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Technoeconomic assessment of a biorefinery for the production of high-value compounds from the macroalgae *Kappaphycus alvarezii*

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ABSTRACT

Third generation (3G) products derived from marine biomass have emerged as a promising avenue for the blue bioeconomy, offering a sustainable and friendly alternative to traditional products. However, large-scale production of these compounds faces several challenges, primarily related to cost estimation difficulties, technological hurdles, and a lack of scale-up economics data. This work proposes a methodology for estimating the production costs of a target product (lactic acid) and byproducts (carrageenan and biofertilizer) at industrial scale, based on process simulation and techno-economic analysis. Results show the economic viability of the macroalgae biorefinery design is supported by the estimated minimum selling price of lactic acid at 1,685.25 USD.t^{-1}, which is competitive with current market prices. A risk analysis was carried out to evaluate the impacts of several process parameters on the project's technoeconomic analysis, resulting in byproduct revenue and macroalgae price with the highest impact on economic viability.

Keywords: Third-generation products. Macroalgae. Biorefinery. Techno-economic assessment.

1 INTRODUCTION

Third generation (3G) bioproducts derived from macroalgae have emerged as a focal point of research in recent years, driven by their remarkable attributes: rapid growth rates, high lipid content, exceptional CO_2 fixation capabilities, and the ability to thrive in harsh environments without competing for the land with the food industry.[1] The blue bioeconomy encompasses economic activities that harness renewable aquatic biological resources to generate valuable products.[2] At the 2018 Blue Bioeconomy Conference held in Europe, participants envisioned a burgeoning global blue bioeconomy market reaching € 10 billion by 2030, poised to make significant contributions to the pharmaceutical, agricultural, energy, and other industries.[3]

The red seaweed *Kappaphycus (K.) alvarezii* is a prolific source of the galactan polymer carrageenan. This sulfated polysaccharide is particularly rich in galactose units. *K. alvarezii* cultivation is primarily driven by its high carrageenan content, which can reach up to 49% dry weight.[4] In addition, liquid biofertilizer (sap) from fresh *K. alvarezii* can be sold as byproduct in the carrageenan process production.[5] The water-soluble fraction of *K. alvarezii*, largely comprised of carrageenan, exhibits a characteristic composition, on average, it contains 31.6 % of galactose and 25 % (in molar basis) of 3,6-anhydrogalactose.[6] Studied *Lactobacillus pentosus* strains are known to consume galactose,[7] the main sugar product of carrageenan hydrolysis to produce lactic acid, another valuable product with several applications. To demonstrate the potential of *K. alvarezii* biomass biorefinery, this work proposes the investigation of economic performance process design for commercial biofertilizer, carrageenan and lactic acid (main product) production. A comprehensive techno-economic assessment is carried out to determine the economic competitiveness. Moreover, a risk analysis enables the evaluation of the impacts of several economic parameters in process design.

2 MATERIALS & METHODS

The methodology applied in this work is based on process simulation and cost estimates supported by Aspen Engineering Software (mainly Aspen Plus® and Aspen Process Economics Analyzer®). A Block Diagram (BFD) was generated through an extensive literature review (including patents, scientific articles, specialized reports, and technical books), giving the first view of the process. The BFD guides the process data (*e.g.*, raw material composition, pressures, temperatures, reactions stoichiometry) collection and is detailed to specify the leading equipment defining the technology and generating the Process Flow Diagram (PFD). A Process Simulation Diagram (PSD) was built in the Aspen Plus® V12 to generate mass and energy balances based on the PFD and data collected. Figure 1a provides an overview of the main methodological steps adopted and Figure 1b shows the block diagram for the process investigated in this work.

