A CIRCULAR BIOECONOMY CHAIN: INDICATORS APPLIED TO THE SUSTAINABLE PRODUCTION OF MICROALGAE FOR INDUSTRIAL PURPOSES

**1TIZIANA BELTRANI, 2GABRIELE RACITI, 2SERGIO ARFO’,**

**3RACHELE CASTRO, 4SANTI TOMASELLI, 2AGATA MATARAZZO**

1Laboratory for Resources Valorization (RISE), Department for Sustainability, ENEA-Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Italy

*2Department of Economics and Business, University of Catania, Corso Italia 55, Catania, Italy*

3Consiglio Nazionale delle Ricerche, Istituto per la Ricerca e l’Innovazione Biomedica (CNR-IRIB)

4Department of International Economics at European Funds, University of Milan, Via Settembrini 33, Milan, Italy

1tiziana.beltrani@enea.it; 2amatara@unict.it.

ORCID: 10000-0003-1537-1915

**Abstract:** The importance of environmental sustainability, together with its economic and social pillar, and Circular Economy issues are permeating more and more any aspect of our daily life through proactive initiatives, tending to zero-waste and zero-pollutant production processes to the ongoing ecological transition. Hence, the need for some industries, such as the nutraceutical, pharmaceutical and the cosmetic one, of innovating their production processes in a circular perspective, trying to ensure the minimum environmental impact, a high level of quality throughout the LCA of its products and services as well as the maximum expression of hi-tech – hi-green performance combination. This paper aims to demonstrate how internationally shared sustainability objectives can guide and bring concrete benefits through companies that embrace a Circular Bioeconomy approach and how this, in turn, can be the basis of a multi-output production process related to markets and bioeconomy sectors. To this end, a case was studied concerning a pilot project dedicated to research and development activities applied to the nutraceutical, cosmetic, pharmaceutical and green agriculture sectors. Its implementation should take place as part of the activities of the Micro Algae District, where the production of algae, phytochemicals and other substances of pharmaceutical, cosmetic and nutraceutical interest is planned through a combination of mathematical models, artificial intelligence and hi-tech technologies.

**Keywords:** Bioeconomy1, Sustainability2, Circular Economy3, Nutraceuticals sector4, Microalgae District Symbiosis5

**1.1** **Introduction**

The last few years have been characterized by a positive change from a technological point of view and environmental sensitivity (Ziesel 1999). In every international, European and national scenario, this renewed sensitivity guides both individuals’ lifestyles and the industrial and production possibilities. Within the Sicilian Region, there is a great turmoil in this direction, as evidence of this is the yet-to-be-established *Micro Algae District* (DEI, *Distretto Europeo Innovazione Ibleo*) which, in a circular perspective, aims to create plants for the treatment of microalgae to produce micro granular capsules and other products for the pharmaceutical, cosmetic and nutraceutical market (Decreto 9 luglio 2012). This paper aims to illustrate how the Micro Algae District, which is expected to be effective from autumn 2022 or early 2023 in the Green Energy Valley, will embody an economic actor in the ecological transition through investments in microalgae plants (e.g., Spirulina, Chlorella, Dunaliella), thanks to an innovative circular vision along with a connection language sensor system ( Decreto 9 luglio 2012).

* 1. **Review of the literature**

The ambition of the *Micro Algae District* (DEI, *Distretto Europeo Innovazione Ibleo*) is to create an area focused on green bioenergy, where a range of algae species can be marketed in the nutraceutical, pharmaceutical and cosmetic sectors. Moreover, these outputs will also become inputs for materials used in agriculture and zootechnics (Ullmann and Grim 2021). The innovation of the district is given precisely by the use of algorithms based on artificial intelligence and by its focus on environmental sustainability since CO2 will be naturally reduced through photosynthesis, which transforms CO2 into oxygen and sugars; additionally, water resources will be indirectly protected as they will not be directly consumed (European Commission, *The European Green Deal*, Brussels, 2019).

The *DEI Micro Algae District* will increase the extraction and conversion of microalgal lipids and carbohydrates that can be converted into different organic compounds of interest. Above all, the District will handle the commercial production of new major products from microalgae, including food, phytochemicals, nutraceuticals and feed: algae have great potential to produce a wide range of valuable compounds, beyond their current exploitation.

