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Techno-Economic and Environmental Optimization of Palm-based Biorefineries in the Brazilian Context

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Abstract

Due to the global increase in energy consumption, greenhouse gas emissions, and the depletion of fossil energy resources, the research presented here is focused on finding economically and environmentally competitive renewable energy resources. Fuel production from biomass is an attractive solution in this regard. Competing interests between food and energy have yielded increased interest in lignocellulosic biomass (LGB) as a feedstock. Processes such as biodiesel production from palm oil generate large volumes of LGB residues. Valorization of these residues through biorefineries may bring economic and environmental benefits through substitution of fossil fuels and such options must be studied in a systematic manner. The goal of this research is to propose a methodology for economic and environmental analysis of such biorefineries. A case study of a palm-based biorefinery in Brazil is used to illustrate this. Results indicate that multi-product processes can yield significant cost and environmental benefits.

Keywords: Life cycle assessment, Process integration, Biorefinery, Optimization, Palm biomass.

1. Introduction

Brazil is rapidly advancing in biodiesel production from palm oil with an increase from 736 m^3 in 2005 to more than 3.5 million m^3 in 2016 (ANP, 2016). These activities lead to increasing volumes of industrial residues which are often dispersed in the palm plantations or used as a fuel in boiler and cogeneration systems for electricity and steam production. The components of the residue can be classified as empty fruit bunch (EFB), palm press fiber (PPF), palm kernel shell (PKS), palm kernel cake (PKC), and palm mill effluent (POME) which are collectively categorized as lignocellulosic biomass (LGB). Currently, PKCs are used as animal feed, PPFs, EFBs and PKSs are partly combusted for steam production while POME is treated and produces biogas through anaerobic digestion.

Over the past decade, several technological advances have been proposed to produce a broad array of value-added products from LGBs. Figure 1 presents possible biorefinery pathways using residues from the palm oil industry. Gutiérrez et al., (2009) firstly investigated process integration possibilities among palm-based biodiesel and bioethanol plants and showed that integration of the plants was economically promising. Life cycle assessment (LCA) of palm-based biorefineries has been mainly focused on the joint production of bioethanol and biodiesel (Delivand and Gnansounou, 2013; Lim and Lee, 2011). Kasivisvanathan et al., (2012) applied multi-objective optimization to retrofit a palm oil mill into a biorefinery considering both economic and environmental impacts. The most recent review (Garcia-Nunez et al., 2016) presented the current trends in palm-based biorefineries and underlined the growing interest in multi-criteria decision-making in biorefineries. Aristizábal et al., (2016) performed a techno-economic and life cycle assessment of producing several bio-products in Columbia. A holistic approach for economic, environmental, and technical feasibility analysis of such integrated biorefineries is currently lacking. As a result, the goal of this paper is to present a comprehensive methodology for techno-economic and environmental assessment of biorefineries to help decision makers identify major barriers in palm-based biorefineries.

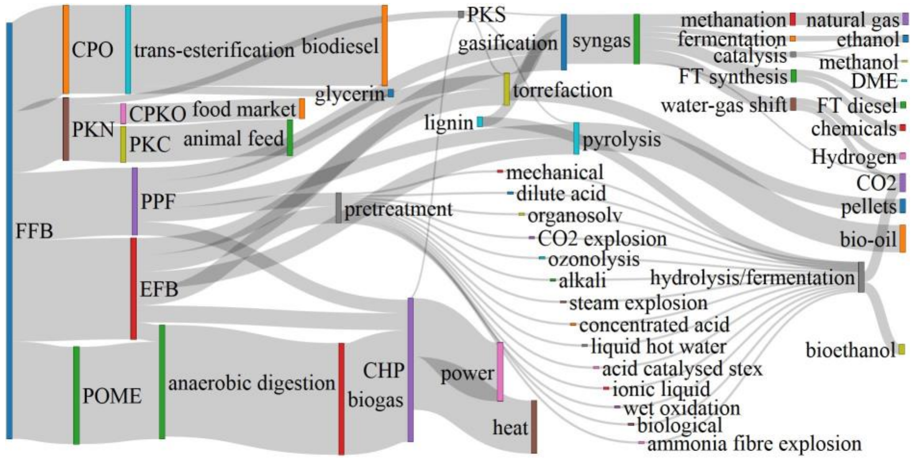

Figure 1. Possible palm-based biorefinery pathways

2. Methodology

Figure 2 illustrates the schematic of the proposed methodology. Environmental impact assessment and optimization is based on (Gerber, 2012). Process integration is carried out through simultaneous optimization of mass and energy conversion with the objective function of minimizing the total annualized cost of the system. Life cycle assessment is completed for the optimized system but could alternatively be included in the objective function using a weighting factor.

