MACROALGAE-BASED NANOCELLULOSE: SCALE UP AND ECONOMIC ASSESSMENT

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ABSTRACT

Nowadays, the need to replace fossil-based materials with renewable alternatives is urgent. In this scenario, the use of marine lignocellulosic biomass (especially seaweeds) as feedstock to produce nanocellulose has been highlighted in the last decades. Even so, there are still challenges for its commercial manufacturing. In this sense, this work aimed to evaluate the nanocellulose industrial production using macroalgae in a preliminary way by acid hydrolysis route. The process was simulated through material and energy balances using experimental and literature data. Then the process was economically evaluated employing different economic performance indicators. The results showed a potential process to generate high value-added products even if linked to high, but compatible, capital (MM US$ 145) and operational (MM US$ 29) expenses. The minimum selling price estimated for cellulose nanocrystals (US$ 16,000 per dry ton), looks competitive considering the current level of technological maturity of the process.

Keywords: Nanocellulose. Seaweed. Scale-up. Techno-economic analysis.

1 INTRODUCTION

The expansion of the use of renewable resources is a survival matter for humanity. Day by day, the need to replace the use of fossil-based materials with biodegradable and environmentally friendly alternatives to develop a sustainable and low-carbon economy becomes more urgent. This challenge driven by the sustainable development goals promoted by the United Nations (UN) has extensively boosting the global demand of biological and green resources to produce new materials. In this context, cellulose in its nanometric size, obtained by the cleavage of large cellulose units, and widely known as nanocellulose, has stood out as a promising alternative material for the fossil-based resources transition.[1,2]

The nanocellulose sources typically rely on terrestrial biomass, especially wood and cotton, which can bring out socioeconomic losses due to the food competition (on arable land) and the use of severe and energetically intense chemical treatments.[3] Currently, for these and other reasons, seaweeds have attracted attention as alternative feedstocks. Besides having lower lignin content than the traditional terrestrial biomass, which make the cellulose extraction easier, algae are a low cost and fast-growing carbon source. These characteristics enable the isolation of nanocellulose with superior thermal, optical, and mechanical properties. In addition to this interesting set of features, the algae-derived nanocellulosic materials have great environmental appeal which become them a promising additive for pharmaceutical, food, chemical, biomedical industries, among others.[2]

However, although nanocellulose promising set of applications, the main challenge remains the transition from lab scale to industrial production.[2] This work evaluated preliminarily the technical and economic feasibility of nanocellulose production from macroalgae (*Sargassum*), which is abundant on the Brazilian coast, by acid hydrolysis route using different chemical and economic engineering tools.

2 MATERIAL & METHODS

The preliminary feasibility study of nanocellulose production from seaweed via acid hydrolysis was elaborated mainly according to technical and economic aspects.

The technical analysis was developed under the perspective of scale-up of lab experimental procedures supported by pilot process data, both described in the literature, such as reported by Araujo and Batista.[4,5] Thus, the industrial process was synthesized by the rational combination of empirical elements and design heuristics resulting in the block flow diagram exhibited in Figure 1. The process simulation, material and energy balances, was performed using a Microsoft Excel spreadsheet considering a base case of a 3600-kta-capacity-factory. When more complex thermodynamic data were required, the process simulation software DWSIM was used. The equipment design was obtained, when necessary, applying typical shortcut project equations to the material and energy balances.