In turn, the DEI district is part of the “Green Energy Valley” joint venture, which includes other Italian and foreign companies, institutions and universities:

* DEI Micro Algae District (the province of Ragusa is the projected location), with Ragusa Algae Project SRL, Ragusa Green World SRL
* EmmeC2 Artificial Intelligence District
* E.I.F.E. International Economy Department European Funds & Innovation
* PAL 4 Solar Energy LLC (based in the United Arab Emirates), whose adhesion and negotiation are still in progress.

Ragusa Algae Project and Ragusa Green World are both Limited Liability Companies (SRL), with registered offices in Via P. Martinelli n. 8, 97100 - Ragusa (RG), VAT no. 01693030882 and 01701040881 respectively. The former intends to create an agricultural division with very high technological innovation for the cultivation of microalgae aimed at the production of algae biomass. For this initiative, the Company has the possession of a plot of land located in the municipality of Acate Gulfi, in the district of Poggio di Ferro, with a total area of approximately 25,970 m2 divided into macro-zones called Block A (office, changing room, canteen, laboratory, inoculation PBR, warehouse, transformer room and electrical panels, technical room for drinking water), Blocks B and B1 (osmosis technical room, nutrient box, nutrient warehouse, filtration, drying and packaging, cyclones, hot air generator, crushing mill, controlled temperature warehouse, anteroom and toilet), Block C (water tanks of various types) and Block D (greenhouse) and parking (Directive 2002/46/EC).

The activity that the Company intends to implement represents a milestone of the green economy as well as a novelty in the whole Sicilian territory and allows to obtain, simultaneously, various benefits, including processes with extremely low environmental impact, consumption of CO2 as a nutrient main for algal growth, placing organic products on the market, improvement of local employment levels. Indeed, the company aims to enter a rapidly expanding market by presenting itself on the Sicilian and national territory through the integration of an innovative project and advanced technologies. In fact, the Agricultural Division for the intensive cultivation of microalgae consists of an innovative plant where the algae cultivation cycle takes place inside closed PBRs, located inside a greenhouse, to allow the creation of a constant microclimate, while the transformation activity takes place in special technical spaces. The cultivation and transformation cycles are aimed at obtaining Spirulina or, alternatively, Chlorella, Dunaliella or Haematococcus (Santini et al 2017).

* 1. **Materials and Methods**

It is important to identify reference sectors, types of companies or entities and the number of subjects potentially interested. Then, a maturity analysis evaluates the maturity stages for the application of the good practice, it is followed by the quantification of the impact in terms of magnitude and economic, environmental and social performance. Actors characterization takes place by identifying once more the reference sector, the type of company and/or entity (turnover, number of employees, population), any relevant attributes, geographical location, any collaborations with other actors, the amount of the investment, and the possible use of a patent. Subsequently, the target population is defined, quantifying the number of companies and/or entities, their geographical location and the names of possible implementers (Verma and Popli 2018). To quantify the magnitude of the impact it is necessary to multiply the population of implementers by the results achieved, taking into account their degree of Circular Economy maturity (Regulation (EC) No. 258/97).

Given that the Micro Algae District is still in its planning phase, the company intends to respect the preliminary indicators named below elaborated by ICESP’s Working Group 6 which allow to carry out a replicability comparison, distinguishing environmental, economic and social results. Those most consistent with the company’s activities will be verified and tested only when data will be available and reliable; on the other hand, those that are not compatible with the company’s activities will contribute to the quantification of further indicators of Circular Economy (European Commission Brussels, 2020).

Environmental results: Percentage of materials used that are recycled as input materials; Energy consumption within the organization; Reduction of water consumption; Reduction of energy consumption; Extension of the life cycle of materials after recycling; Reduction of CO2 emissions; Rate of biodiversity loss; Percentage of recycled waste (packaging); Quantification of ecological footprint (through SIMA PRO software); Percentage of recycled biomass; Water sources significantly affected by water withdrawal; Water Exploitation Index (WEI); Percentage of use of materials with low environmental impact; Percentage and total volume of water recycled and reused; Percentage of use of self-produced electricity from renewable resources.

