Chemicals and Polymers from Microalgae: an Economic Assessment

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Nowadays, microalgal biomass constitutes one of the solutions to ameliorate the dependence on fossil resources and reduce the greenhouse gas emissions. Microalgae present numerous advantages, such as high productivity, the use of non-productive and non-arable land, the utilization of non-fresh water, the production of multiple products and the recycling of CO_2. To date, numerous pathways exist for the utilization of microalgae (focusing primarily to biofuels), however, their maturity level is still in a demo-level. Each microalgae-based value chain is determined by the economic potential of the applied technology, according to the relevant production cost. Given the multiple technology options and their interdependencies, an integrated techno-economic analysis is crucial in guiding research efforts towards a sustainable microalgal industry. In this context, a mathematical model is developed to design a microalgae-based plant for the production of 'extracellular' polysaccharides (EPS) and hydrocarbons (HCs) and their conversion to chemical and polymers. The model accounts for multiple alternative technologies for the process steps, thus enabling the comparison of different value chains. The flowsheet variants reflect the options offered by making use of different strains, upstream technologies, downstream processing and conversion processes.

The conceptual design of the 2 microalgal platforms (EPS- and HCs-based) led to the identification of 8 scenarios for the production of primary and secondary chemicals and polymers. The consideration of EPS and HCs as the final products is economically more promising, due to the more simple plants, with respect to the demanded process areas and equipment, and the larger value of the products. Generally, the ratio of product value to production cost should be >0.4-0.5 so that a plant can be economically viable, upon process optimization. For all the scenarios, the area with the major contribution on both CAPEX and OPEX is the one with the PBR units, followed by the recovery/'milking' area; the conversion to chemicals and polymers area presents a smaller effect to the economics. As a result, the clear 'hot-spots' of the integrated process are the PBR units: both CAPEX and OPEX values are the largest among the other process steps. Thus, the PBRs should be the primary target for process optimization. From the selected key-process parameters, the biomass specific growth rate and the EPS/HCs yield (both associated with the cultivation area) are the ones with the major effect on the production cost, followed by the 'milking' and drying efficiencies (both associated with the downstream processing). The impact of raw materials and utilities on the production cost is modest, with the CO_2 being the most important one. In principle, a microalgae-based plant should operate in a >5,000 tons/year capacity, to be less dependent on this parameter. In any case, it is important to consider complementary products, such as the 'bleeding' biomass, as the means to increase the revenue of the plant. It can be concluded that the developed cultivation and 'milking' technologies have the potential to operate under economic sustainability, provided that all the involved processes will be optimized and the targeted products are of higher than commodities value.

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Supplementary Material

Investigated Scenarios

- S1a: A plant for the production of high volume-low value EPS: capacity 20,000 tons/year.
- S1b: A plant for the production of low volume-high value EPS: capacity 200 tons/year.
- S2a: A plant for the production of high volume-low value HCs: capacity 10,000 tons/year.
- S2b: A plant for the production of low volume-high value HCs: capacity 500 tons/year.
- S3a: An EPS-derivatives plant for the production of 1,4-pentanediol (PenDO) and its polymerization to polyesters/polyamides: capacity 2,000 tons/year.
- S3b: An EPS-derivatives plant for the production of 2,5-furandicarboxylic acid (FDCA) and its polymerization to poly(ethylene 2,5-furandioate) (PEF): capacity 10,000 tons/year.
- S3c: An EPS-derivatives plant for the production of adipic acid and its polymerization to polyesters/polyamides: capacity 10,000 tons/year.
- S4: A HCs-refinery plant for ethylene/propylene production: capacity 100,000 tons/year.

