both macroalgae and microalgae, with 33% specializing in microalga. Additionally, 222 *Spirulina* producers were identified, with 15% also producing microalgae. Spain, France, and Ireland are leading in algae production, followed by Norway, the United Kingdom, Germany, and Portugal. Norway, France, and Ireland are the top producers of seaweed biomass in Europe. Over the last decade, there has been a 150% increase in new algae-producing companies, with some companies operating since before 1980. Despite this growth, algae production is not the primary activity for less than 10% of these companies. The increasing trend in new algae production companies highlights the sector's potential for growth but also underscores the need for critical analysis, considering the closure or diversion of activities by other companies over the years. While studies emphasize the economic sustainability of algae biomass production in Europe, challenges such as small market size, variability in biomass supply, and technological limitations persist, hindering sector expansion.

3. EXTREMOPHILIC ALGAE IN THE BLUE BIOECONOMY

Extremophiles are organisms that thrive in extreme environments that are hostile to most life forms. These environments can include extreme temperatures, high or low pH levels, high salt concentrations, high pressure, and even high levels of radiation. They are found in a wide range of habitats, from deep-sea hydrothermal vents to acidic hot springs to polar ice. By an ecological point of view, extremophiles play crucial roles in their respective ecosystems, contributing to nutrient cycling, energy flow, and ecosystem resilience. They serve as primary producers in extreme environments, providing energy and organic matter for higher trophic levels. They also serve as models for studying the limits of life and the potential for life beyond Earth, informing astrobiology research and space exploration.

Extremophiles have evolved various adaptations to survive and thrive in extreme conditions. These adaptations may include unique enzyme systems, cell membrane structures, and metabolic pathways. Thermophiles, for instance, produce thermostable enzymes that can function at high temperatures without denaturation, while halophiles have osmoregulatory mechanisms to maintain cellular water balance in high-salt environments. These biochemical properties give a reliable mean on the significant biotechnological and industrial applications. Enzymes produced by extremophiles, such as polymerases, lipases, and proteases, are widely used in biotechnology, including PCR (polymerase chain reaction), industrial processes, and pharmaceuticals. Extremophiles are also studied for their potential in environmental remediation, including bioremediation of contaminated sites and wastewater treatment.

3.1 Emerging sectors of employment of extremophilic algae

Bioremediation and Wastewater Treatment. Extremophilic algae are valuable for bioremediation efforts in polluted water bodies and industrial wastewater treatment. They can absorb heavy metals, pollutants, and excess nutrients, thereby helping to clean contaminated water sources and contributing to environmental sustainability. Species of *Dunaliella* and *Chlamydomonas*, have been investigated for their ability to bioaccumulate heavy metals from contaminated environments. These algae can absorb metals like cadmium, lead, and mercury from water, effectively reducing their concentration and mitigating environmental pollution. *Chlorella* and *Botryococcus*, have demonstrated the ability to degrade hydrocarbons found in oil spills. These algae can metabolize and break down crude oil components, assisting in the remediation of contaminated aquatic environments.

Algae-based systems, such as algal bioreactors or constructed wetlands, utilize extremophilic algae to remove nutrients like nitrogen and phosphorus from wastewater. These algae absorb nutrients for growth, thereby reducing nutrient levels in the water and preventing eutrophication of receiving water bodies. Some extremophilic algae, particularly those adapted to high-salinity environments, can thrive in saline wastewater or brackish water. These algae can be used in wastewater treatment systems to simultaneously remove pollutants while producing biomass suitable for biogas production through anaerobic digestion. This process helps in both wastewater treatment and renewable energy generation. *Nutraceuticals and Pharmaceuticals*: Extremophilic algae produce unique compounds and bioactive molecules that have potential applications in the pharmaceutical and nutraceutical industries. These compounds may exhibit antimicrobial, antioxidant, or anti-inflammatory properties, making them valuable for drug discovery and development. Additionally, extremophilic algae-derived products may be used as dietary supplements or functional ingredients in food and beverage formulations.

Biotechnology and Bioproducts: Extremophilic algae offer opportunities for biotechnological applications, including the production of enzymes, pigments, and biopolymers. Enzymes derived from extremophilic algae can withstand harsh conditions and catalyze biochemical reactions in industrial processes such as bioremediation, bioconversion, and biocatalysis.

3.2 The case of the extremophilic *Galdieria*

Galdieria, a member of the Cyanidiophyceae class, encompasses unicellular red algae thriving in extreme acidic geothermal settings with high temperatures and low pH, showcasing 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. Leveraging its extremophilic nature, *Galdieria* holds considerable potential for diverse biotechnological applications in environments characterized by high temperatures, low pH levels, and elevated concentrations of heavy metals and organic compounds, notably sugars. Unlike many other microalgae, *Galdieria* can be cultivated under conditions resistant to contamination by microorganisms, a common hurdle in biotechnological applications (Iovinella et al., 2022; Palmieri et al.,2022). Research on *Galdieria* predominantly focuses on its autotrophic cultivation, yielding valuable microalgal pigments such as ß-carotene, astaxanthin, and phycocyanin, utilized in various sectors including animal feed, food products, health supplements, and biofuel production. The composition of storage compounds such as glycogen and lipids can be modulated significantly based on growth conditions, enhancing its potential for biofuel production. Moreover, *Galdieria* biomass holds promise as a food ingredient, offering options for protein-rich or insoluble dietary fiber-rich diets, alongside its low lipid content. *Galdieria*, with its remarkable extremophilic characteristics, stands out not only among eukaryotic organisms but even among extremophilic prokaryotes, making it highly valuable in biotechnology. It is the sole algae capable of thriving through photo-, mixo-, and heterotrophic growth, achieving biomass concentrations exceeding 100 g/L dry weight. In heterotrophic conditions, it can utilize over 27 different sugars and polyols, yielding substantial biomass and beneficial compounds.

