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Techno-economic analysis of the process in obtaining bioethanol from rice husks and whey

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Abstract

This work proposes a novel integrated process for second-generation bioethanol production with an approach simulated in Aspen HYSYS®. Rice husk and dairy whey were used to revalorize for this bioprocess. The energy recovery of the bioprocess was optimized using the Pinch method; savings of 45.45% and 100% were obtained for heating and cooling utilities, respectively, concerning the process without a heat exchange network (HEN). It was possible to compare the costs of mutually exclusive alternatives between the process alternatives with and without HEN. The capital investment with HEN was similar to the process without HEN. Instead, savings by 77.8% of utility costs per year was found in the process with HEN. A differential cash flow for ten years was generated, and a positive differential net present value (NPV) was determined. Therefore, HEN is an economically convenient and environmentally friendly option since energy consumption reduction can minimize environmental damage.

Keywords: Waste food; bioethanol; HEN; pinch; differential economic analysis

1. Introduction

Nowadays, given the scarcity of fossil fuels, the need to generate new energy alternatives to conventional energy obtained mainly from petroleum has arisen [1,2,3]. The development of sustainable production technologies also arises from the need to protect the environment and safeguard both renewable and non-renewable resources.

This situation has then led to the use of natural raw materials, giving rise to the so-called biofuels, some of which are biodiesel and bioethanol as the most important ones [4]. Bioethanol has a higher octane rating than diesel, which gives superior blending properties. Bioethanol molecule contains oxygen, so the combustion in the vehicle engine is practically complete, resulting in lower toxic emissions to the atmosphere [5].

Bioethanol can be obtained from the alcoholic fermentation of high sugar and starch products. The obtention process of second-generation (2G) biofuels uses non-food resources or crop residues for fuel production with lignocellulosic biomass as the main component [6]. Lignocellulosic biomass includes waste and residues from different sectors (forest, agriculture, wood processing, municipal solid waste, or paper waste). However, regardless of the source, it is mainly composed of cellulose (35–50%), hemicellulose (20–35%) and lignin (10–25%) [7].

Rice husk is lignocellulosic biomass produced as a by-product in the rice grain milling process. This biomass is rich in cellulose and hemicellulose polymers. It is possible to convert it into monosaccharide sugars through chemical, physical, or biological processes for their subsequent conversion into ethanol [8,9]. The rice husks generation is estimated to correspond to 16-21% of the total rice production [10]. Rice husks with low lignin content (19% total lignin and more than 50% carbohydrates in its composition) pretreated with dilute sulfuric acid (0.3% w/v) for 33 minutes at 5 atm and 152°C have been shown to produce a high proportion of glucans. These glucans can be hydrolyzed to obtain glucose and fermented to obtain bioethanol [11].

Another way of producing bioethanol is through a fermentation process from the monosaccharide present in dairy whey, a waste generated by the dairy industries that causes an environmental problem due to the large volumes with a high organic load generated [12]. The whey is composed of 5% w/w

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of lactose, and the use of contained water would reduce the contamination of the physical and biotic environment.

According to the National Secretariat of Energy [13], Argentina annually produces about 1,200 million liters of bioethanol. This biofuel is obtained mainly from corn and molasses, a by-product of sugar production. There are 19 bioethanol plants in Argentina, which mainly use 28% cereal grains and 72% sugar cane as raw material. Second-generation processing from lignocellulosic raw material has not yet had any incidence in the country, so it represents an innovative alternative.

In process optimization, heat exchange networks (HEN) represent a technologic alternative that allows efficient process energy use while reducing energy consumption [14]. The Pinch methodology is a tool that can be used to achieve efficient energy utilization [15,16]. Gonzalez-Contreras et al. [17] used the Pinch method for heat integration in the 2G bioethanol production process using wheat straw as feedstock.

Commonly, engineering projects involve different design alternatives. When one of these alternatives excludes the selection of any of the others, they are stated to be mutually exclusive. These alternatives may require different capital investments with various revenues and costs. As a consequence, an economic analysis is required to determine which mutually-excluding alternatives should be selected and how much capital should be invested [18,19].