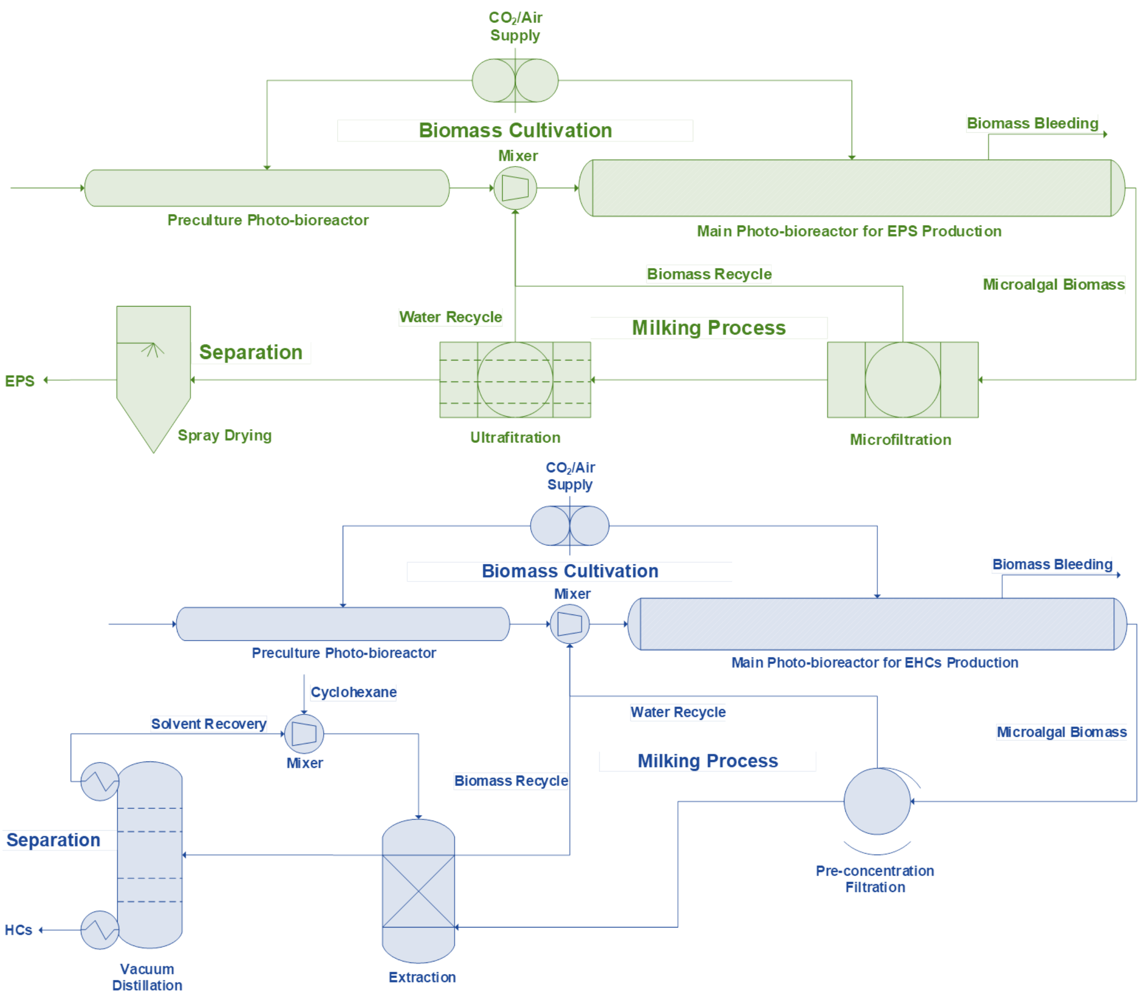


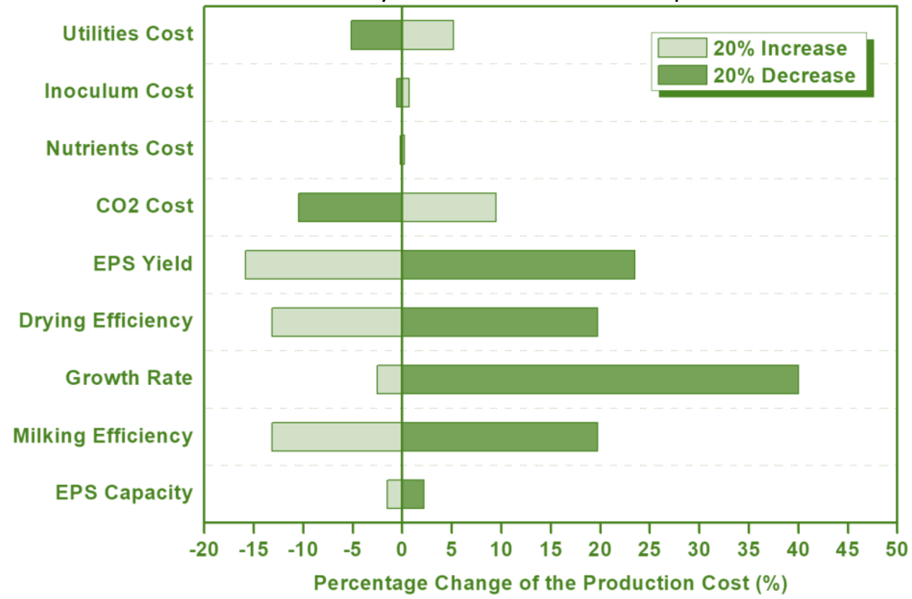
Figure S1. Flowsheets for the production of EPS in S1a/S1b (up) and HCs in S2a/S2b (down).

Table S1. Overview of the selected key-process parameters, the capital expenditures, the production cost and the product price/value.

Scenario	S1a	S1b	S2a	S2b	S3a	S3b	S3c	S4
Plant Capacity (ktons/year)	20	0.2	10	0.5	2	10	10	100
Biomass Capacity (ktons/year)	66.3	0.66	40.2	2.01	10.3	51.7	37.8	386.4
EPS/HCs Content (%w/w)	40	40	35	35	40	40	40	35
Milking Efficiency (%w/w)	40	40	35	35	40	40	40	35
Conversion/Recovery (%w/w)	95	95	95	95	50	50	75	95
CAPEX (M€)	94.88	12.67	50.22	13.11	37.92	90.21	74.13	220.3
OPEX (M€/year)	66.13	3.76	37.40	4.89	19.99	72.35	62.24	317.8
Production Cost (€/kg)	3.31	18.81	3.74	9.78	9.99	7.23	6.22	3.18
Product Value (€/kg)	6	15	4	20	5	3	2.5	1.5
Product Value/Production Cost	1.81	0.79	1.07	2.04	0.50	0.41	0.40	0.47
Price for Viability (€/kg)	5.34	37.5	4.85	17.25	15.2	9.43	8.08	3.46

Table S2. CAPEX (left) and OPEX (right) breakdown for scenario S1a.