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

Rare earth elements (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. Furthermore, with the growing demand for REEs, there is a pressing need for sustainable and cost- effective recycling solutions to mitigate resource scarcity risks. Efforts have been focused on developing biological methods for recovering REEs from wastewater systems, including biosorption by algae or cyanobacteria. *Galdieria* cells have shown effectiveness in recovering various crucial elements, including phosphates and REEs, simplifying the extraction process.

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. While most microalgae exhibit low production of phycocyanin when grown heterotrophically, *G. sulphuraria* stands out for its ability to produce significant amounts of phycocyanin even under heterotrophic conditions in darkness. Compared to other microalgae like *Arthrospira (Spirulina) platensis*, which relies on sunlight and climatic conditions, *G. sulphuraria* demonstrates superior biomass productivity, resulting in 1–2 orders of magnitude greater phycocyanin productivity. The potential of *G. sulphuraria* extends beyond phycocyanin production. It produces glycogen as energy and carbon reserves, offering advantages over starch in terms of solubility and accessibility. *G. sulphuraria* heterotrophic growth allows for high biomass concentrations, with glycogen accumulation reaching up to 50% of the dry cell weight. Additionally, *G.*

sulphuraria biomass possesses nutritional value, being rich in proteins and polysaccharides, making it suitable for various dietary applications. In summary, *G. sulphuraria* emerges as a versatile organism with potential applications in phycocyanin production, glycogen accumulation, and as a nutritional ingredient. Its unique properties, including heterotrophic growth capabilities and high tolerance to environmental extremes, make it a promising candidate for biotechnological and nutritional advancements.

3. CONCLUSIONS

The European algae industry holds significant potential to address critical societal challenges, including carbon neutrality, sustainable food systems, and the development of a circular bioeconomy. While many production units are small, they provide essential livelihoods in coastal areas. Microalgae, primarily produced in photobioreactors, show potential for high-value products but face challenges in scaling for biofuel production. The sector is balanced between Spirulina and other algae, with opportunities for diversification. Extremophilic algae, such as G. sulphuraria represent a valuable resource in biotechnology, offering unique capabilities and opportunities for innovation in environmental remediation, industrial processes, and the discovery of novel bioactive compounds. Future growth depends on technical innovations, cost reduction, market expansion, and regulatory streamlining.

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REFERENCES

Araújo, R., Vázquez Calderón, F., Sánchez López, J., Azevedo, I.C., Bruhn, A., Fluch, S., Garcia Tasende, M. Ghaderiardakani, F., Ilmjärv, T., Laurans, M., Mac Monagail, M,. Mangini, S,. Peteiro, C., Rebours, C., Stefansson, T. and Ullmann, J.,2021. Current Status of the Algae Production Industry in Europe: An Emerging Sector of the Blue Bioeconomy Front. Mar. Sci. 7:626389. doi: 10.3389/fmars.2020.626389

Ciniglia, C., Yang, E.C., Pollio, A, Pinto, G., Iovinella, M., Vitale, L., Yoon, H.S., 2014.Cyanidiophyceae in Iceland: Plastid rbc L gene elucidates origin and dispersal of extremophilic Galdieria sulphuraria and G. maxima (Galdieriaceae, Rhodophyta). *Phycologia* , 53, 542–551

di Cicco, M.R.;,Palmieri, M., Lubritto, C., Ciniglia, C., 2022. Microalgae-Based Nutrient Recovery from Urban Wastewater. In *Algal Biorefineries and the Circular Bioeconomy*; CRC Press: Boca Raton, FL, USA,; pp. 115–145. ISBN 9781003195429.

EC, 2020. Commission Communication COM/2020/381. A Farm to Fork Strategy for a Fair, Healthy and Environmentally-Friendly Food System. Available online at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0381 (accessed May, 2020).

Iovinella, M.; Lombardo, F.; Ciniglia, C.; Palmieri, M.; di Cicco, M.R.; Trifuoggi, M.; Race, M.; Manfredi, C.; Lubritto, C.; Fabbricino, M.; et al., 2022. Bioremoval of Yttrium (III), Cerium (III), Europium (III), and Terbium (III) from Single and Quaternary Aqueous Solutions Using the Extremophile Galdieria sulphuraria (Galdieriaceae, Rhodophyta). *Plants* , *11*, 1376

Jung, F., Krüger-Genge, A., Waldeck, P., and Küpper, J.-H. ,2019. *Spirulina platensis*, a super food? J. Cell. Biotech. 5, 43–54. doi: 10.3233/jcb-189012

Kinley, R. D., Martinez-Fernandez, G., Matthews, M. K., de Nys, R., and Magnusson, M., 2020. Mitigating the carbon footprint and improving productivity of ruminant livestock agriculture using a red seaweed. J. Clean. Prod. 259:120836. doi: 10.1016/j.jclepro.2020.120836

Niccolai, A., Zittelli, G. C., Rodolfi, L., Biondi, N., and Tredici, M. R., 2019. Microalgae of interest as food source: biochemical composition and digestibility. Algal Res. 42:101617. doi: 10.1016/j.algal.2019.101617

Palmieri M, Iovinella M, Davis SJ, di Cicco MR, Lubritto C, Race M, Papa S, Fabbricino M, 2022. Ciniglia C.*Galdieria sulphuraria* ACUF427 Freeze-Dried Biomass as Novel Biosorbent for Rare Earth Elements. *Microorganisms*.; 10(11):2138. https://doi.org/10.3390/microorganisms10112138

