SCALING UP A BIOREFINERY FOR MACROALGAE PROCESSING: AN ECONOMIC ASSESSMENT

Simon Y. Kanematsu[1], João P.G.R. dos Santos[2], Rosana R.L. Araújo[3], Renata M.R.G. Almeida[3], Cristiane S. Farinas[4], Antonio J.G. Cruz[1,2]*

[1] Chemical Engineering Graduate Program, Federal University of São Carlos (PPGEQ-UFSCar)
[2] Chemical Engineering Department, Federal University of São Carlos (DEQ-UFSCar)
[3] Chemical Engineering Graduate Program, Federal University of Alagoas (PPGEQ-UFAL)
[4] Brazilian Agricultural Research Corporation (EMBRAPA)
** Corresponding author's email address: ajgcruz@ufscar.br*

ABSTRACT

Nowadays, the focus of many researches is on replacing materials of fossil origin to renewable and biodegradable materials. One of these materials is nanocellulose, which possesses characteristics such as biodegradability, biocompatibility, and non-toxicity. It is used in a wide range of practical applications. Macroalgae offers several advantages over terrestrial plants for nanocellulose extraction. The aim of this study is to scale up and assess the techno-economic feasibility of an industrial macroalgae biorefinery based on laboratory-scale data. The proposed plant processes 177 kton/year of seaweed, producing yearly 96.518 kton of sap (a biofertilizer), 5.886 kton of alginic acid, 0.688 kton of protein, and 2.176 kton of CNC (Cellulose Nanocrystals). The CAPEX and OPEX were estimated at US$ 42.88 million and US$ 50.55 million, respectively. A cash flow analysis, considering a minimum attractiveness rate of 11% and a project lifespan of 25 years, revealed that the price of sap had a significant impact on determining the Minimum Selling Price (MSP) of CNC. For sap prices ranging from US$ 362.62/ton to US$ 539.50/ton, the MSP of CNC was found to range from US$ 33,884/ton to zero, indicating a substantial dependency on sap pricing.

Keywords: Seaweed biorefinery. Cellulose Nanocrystal production. Techno-Economic Analysis.

1 INTRODUCTION

Recent studies reveal that biopolymeric and biodegradable materials extracted from renewable natural resources such as cellulose, starch, alginate, chitin, chitosan, proteins, triglycerides, natural gums, and polyphenols have presented as promising candidates to replace current synthetic plastics.[1] Among them, cellulose is certainly the most abundant compound obtained from the biosphere, Cellulose in its nanometric form is widely known as nanocellulose and the classification according to their morphological structures is into two main groups: cellulose nanocrystals (CNCs) and cellulose nanofibers (CNFs). Both classes have unique characteristics, like biocompatibility, non-toxicity, resistance, optical transparency, high specific surface area, among others, which give them versatility for use in a wide range of practical applications.[2]

Macroalgae have some advantages over terrestrial plants for nanocellulose production like low levels of lignin in their composition, higher growth, does not need fertilizers, pesticides, arable land, and water to irrigation.[3] Many authors like Araújo[4] and Baghel *et al*.[5] have studied the production of CNC and other products from macroalgae in laboratory scale. The first author extracted CNC from *Sargassum* macroalgae of the coast of Alagoas state (Brazil) using Soxhlet extraction with hexane and ethanol, mercerization with NaOH, H_2O_2 bleaching, and sulfuric acid hydrolysis. The second one proposed to produce a set of value-added products including the soluble algae products (sap, a biofertilizer), alginic acid, protein, and cellulose, from *Sargassum* seaweed found along the western coast of India. The aim of this work is to evaluate technical and economic feasibility of a commercial scale macroalgae biorefinery producing sap, alginic acid, protein, and CNC based on the experimental data found in the aforementioned studies.