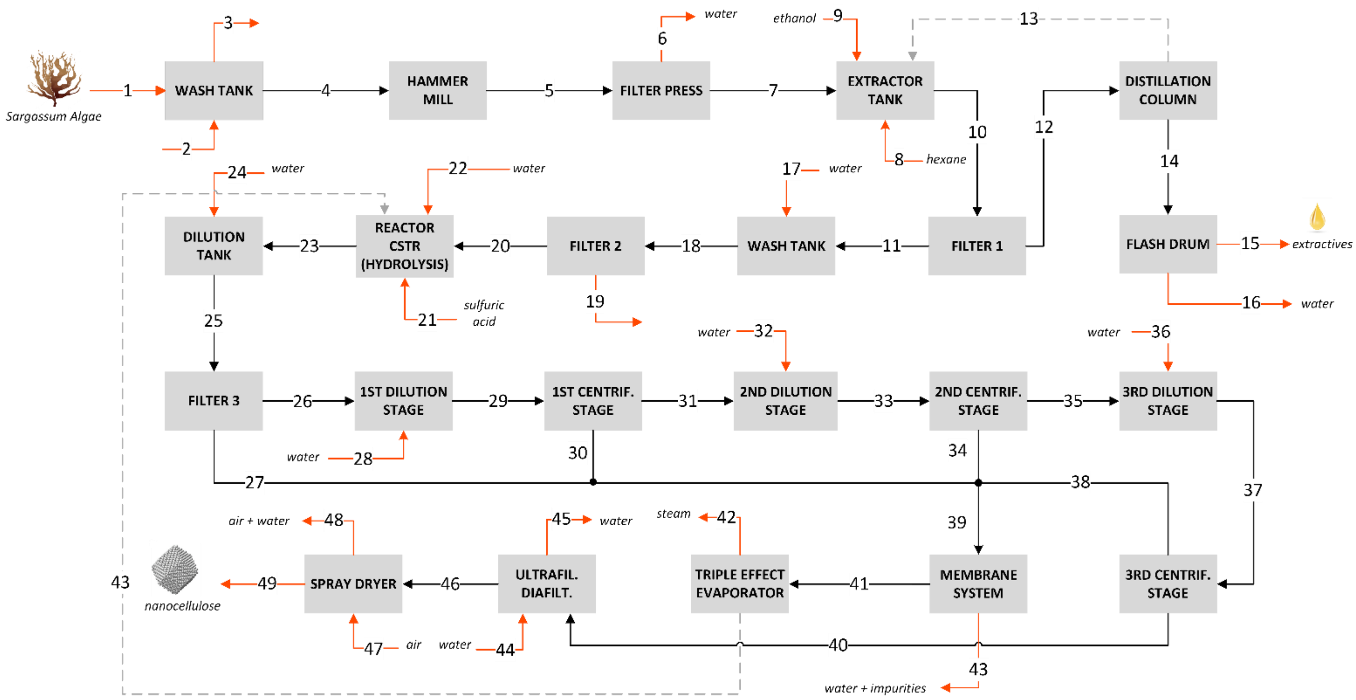

Figure 1 Block flow diagram of the the nanocellulose production.

The economic assessment was carried out based on the analysis of capital expenditure (CAPEX - bare cost, installation costs, control, instrumentation supervision, and engineering project costs), operational expenditure (OPEX – as fixed – maintenance, salaries, overhead, and contingencies – and variable – utilities and feedstock – costs and credits provided by the byproducts monetization) and minimum selling price (MSP - CAPEX, OPEX, taxes, depreciation, and inflation). For CAPEX study, CAPCOST and the "six tenth rule" (for those equipment not covered by Turton methodology, this scale similarity relationship was applied using as base the unit operations reported by Batista) was combined to multiplicative/corrective factors to estimate direct, indirect and purchase equipment costs.[5,6] Similarly, specific consumptions evaluated in the material and energy balances were coupled to the updated typical prices of input and utilities, besides the operational cost factors to compose OPEX.[5] Finally, CAPEX and OPEX were evaluated together to estimate MSP by cash flow analysis. Table 1 summarizes the main parameters used in the cash flow assessment.

Table 1 Cash flow parameters.

Unit Deployment		
Total Time for Unit Construction	3 years	
CAPEX – Direct Costs Installment Strategy	2 years – 50% in each of the first two years	
CAPEX – Indirect Costs Installment Strategy	3 years – 35% in each of the first two years and 30% in the third year	
Capital Reinvestment Strategy	1% of CAPEX* per year	
Project Lifespan (expected)	25 years	
Unit Production		
Stream Factor	91%	
Production on First Year	85% of capacity	
Annual Production Increase	0.5% per year (from the third year of production)	
Financial Assumptions		
Analysis Time Horizon	25 years	
Expected Average Inflation	4.5% per year	
Depreciation	Linear, 10 years	
Working Capital	⅛ of annual OPEX (1.5 months)	
Minimum Attractiveness Rate (MAR)	11% per year	
Dollar Exchange Rate	US$ 1 = R$ 4.99 (2023 average)	
Brazilian Taxes		
Corporate Income Tax (IRPJ)	15.00% 10.00%**	These taxes are applied to Net Profit (Revenues – Expenses)
Social Contribution on Net Income (CSLL)	9.00%	
Social Integration Program (PIS)	1.65%	
Contribution to Social security Financing (COFINS)	7.60%	