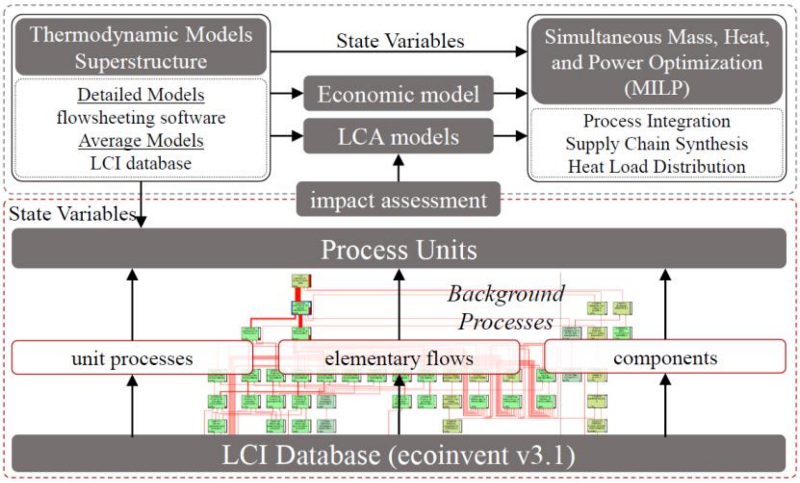

Figure 2. Methodology for economic and environmental optimization of energy systems

3. Modelling

A 20 000 ha palm plantation was selected as the functional unit with productivity of 24 t/ha.y of fresh fruit bunches (FFBs). 30.5 t/h of crude palm oil (CPO) and 35 t/h of EFB are available. Operating time of the plant is assumed to be 3570 h/y (galp energia, 2013)

3.1. Thermodynamic models

CPO production from EFB is modelled using data from Ecoinvent v3.1 (Weidema et al., 2013). The biodiesel process and its principles are based on Patle et al., (2014). From 30.5 t/h of CPO, 30 t/h of biodiesel and 3.3 t/h of glycerin can be produced.

The biochemical pathway using dilute acid pretreatment for ethanol production has been selected and modelled using Aspen Plus®. The pretreatment and enzymatic hydrolysis are based on (Raman and Gnansounou, 2014). The glucose concentration is increased in a triple-effect evaporator to 17 % before fermentation (Albarelli, 2013). Anhydrous ethanol with purity of 99.3 % is produced (Albarelli, 2013).

Besides EFBs, other residues are considered to be used for heat and power generation. A detailed wood boiler model is adapted to the use of PKS and PPF. The lower heating value of PKS (30 % moisture content) and PPF (35 % moisture content) are estimated to be 13.4 and 11 MJ/kg, respectively (using Boie's correlation). POME is treated in anaerobic digestion to produce biogas. Steam and electricity production are modelled using a steam network superstructure adapted from (Maréchal and Kalitventzeff, 1999) to ensure the simultaneous optimization of mass conversion and the production of heat and electricity. Figure 3 presents all the processes considered.