2 MATERIAL & METHODS

The biorefinery proposed in this work is based on the scale up of macroalgae laboratory processing steps described by Araújo[4] (for CNC) and Baghel *et al*.[5] (for sap, alginic acid, protein, and cellulose). The industrial process uses models and scalability proposed by Piccino *et al*.[6] Nanocellulose production from *Sargassum* seaweed involves acid hydrolysis using 64% m/m H_2SO_4, with acid recycling. Steam generated from natural gas is utilized to supply energy to the process. Mass and energy balances were simulated based on laboratory data and process conditions previously reported in the literature. The calculations were implemented in spreadsheets (Microsoft Excel^{TM}) following the procedures describe by Batista.[7]

The economic analysis fits into an intermediate category between study estimate and preliminary estimate, since there is no layout view of the equipment coupled with assessments of piping, instrumentation, and electrical. It was performed a financial analysis using economic engineering tools and its investment evaluation methods to determinate the Minimum Selling Price (MSP) for CNC, based on Capital Expenditure (CAPEX) and Operation Expenditure (OPEX) of the process, following the cash-flow methodology. When necessary, the size of each piece of equipment was adjusted using the "six tenth rule" heuristic to fit the scale. It was used the CEPCI index to update the prices (January 2024). In this work, a factor of tropicalization of 75% to imported units and 25% to those ones nationally produced was adopted to consider elements such as freight and import taxes.[7] The multiplicative factor is 3.98 for locally built pieces of equipment's and 4.48 for imported ones were applied to total equipment deployment costs, in addition to installation costs.[7] The main premises used for the economic analysis are shown on Table 1.

Table 1 Premises adopted for the economic analysis of an industrial macroalgae (*Sargassum*) biorefinery[7]

Premise		Value
Direct Costs of Installation (DCI)		Sum of cost of all equipments
Indirect Costs of Installation (ICI)	Project Execution	4% of DCI
	Basic Enginnering of Project	6% of DCI
	Detailed Engineering of Project	12% of DCI
	Contingency	25% of DCI
	Buildings	2% of DCI
	Total Indirect Costs of Installation	Sum of all ICI
CAPEX		DCI + ICI
OPEX		Sum of all raw materials and utilities
Cash Flow Premises		
Total time for plant construction		3 years
Direct Costs paid by first years		50%, 50% first 2 years
Indirect Costs paid by first years		35%, 35%, 30% first 3 years
Expected Average Inflation for Brazil		4.3% per year

Cash Flow Premises (Continued)	
Minimum Atractiveness Rate	11% per year
Taxes on EBIT	34% per year
Linear Depreciation	10 years
Yearly hour production	8000h
Capital Maintenance	1% of Total Invested Capital (TIC)
Production on Zero year	80%
Annual Production Increase	0.5%
Working Capital (relative to next year revenue)	10%
Business Operation Costs	2% of gross revenue
Other Fixed Costs (plant ins., prop. taxes, emissions)	1.2% of TIC
Labor Annual Costs	0.86 million of US$/year
Labor Trainings (before Zero year)	0.43 million of US$
Brazilian R$ to US$ Conversion (2024)	5.06
Regular Maintenance Service	1.5% of TIC