Economic results: Reduction of waste disposal costs; Reduction of raw material costs; Reduction of energy costs; Reduction of water costs; Reduction of transport costs; Increase in revenues; Increase in corporate reputation; Increase in waste treatment costs; Increase in equipment costs; Increase in costs of specialized personnel; NPV of the investment; Pay Back Period; Revenues from the sale of new products generated by the use of biomass; Revenues from the sale of new products generated by the use of waste; Cost savings resulting from the use of recycled products; Public financial support and private investments; Additional costs resulting from the adoption of the Good Practice (Directive 2004/24/EC).

Social results: Human health improvement; Job creation; Quality of life improvement; Increased consumer awareness; Education of workers on the green economy; Number of stakeholders, from various groups, involved in consultations; Job retention.

Currently, the indicators in Table 1 below can be quantified through a meta-analysis based on existing literature that meets the dimensional requirements and aspirations the district intends to achieve (Garcia et al 2017). These indicators are: water sources significantly affected by water withdrawal, the percentage of water recycled and reused, the percentage of use of self-produced electricity from renewable resources and the reduction of CO2 emissions for the environmental indicators; the reduction of waste disposal costs among the economic indicators; job creation for the social indicators (Regulation (EC) No. 1924/2006).

Table 1. Preliminary computation of the replicability study indicators.

|  |  |  |
| --- | --- | --- |
| **Indicator** | **Method(s)** | **Result** |
| Water sources significantly affected by water withdrawal | Life-Cycle Water Use | 32 (L/L) |
| Percentage of water recycled and reused | Water recycled (L) x 100 / total water (L) | 80% |
| Percentage of use of self-produced electricity from renewable resources | Self-produced energy x 100 / total energy produced | 80% |
| Reduction of CO2 emissions | Life-Cycle CO2 Emissions | -1.1 kg CO2 |
| Reduction of waste disposal costs | Regional tables comparison | -20% |
| Job creation | Estimation in Table 3.2 | 76+ |

Source: Personal estimation through meta-analysis.

* 1. **Results and discussions**

Microalgal biomass contains about 50% carbon, usually obtained photosynthetically from CO2, that coupled with their ability to grow on non-arable land, utilizing waste nutrients, have made them an attractive potential vehicle for carbon sequestration, storage and reduction of CO2 from the atmosphere (Regulation (EC) No. 178/2002). Other environmental advantages derive from the processes: at the base of the industrial processes, there is renewable energy, which achieves a low environmental impact and therefore reduces the pollution and the ecological footprint of the company on the territory. Furthermore, water resources are protected since water consumption will be drastically reduced as wastewater is reintroduced into a circular cycle to avoid environmental impacts, in the perspective of industrial symbiosis. The addition of microalgae to the tanks of aquaculture organisms has additional positive benefits: indeed, algae help to improve the quality of the water, leading to higher survival and growth rates. Some by-products are targeted to restore soil fertility and, therefore, contribute to the processes of restorative agriculture. Still, nitrogen (N)-fixing microalgae can absorb and transform N from the atmosphere into a form accessible to higher plants as they can provide more than 20kg N/Ha/year or up to a third of the requirements of traditional cultivars. These environmental advantages meet the requirements of the replicability study since they involve greenhouse gases and waste reduction, reduction of consumption of non-renewable resources (in water, soil, minerals, raw materials) and increased use of secondary raw materials. Moreover, based on the evolution of the project, a photovoltaic system functional to the CO2 absorption process could be exploited within the technology park, trying to achieve the objectives of carbon neutrality (Nasri et al 2014). The bio-district is unique in its kind, which is why it will attract further investments and funds and will be a starting point for the creation of new forms of the sustainable supply chain.

For the granting of EU funding, which amounts to about 8-10 million euros, there must be an incremental innovative benefit given by a pending patent that will affect the added value of the extracted elements useful in the sectors of interest of the actors and, in particular, the pharmaceutical and agricultural one. The high cost of closed photobioreactors can only be offset by a high-value product. Photosynthetic production costs are expected to be higher than about €140/kg dry weight, representing a substantial part of the production cost. This suggests the need to focus on improved algal productivity and efficiency of production of the required scale to improve competitiveness, as their value in aquaculture is well recognized. Again, these economic benefits are in line with the requirements of the replicability study since they involve cost reductions, revenues from new products, image and reputation. One of the most expensive items in the cultivation of Spirulina is represented by the cost of nutrients, which are mainly salts containing nitrogen, phosphorus, iron, calcium, or chemical compounds with a wide range of uses and therefore easily available in a variety of formats that appear to be sort of pure depending on the presence of contaminants. One method to reduce the cost of nutrients is to recycle the culture medium, a practice that is carried out by injecting the cultivation water back into the PBRs during or after the filtration processes necessary for harvesting (Pagliaro 2020).