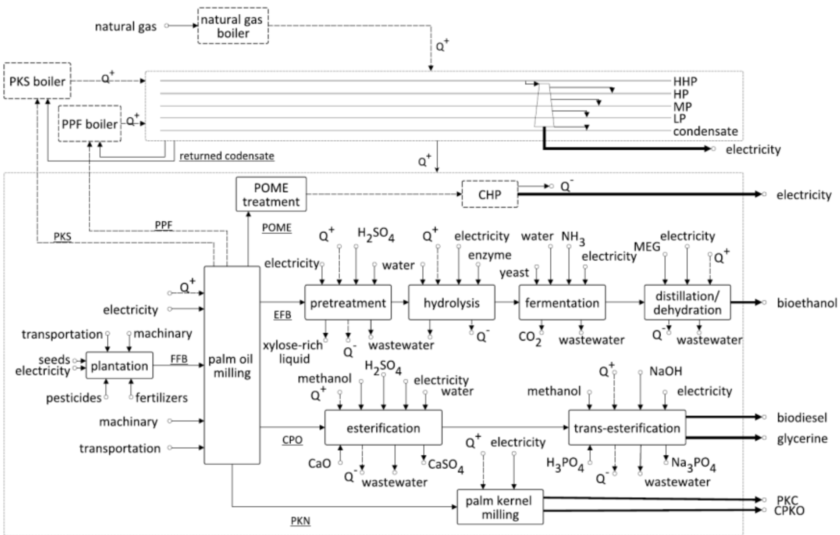

Figure 3. System boundaries for palm-based biorefinery including the utilities

3.2. Economic models

The costs of CPO and CPKO production are used to estimate all upstream costs related to FFB plantation, harvesting and milling. Transportation costs are neglected. Since this study was conducted for a fixed rate of feedstock, the cost of equipment for biodiesel and bioethanol plants were fixed and were extracted from Aspen Process Economic Analyzer®. As energy integration will be applied to the overall system, the cost of coolers and heaters are excluded. A conversion factor of 5.69 is selected to estimate the total capital cost of the plant from the equipment cost (Alejandro Anaya Durand, 2016).

Utility costs are estimated using formulas by (Bailie et al., 2008). Table 1 shows the price of resources, services and products. The formula presented in (Taal et al., 2003) is used to estimate the overall cost of heat exchanger network.

Table 1. Price of resource, services, and products

Resource	Value	Reference	Resource	Value	Reference
CPO	390 [$/t]	(Patle et al., 2014)	CaO	46 [$/t]	(Patle et al., 2014)
CPKO	444 [$/t]	Ecoinvent v3.1	H_3PO_4	800 [$/t]	(Gubicza et al., 2016)
PKC	0.075 [$/t]	(Lee, 2013)	NaOH	750 [$/t]	(Patle et al., 2014)
Electricity	0.077 [$/kWh]	-	Natural Gas	78 [$/kWh]	
Methanol	375 [$/t]	(HIS, 2016)	Enzyme	10 [$/kg]	(Agostinho et al., 2015)
Yeast	1250 [$/t]	(Do et al., 2015)	H_2SO_4	88 [$/t]	(Do et al., 2015)

Due to the fluctuating nature of market prices and having a variety of products for which market prices cannot represent a true relative value, an exergy-based cost allocation method was selected (exergetic content of biodiesel, bioethanol, glycerin, electricity, and CPKO are 36.5 MJ/kg, 24.5 MJ/kg, 16.2 MJ/kg, 1 MJ/MJ, and 38 MJ/kg, respectively (Lee, 2013)).

3.3. Life cycle inventory

Life cycle inventories are based on Ecoinvent v3.1 for all resources except enzymes used in the hydrolysis process. Table 2 presents a range of environmental impact of the set of enzymes, their selected values in this study, and their related LCA method selected for this study. No environmental impact is associated with the construction phase, equipment or labor as they were shown to be insignificant (Lim and Lee, 2011). The impact of producing CPO and CPKO were selected, which also account for all background impacts related to the palm plantation. LCA in this work is based on the “cradle-to-gate” approach. As with cost allocation, impact allocation is based on exergy content of the products.

Table 2. Life cycle inventory of enzymes used in this study and the selected LCA methods (Agostinho et al., 2015; Nielsen et al., 2007) (The values are per kg of enzyme)

name	Range (value) [unit]	Assumed LCA method
GWP	1-22 (21) [kg CO_2-eq]	IPCC 2007, climate change, GWP 100a EDIP 2003, global warming, GWP 100a
Acidification	4-33 (7) [g SO_2-eq]	CML 2001, acidification potential, generic
Nutrient enrichment	2-33 (10) [g PO_4-eq]	CML 2001, eutrophication potential, generic
Ozone formation	0.5-3 (1.5) [g ethylene]	EDIP, environmental impact, photochemical ozone formation
Agricultural land use	0.3-3.4 (1) [m^2.y]	ReCiPe Midpoint (H), agricultural land occupation, ALOP

4. Results and discussions

For this analysis, three scenarios were investigated (in all scenarios, PKS and PPF were available for combustion):

1. Scenario I (business-as-usual): Production of biodiesel using CPO while selling the CPKO to the market. EFBs are dumped in the field.
2. Scenario II (bioethanol): System expansion by producing bioethanol using EFBs.
3. Scenario III (biorefinery): System expansion by treating POME using anaerobic digestion for biogas production and using a CHP system.

Preliminary heat integration: The availability of high temperature heat in the bioethanol plant shows promising potential for integration within the biodiesel plant. Heat integration between the two will reduce the hot and cold utilities by 13 %. This is carried out in scenarios II and III.