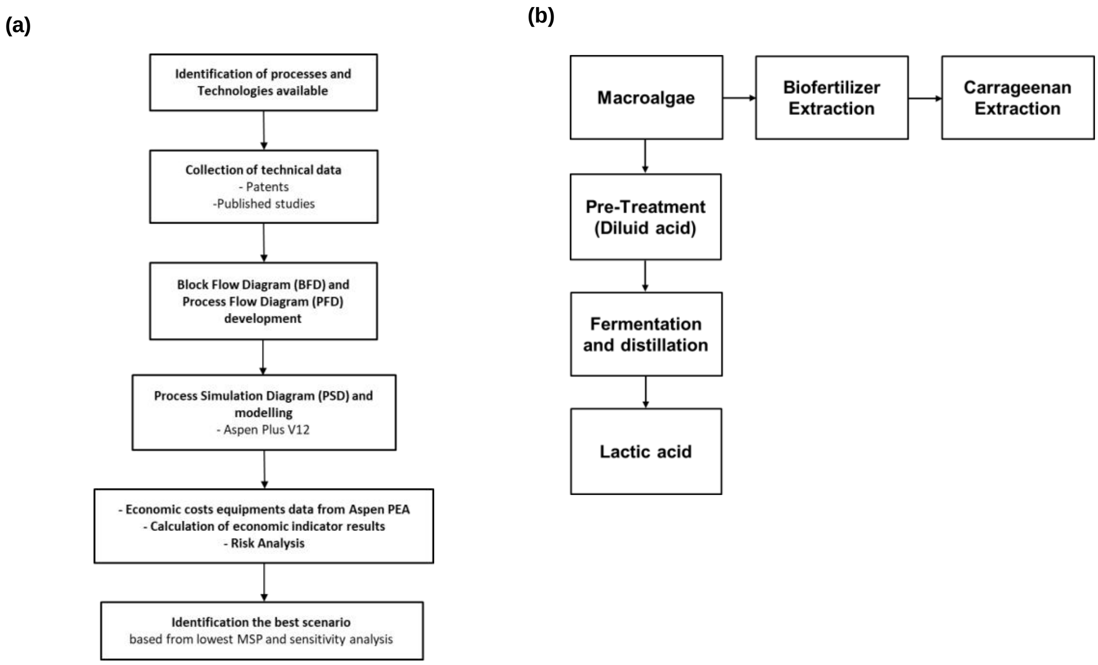

Figure 1 (a) Summary of the methodological steps adopted; (b) Block flow diagram of the process.

3 RESULTS & DISCUSSION

This section presents economic analysis results for the lactic acid (LA) process evaluated in this work, obtained via financial engineering rules and heuristics aided by Aspen Plus simulation and Aspen PEA (Aspen Process Economic Analyzer) cost estimates, following the methodology described in Section 2. Aspen Plus Simulation was employed to obtained mass and energy balances for the LA production process. From this data, Aspen PEA was utilized to estimate the Inside Battery Limit (ISBL), Outside Battery Limits (OSBL) costs and, consequently, the Capital Expenditure (CAPEX).

The Minimum Selling Price (MSP) is the main economic output addressed in this study. Nevertheless, the implemented methodology delivers a comprehensive cash flow analysis based on CAPEX and Operating Expenditure (OPEX) to estimate LA process cost.[8] LA MSP was of 1,685.25 USD.t^{-1} for estimated plant capacity of 1 kt.year^{-1} and operated 8,000 hours per year, competitive value with market price (2,000 USD.t^{-1}).[9] However, this price was obtained from sale of biofertilizer (sap) and carrageenan, both by-products, assuming that half of the macroalgae feed was directed to this purpose. The residue obtained from extracted carrageenan process, rich in glucose, could be used for bioethanol production, but an enzymatic hydrolysis step would be necessary before ethanol fermentation process. Revenue generated from the commercialization of bioethanol could lead to a decrease in the production costs of lactic acid, enhancing its market competitiveness.[10]

To study the effect of design parameters on the technoeconomic feasibility for biorefinery design evaluated, a risk analysis was performed by varying six variables that could impact the project's net present value (NPV): capacity, *K. alvarezii* price (macroalgae), byproducts revenue, Minimum Acceptable Rate of Return (MARR), lactic acid selling price and CAPEX. The uncertainty ranges considered for each variable were -25 to +25%. The tornado diagram and revenue composition are illustrated in Figure 2 and Figure 3, respectively.