*Only ISBL equipment without engineering project expenses
**Applied only if the annual profit exceeds approximately US$ 46,500

3 RESULTS & DISCUSSION

CAPEX including installed equipment and engineering project for a 3.6 kta-industrial-factory was estimated at around 145 million dollars, of which 71% refers to unit operations inside battery limits (48% equipment purchase and deployment and 23% engineering project expenses). Upstream operations boosted by pretreatment steps, especially pressure extraction tanks, make up the main capital costs (38%), followed by off sites (29%), project, downstream (9%), and reaction (1%) sections, as indicated in Figure 2 (A). Capital costs calculated here are higher than most of literature works, mainly those evaluate CNC production from sugarcane bagasse, such as done by Batista.[5] This fact is justified by the high moisture content and the low cellulose concentration found in seaweed compared to sugarcane bagasse. Anyway, the CAPEX obtained for the presented process is, in general, in the same order of magnitude with other production process for bio-based materials.[5,7]

Gross annual OPEX (disregarding the revenues obtained from byproducts monetization) was evaluated at approximately MM US$ 48. Feedstocks, mainly the solvent mixture of hexane and ethanol (73%); direct fixed costs, especially maintenance and worker's salaries (11%); allocated fixed costs (9%), and utilities (7%) were the main operational expenses contributions. However, considering the seaweed extractives sale that can be monetized, sold as crude algae extract to be further purified and with market price suggested by Charoensiddhi et al. (2018), and then reducing significantly the OPEX from MM US$ 48 to MM US$ 29.[8]

(A) (B)

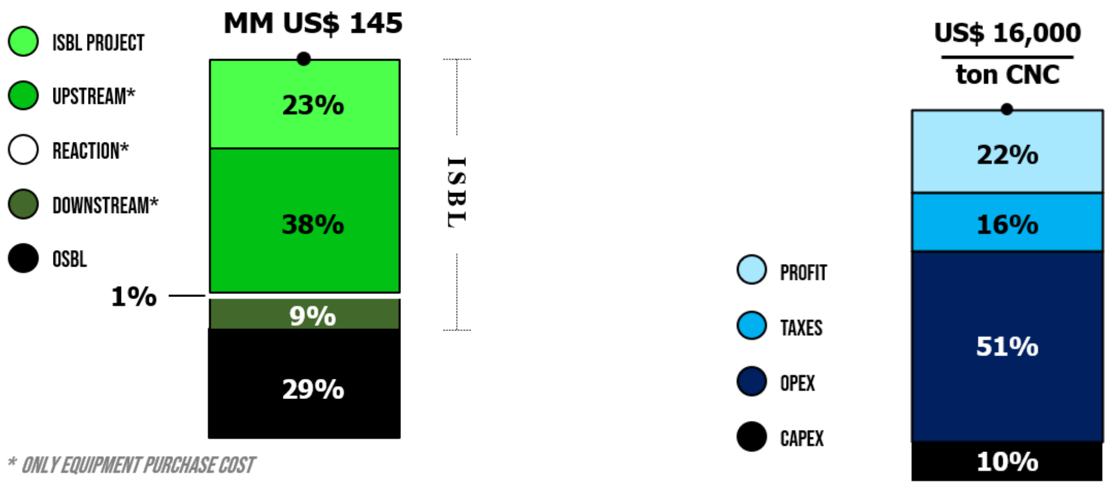

Figure 2 (A) CAPEX and (B) minimum selling price cost stratification.

As illustrated in Figure 2 (B), the minimum selling price for CNC obtained from the proposed process was estimated at around US$16,000 per dry ton. The operational costs including feedstock, utilities, labor and maintenance lead contributing with more than 50% of price (US$ 8,200 / ton) followed by profit (US$ 3500 / ton) – portion of price that enables MAR of 11% per year – taxes (US$ 2,600 / ton), and CAPEX (US$ 1,700). The use of a more rigorous set of financial parameters makes the process closer to a real application scenario. All the results are reasonably promising under current literature data, showing promising technical and economic forecast applicability for CNCs from seaweeds algae.

4 CONCLUSION

The technical and economic assessment shows the process proposed in this work is capable of operating at competitive prices considering current technology maturity, as indicated by literature benchmarks for CNC from different sources (ranging from US$ 5.000,00 to US$ 20.000,00 per dry ton of CNC).[5,7,9] Additionally, the monetization of byproduct demonstrates a strong effect on commercial feasibility and consequently, profitability.

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