According to the World Health Organisation, malnutrition or lack of essential amino acids, fatty acids, minerals, antioxidants and vitamins are linked to numerous diseases of growing concern, such as nutritional anaemia (iron and vitamin B12 deficiency), xerophthalmia (vitamin A deficiency) and endemic goitre (iodine deficiency). Using the advantages of new technologies in the microalgae industry would solve nutritional deficiencies and be a great benefit to the environment and to the product quality which would assumingly reflect a better living standard of society, transforming the market and fulfilling the SDGs described in Chapter 1 (Ellen MacArthur Foundation, 2015).

There is a huge potential for developing a sustainable algae industry along the whole value chain, supported by applied research and the valorisation of strain collections and genetic resources along with patents, new applications, technologies, and product developments (Palahí et al 2020).

This could be an important step towards developing a bioeconomy while creating new education possibilities, innovations, services, indirect employment (including suppliers of resources and technology necessary for algal biofuels, such as nutrients, CO2, polyethylene liners, PBRs, pumps), low- and high-profile jobs linked to the cultural, technological and cognitive growth of specialists.

In social acceptability, transparency in how indicators are reported and the extent to which a company’s sustainability goals are implemented in facility operations, products, and general strategies are important factors (Pursula et al 2018).

These goals include safety of operation and, therefore, workdays lost to injury, even if few types of health issues or injuries are specific to algal production (Bröring et al 2020). However, employment numbers are sensitive to technical parameters such as biomass productivity, project duration, lipid content extraction and conversion rate.

Table 2 below shows an estimate of the human resources involved, which could amount to 76 individuals, considering the positions that will be needed.

To these, multi-firm medical representatives, who deal with the sale of active ingredients, should be added (Basu et al 2007). In the future, the model will be likely to be exported by creating different branches and therefore it would be possible to multiply the number of jobs.

These social advantages match the requirements of the replicability study since they involve positive impacts on society (Ellen MacArthur Foundation, 2019).

Table 2. Estimation of Human Resources involved.

|  |  |  |
| --- | --- | --- |
| **Section or job** | **Description** | **Total** |
| Construction of structures and outbuildings | 2 teams of 10 workers | 20 |
| Artificial intelligence algorithms and renewable energy sources | Team of photovoltaic installers (5 workers) +  Management and installation of cables and sensors (5 workers) | 10 |
| Technical management of the plant | Nursery (3 biologists + 1 chemist) + Factory (2 sensor workers + 3 technicians) + R&D (5 multidisciplinary team) | 14 |
| Technical Scientific Committee | DEI (6) + EmmeC2 (3) + E.I.F.E. (3) + PAL 4 Solar Energy (3) | 15 |
| Research grants and researchers | 1 x Physics, computer science, economics, biology, chemistry, engineering | 6 |
| Security | Surveillance activities in the morning (2) and evening (2) | 4 |
| Commercial and communication office | Sales manager (1) + operators (3) + secretary (1) | 5 |
| Practices management unit | Engineer (1) + assistant (1) | 2 |
|  |  | Total: 76 |

Source: Personal estimation based on current personnel needs.

In order to support corporate decisions and to better understand the context surrounding the site of the *DEI Micro Algae District*, it is possible to quantify, individually, some of the indicators that make up the Human Resource Development Index (HRDI) (Bryden et al 2017). In particular, as displayed in Table 3, the HRDI is a flexible index made up of 6 sub-indexes: the Employment Index; the Education Index, which, in turn, is given by the weighted sum of the Literacy Index and the Educational Facility Index; the Sex Ratio Index; the Health Facilities Index; the Living Conditions Index that is being replaced by the Climate Risk Index (CRI); the Income Index (Wong et al 2015).