Cost and Estimation	Value (M€)	Cost and Estimation	Value (M€/yr)
Major Equipment (Simulated: 100%)	10.670	1.Raw Materials (Simulated)	25.857
Auxiliary Equipment (Simulated)	5.445	2.Land Lease (Calculated)	0.339
Installation (47%)	7.574	3.Auxiliary Equipment (Simulated)	0.389
Instrumentation/Control (36%)	5.801	4.Labor (Calculated)	0.813
Piping (68%)	10.958	5.Supervision (15%·A4)	0.122
Insulations (8%)	1.289	6.Utilities (Simulated)	14.744
Electrical (11%)	1.773	7.Consumables (Calculated)	0.967
Buildings/Services (18%)	2.901	8.Wastewater Treatment (Calculated)	1.014
Land Improvements (10%)	1.611	9.Maintenance (5%·I_F)	4.125
Service Facilities (70%)	11.280	10.Operating Supplies (15%·A9)	0.619
Total Direct Costs (DC)	59.303	11.Laboratory (10%·A4)	0.081
Engineering/Supervision (33%)	5.318	12.Overheads (1%·C_W)	0.491
Construction Expenses (41%)	6.607	Total Direct Production Costs (DPC)	49.562
Total Indirect Costs (IC)	11.925	1.Total Taxes (2%·I_F)	1.650
Legal Fees (4%)	0.645	2.Insurances (1%·I_F)	0.825
Contractor's Fees (22%)	3.545	3.Depreciation (10%·I_F)	8.251
Contingencies (33%)	7.091	4.Contingencies (70%·(A4+A5+A9))	3.542
Total Other Costs (OC)	11.280	Total Annual Fixed Costs (AFC)	14.268
Fixed Capital Investment (I_F) (DC+IC+OC)	82.508	1.Administration (20%·A4)	0.163
		2.Marketing (3%·C_W)	1.472
Working Capital (I_W) (15%·I_F)	12.376	3.Interests (8%·B3)	0.660
Total Fixed Capital Investment (I)	94.885	Total General Costs (TGC)	2.295
		Total Production Cost (TPC) DPC+AFC+TGC	66.126
		Specific Production Cost (TPC_P)	3.31 €/kg



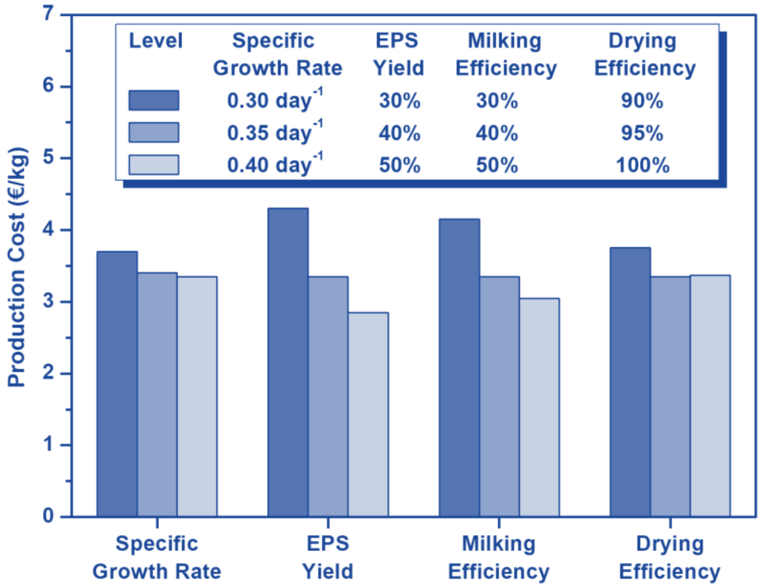


Figure S2. First (up) and second (down) level sensitivity analysis of the selected key-process parameters impact on the production cost for scenario S1a.

Acknowledgment: This research has been co-financed by the European Union and Greek national funds through the Operational Program Competitiveness, Entrepreneurship and Innovation, under the call RESEARCH – CREATE – INNOVATE (Project name: Bioconversion of CO_2 into High-added Value Bioproducts through Sustainable Microalgae Cultivation Processes - ***CO_2-BioProducts***; project code: T1EDK-02681).

European Union
European Regional Development Fund
EPAnEK 2014-2020
OPERATIONAL PROGRAMME
COMPETITIVENESS
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Co-financed by Greece and the European Union
ΕΣΠΑ 2014-2020
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