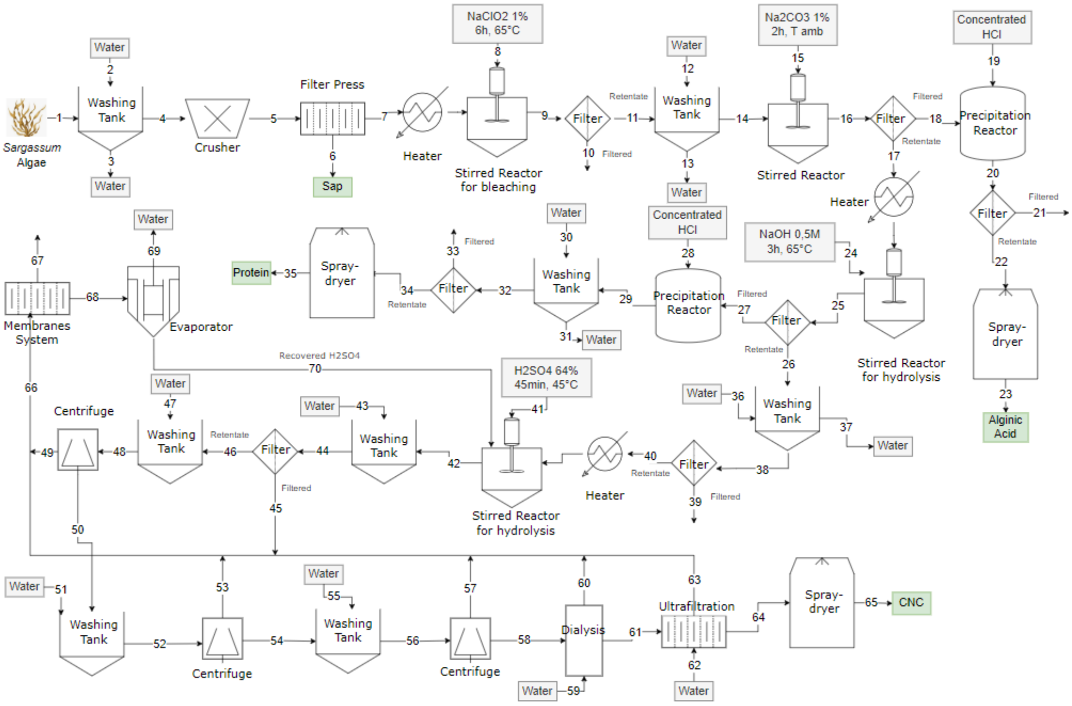


Figure 1 Block flow diagram of the proposed industrial macroalgae (*Sargassum)* biorefinery

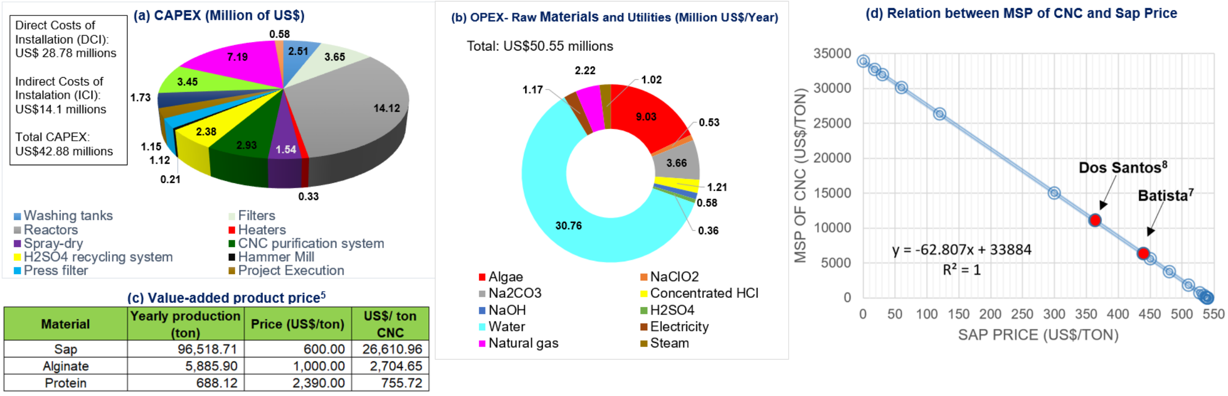
3 RESULTS & DISCUSSION

Figure 1 shows the industrial macroalgae biorefinery proposed in this work. An amount of 22.125 ton per hour of fresh macroalgae *Sargassum* enters in the process (Stream 1). It is washed, crushed, and then sent to a filter press to separate 12.064 ton/h of sap (Stream 6) from the biomass (Stream 7). Then, 13.426 ton/h of sodium chlorite 1% (m/m) (Stream 6) is used to bleach the biomass in a stirred reactor. An amount of 102.184 ton/h of sodium carbonate 1% (m/m) (Stream 15) is used to hydrolyze the biomass and to extract the alginate. The filter separates the biomass (Stream 17) and the filtrated (Stream 18) which contains the alginate. The latter is sent to a precipitation tank where 1.080 ton/h of concentrated hydrochloric acid (Stream19) is added to precipitate the alginate, producing 0.735 ton/h of powdered alginate (96% purity) in the outlet stream of the spray dryer (Stream 23). The retentate from the filter, which contains the biomass (Steam 17), is heated and sent to reactors, where 11.307 ton/h sodium hydroxide 0,5M and 11.87 kg/h of concentrated hydrochloric acid are used, respectively, to hydrolyze and precipitate the biomass. The precipitated (Stream 29) is sent to a washing tank and filter, extracting 86.015kg/h of protein (97.75% purity) in the outlet stream of the spray dryer (Stream 35). The biomass, the outlet stream of the filter (Steam 26) is washed, heated, and sent to a reactor, where 7618 ton/h (364,43 kg/h from make-up (Stream 41) and 7.254 ton/h from recycle of sulfuric acid 64% (m/m) (Stream 70) are used to hydrolyze the biomass. Then the non-hydrolyzed biomass and the CNC produced are sent to a sequence of washes and centrifuges for purification, producing 272.03 kg/h of CNC (90.45% purity) in the spray-dryer (Stream 65). All the effluent generated in the process (Streams 45, 49, 53, 57, 60, and 63) are mixed producing the Stream 66 that is sent to a membrane system. In this unit, the impurities (Stream 67) are separated from water and sulfuric acid (Stream 68). The evaporator concentrates the sulfuric acid until 64% (m/m) in order to recovery the sulfuric acid (recycling process).