Economic and environmental analysis: Table 3 summarizes the results of the economic analysis. Addition of bioethanol production has increased the cost of the products by 16 %. It can be explained by low yield of ethanol production in the process (1715 $kg_{ethanol}$ from 35 t of EFB). The payback time of each investment is calculated assuming the selling price of the product at the current market price. The third scenario showed payback time reduced by 14 % due to the increase in electricity production.

Table 3. Cost allocation to biorefinery products and payback time calculation

Products	**Scenario I**	**Scenario II**	**Scenario III**	**Market price** (Shukery et al., 2016)
Bioethanol [*$/kg*]	-	0.3208	0.3174	0.4500
Biodiesel [*$/kg*]	0.4074	0.4772	0.4721	0.5373
Glycerin [*$/kg*]	0.0196	0.0229	0.0227	0.0440
Electricity [*$/kWh*]	-	0.0470	0.0465	0.0700
Total cost [*Million $/y*]	48.4	59.1	56.9	-
Payback time [*y*]	3.22	7.3	6.3	-

Environmental impact assessment of the studied scenarios showed that an integrated biorefinery platform exhibits less allocated impact per unit of product. In essence, the substitution effects of the products increases which corresponded to a reduction in the overall impact. This is true in all the studied categories except “acidification potential” in scenario III, which is due to POME treatment (19 % of total emissions). From Table 4 it can be concluded that system expansion (scenario III) can also reduce the environmental impact of the main product by valorizing the underutilized co-products.

Table 4. Results of life cycle assessment

Products	scenario I	scenario II	scenario III	scenario I	scenario II	scenario III
	GWP 100a (IPCC 2007) [kg CO_2-eq]			GWP 100a (EDIP 2003) [kg CO_2-eq]		
Bioethanol [/*kg*]	-	2.764	2.741		0.354	0.352
Biodiesel [/*kg*]	4.228	4.111	4.0782	0.517	0.527	0.524
Glycerin [/*kg*]	1.883	1.831	1.816	0.230	0.235	0.233
Electricity [/*kWh*]	-	0.405	0.402		0.0520	0.0517
CPKO [/*kg*]	4.398	4.277	4.242	0.538	0.548	0.545
	Acidification potential [g SO_2-eq]			Eutrophication potential [g PO_4-eq]		
Bioethanol [/*kg*]	-	5.118	6.280	-	3.910	3.880
Biodiesel [/*kg*]	7.719	7.613	9.342	5.968	5.816	5.772
Glycerin [/*kg*]	3.438	3.390	4.160	2.658	2.590	2.570
Electricity [/*kWh*]	-	0.751	0.921	-	0.573	0.569
CPKO [/*kg*]	8.029	7.919	9.717	6.208	6.050	6.005
	Agricultural land use [m^2.y]			Photochemical ozone formation [$g_{ethylene}$-eq]		
Bioethanol [/*kg*]	-	1.028	1.019	-	1.744	1.756
Biodiesel [/*kg*]	1.582	1.529	1.516	2.683	2.594	2.612
Glycerin [/*kg*]	0.704	0.681	0.675	1.195	1.155	1.163
Electricity [/*kWh*]	-	0.151	0.149	-	0.256	0.257
CPKO [/*kg*]	1.646	1.591	1.577	2.791	2.698	2.717

Comparing the results with the literature is unfortunately not straightforward. Each publication used different functional units, LCA methods, allocation techniques and LCI databases. In addition, the LCA methods were often not mentioned. As an example, biodiesel production impacts are cited to be 0.065 (Rocha et al., 2014), 1.31 (Ali et al., 2015) and 5.1 kg CO_2-eq/kg (Ecoinvent v3.1).

5. Concluding remarks

A comprehensive methodology for techno-economic and environmental optimization of biorefineries was presented. The methodology has been applied on a potential palm-based biorefinery in Brazil. Special care was taken in the collection and consistency of the input data, as a wide range of data were often reported. It was observed that through system expansion, recovering residues of palm oil milling and producing a spectrum of value-added products, environmental objectives could be improved (up to 4 %) although sometimes to the detriment of the economic objectives. In addition, different environmental impacts were not observed to always vary in unison which increases the complexity of decision-making. Hence, further analysis by including other technologies (Figure 1) together with multi-objective optimization should be performed. In addition, as pointed out by Varbanov, (2014), radical reduction in the water footprint of biorefineries is critical to their economic competitiveness. It is hoped that the results of this study provide incentives for the research community to adopt such methods, illustrating the necessity of applying a holistic approach for assessment of complex systems.

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