Table 3. Computation of the Human Resource Development Index factors.

|  |  |  |  |
| --- | --- | --- | --- |
| **Index** | **Factors** | **Result** | **Source(s)** |
| Employment Index | Total number of workers / Total population | 0.504 | Istat |
| Education Index | 1/3 Literacy Index  (Total number of literates/Total Population) | 0.283 | Istat,  Comune di Ragusa, scuolaitaly.it |
| 2/3 Educational Facility Index  (Total number of schools and colleges/Total population) |
| Sex Ratio Index | Number of females per 1000 males | 1,016.130 | UrbiStat |
| Health Facilities Index | Total number of hospitals/ total population | 0.0000190 | ASP Ragusa |
| Climate Risk Index | A multi-factor index that shows to what extent countries and regions have been affected by impacts of weather-related loss events | 0.261 | CMCC Foundation |
| Income Index | Total Income /  Total population | € 12,824.00 | Osservatorio Findomestic–Prometeia |

Source: Personal estimation via lab24.ilsole24ore.com/qualita-della-vita/Ragusa/.

The analysis of the HRDI considers the population in the province of Ragusa in 2019, the year of the most recent data, which accounts for 315,601 individuals. The six indexes provide an overall view of the main areas concerning the social, economic and environmental aspects in the province of Ragusa.

* 1. **Conclusions and future perspectives**

The global rise in CO2 levels is an international issue demanding feasible solutions (Pinto da Costa 2017). The ultimate goal should be to drastically curb CO2 emissions through decreasing dependency on fossil fuels as well as investigating options for CO2 sequestration. Microalgae, due to their high growth rates and the fact that they do not require arable land, appear to be a promising solution for the fixation of CO2 photosynthetically from point source emissions (Bux et al 2016). Although the process is technically viable, it is not economically feasible; the main challenge is its implementation on a large scale and the collection of significant investments from private companies and funds from public bodies. Commercialization of new products is expected to be slow, however, microalgal biotechnology is an innovative industry and, therefore, a few significant challenges remain to be solved as the advantages associated with algal production are likely to ensure that efforts continue (Regulation (EC) No. 1925/2006).

With circular Good Practices collected by the ICESP network, several contributions have been provided from different sectors. For their part, companies have set objectives from an ethical point of view and, consistently with their strong orientation towards the Circular Economy, they also aspire to be the final stage for many supply chains in the agrotechnical sector. The DEI Micro Algae District is apt to become the world leader in the sustainable and performing cultivation of microalgae on an industrial scale, allowing the production of raw materials of the highest value and quality. The project aspires to create a unique biotechnological centre of its kind, highly technological and efficient from a production and environmental performance point of view (Zingale et al., 2022). The indicators chosen will ensure high environmental performance and will serve to guide the company's research and development activities toward a new concept of bio-plant, sustainable and perfectly in balance with the territory and its resources (L. 28 dicembre 2015, n. 221).

The previously examined plants outline new traits of industrial production that are increasingly technological and sustainable at the same time, ensuring high production performance. Moreover, the alignment with the objectives set, such as the 2030 Agenda’s SDG 2 (Zero Hunger), SDG 3 (Good Health and Wellbeing), SDG 6 (Clean Water and Sanitation), SDG 7 (Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Production), SDG 14 (Life Below Water), SDG 17 (Partnership for the Goals), the Paris Agreement and carbon neutrality, will allow the export of sustainable production models to other places so that Sicily would strengthen its central position in the Mediterranean basin, gradually becoming an actual hub of innovation, investments and know-how at the highest levels (DG Environment - 2018).

Overall, the *DEI Micro Algae District* represents an important step toward the implementation of a circular economy chain, supported by applied research and the valorisation of resources through patents, new technologies and product development. Indeed, its uniqueness will attract additional private investments and public funds in Sicily, leading to a likely export of the model in several domestic and international branches. In this case, the number of direct and indirect jobs created in the territory will be multiplied together with professional growth possibilities. Moreover, the bio-district’s outputs will also help reduce nutritional deficiencies by supplying vitamins, amino acids and antioxidants to a society moving towards better living standards while making a substantial contribution to the Sustainable Development Goals related to zero hunger, good health and well-being, so as to endorse product quality and consumer protection (Rajeev 2017). They will be communicated with transparency as they are implemented across the entire facility. At the same time, the carbon dioxide absorption process could be boosted by exploiting a photovoltaic system within the technology park, in this way the goals of carbon neutrality set by the 2020 European Climate Law will be achieved.

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