In the implemented process, 58.98% of the mass of wet algae was converted into value-added products. Baghel *et al*.[5] achieved 59.11% of utilization of the weight of the algae (however cellulose is produced instead CNC). They achieved 1% of cellulose yield while in this work it was found 0.87% of CNC yield. Dos Santos[8] simulated an industrial scale of CNC production from *Sargassum* and achieved 2.10% of yield, but the process only produced CNC.

Figure 2 summarizes the main results of the economics analysis. One can see that Directs Costs of Installation (DCI) corresponds to 67.12% of total CAPEX, and Indirect Cost of Installation (ICI) accounts for 32.88%. Reactors have a greater impact on CAPEX (corresponding 32.93% of total CAPEX and 49.06% of DCI), follow by contingency costs (16.77% of CAPEX and 51% of ICI). Water (Figure 2(b)) has a significantly influence on raw materials and utilities costs, corresponding to 60.85% of this cost. The process that most consume water is the washing of the algae (Figure 1, Stream 2). This step of the process consumes 58.04% of all water used in the biorefinery.

The cash flow was based on Table 1 premises and considered the expenses minus the revenue obtained from the sale of the value-added products (Figure 2(c)). The price of sap had a great influence in the MSP of the CNC due to its high production. If the sap was sold by US$600/ton, the process is already viable, i.e., it does not need to sell the CNC for reaching profit. Figure 2(d) illustrated the MSP of the CNC as a function of sap price. The MSP of CNC is zero when the price of sap is US$539.50/ton. If sap was not sold (sap price is set to zero), the MSP of CNC is US$33,884.20/ton. If the alginate and protein were not sold, the MSP of the CNC is US$38,620.34/ton. Batista[7] simulated the CNC production from sugarcane bagasse and found a CAPEX of US$35.37million and MSP of CNC of US$6323/ton. To achieve the same value of this MSP, the sap would need to be sold at US$438.82/ton. Dos Santos[8] found the CAPEX and MSP of CNC of US$118 million and US$11,109/ton respectively. In the same way, the sap would need to be sold for US$362.62/ton (Figure 2(d)).



(c) Value-added product price[5]

Material	Yearly production (ton)	Price (US$/ton)	US$/ ton CNC
Sap	96,518.71	600.00	26,610.96
Alginate	5,885.90	1,000.00	2,704.65
Protein	688.12	2,390.00	755.72

Figure 2. (a) CAPEX, **(b)** OPEX, raw Material and Utilities, **(c)** Value-added product price, and **(d)** Relation between MSP of the CNC and the price of the sap.

4 CONCLUSION

This work implemented a biorefinery for macroalgae Sargassum, producing 2.176 kton of CNC per year. Additionally, 96.518 kton of sap (a biofertilizer), 5.886 kton of alginic acid, and 0.688 kton of protein are produced annually. The CAPEX and OPEX were estimated at US$ 42.88 million and US$ 50.55 million, respectively. A cash flow analysis revealed a strong influence of sap pricing on the MSP of CNC.

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ACKNOWLEDGEMENTS

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001. The authors thank to FAPESP (Process 2019/25261-8) and CNPq (Process 305919/2021-0) for the financial support.