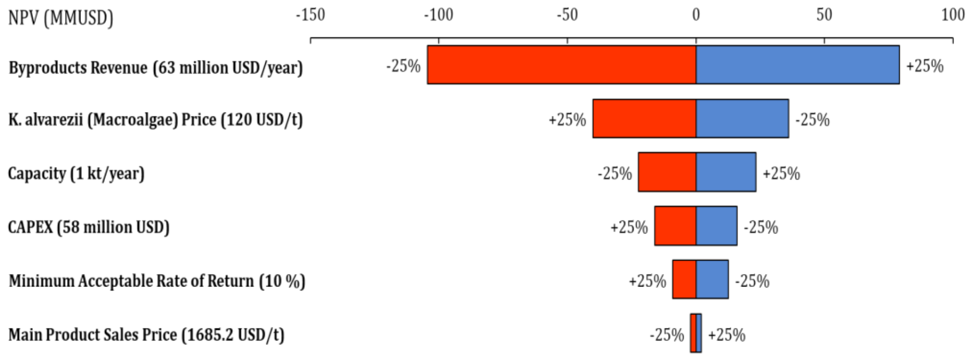

Figure 2 Risk analysis (tornado diagram).

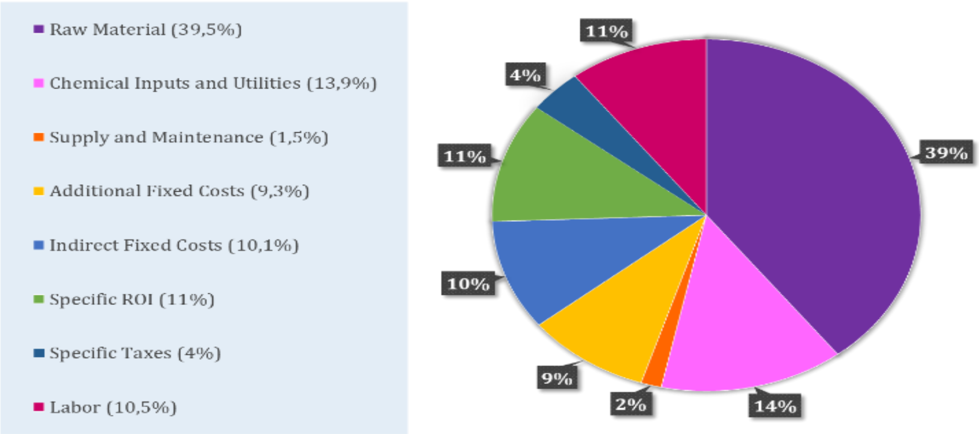

Figure 3 Revenue composition.

The risk analysis revealed that byproduct revenue and macroalgae price were the parameters with the most significant impact on NPV. The market value of byproducts surpasses that of lactic acid, whose values varies from 5000 to 15000 USD.ton^{-1} for carrageenan, and 5000 to 15000 USD.m^{-3} for biofertilizer,[11] Consequently, a more significant impact on the NPV was anticipated. Macroalgae possess a high-water content (approximately 90 wt%) requiring significant processing volumes to attain the target lactic acid production capacity. The analysis of revenue composition indicate that raw material (*K. alvarezii*) constitutes the primary cost driver within the MSP. Chemical inputs and utilities follow in terms of their contribution to the overall cost structure. *K. alvarezzi* is currently not cost effective when compared to other agricultural biomasses. In addition, fresh *K. alvarezii* seaweed is sold at about 120 USD.t^{-1}, and dry weight seaweed can reach up to ten times the production cost.[7] Despite the identified challenges, the macroalgae presents significant economic promise. This stems from its versatility, enabling the co-production of a diverse array of products from a singular feedstock. Moreover, seaweed, as a fast-growing biomass, requires negligible land use, and can be beneficial to the environment through CO_2 fixation and absorption of chemicals.

4 CONCLUSION

This work presents a comprehensive technoeconomic assessment of macroalgae bioprocesses that could provide a sustainable alternative to the fossil fuels and terrestrial biomass feedstock. Based on the methodology presented, it is possible to realize the economic potential of macroalgae biorefinery where value-added products can be obtained from *Kappaphycus alvarezii*, helping decision makers to identify new business opportunities for the further sustainable industry growth.

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