This work aims to conduct a technical-economic analysis of the energy optimization of the bioethanol production process from rice husk and whey.

2. Materials and Methods

This work studied the energy optimization of the process designed for obtaining bioethanol 2G. To revalue food waste, husk and dairy whey were selected as raw materials to yield bioethanol. Of 28.89 t/h of pretreated lignocellulosic biomass and 88 t/h of whey, 7.52 t/h of bioethanol can be produced.

Aspen HYSYS® software was used to simulate the hydrolysis and fermentation stages of whey and rice husk. The thermodynamic model was used NRTL [18,20,21]. Figure 1 shows the flow sheet of the simulation.

Figure 1 shows that the hydrolysis stages occur in continuously stirred tank reactors (CSTR-101 and CSTR-100), while the fermentation step is carried out in a conversion reactor (CRV-100).

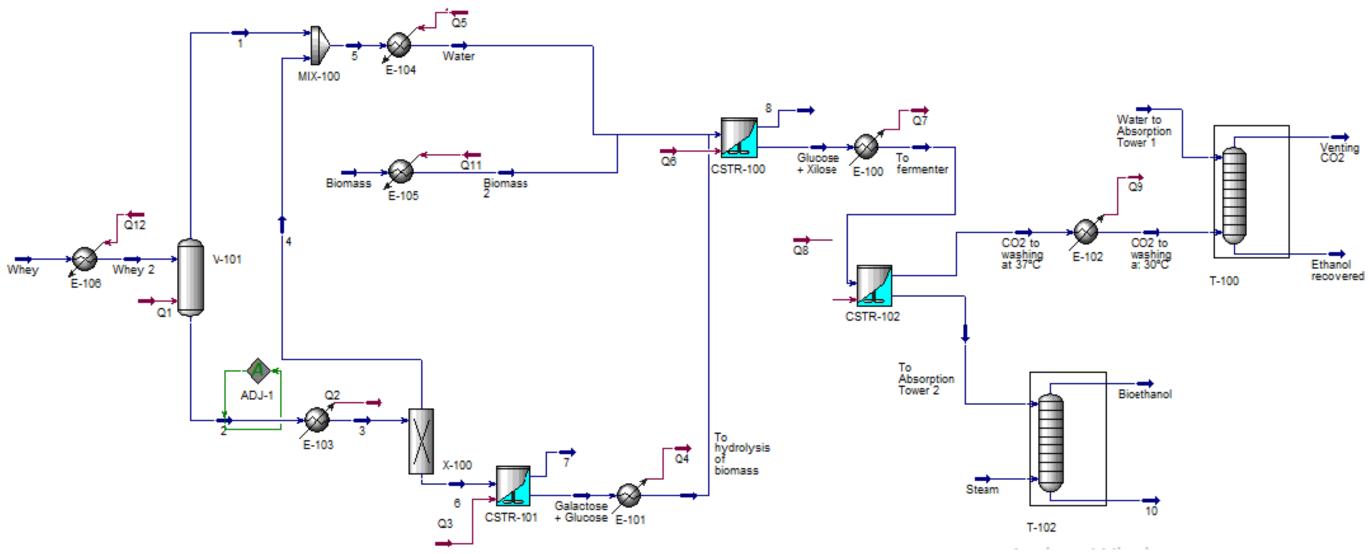

Fig. 1. Flowsheet of the bioethanol production process from rice husks and whey

The feed stream "Whey" was defined with 5% lactose and 95% water mass fractions. The amount and composition of whey are very variable since it depends on the type of cheese. The lactose present in whey is carbohydrate from which it is feasible to obtain bioethanol. This disaccharide subjected to hydrolysis provides equimolar amounts of D-glucose and D-galactose [22]. A lactose content close to 5% p/p is suitable for the growth of microorganisms in the fermentation process as it represents the source of carbon, hydrogen and metabolic energy [23]. Before the hydrolysis of lactose, the feed stream "Whey" (88 t/h) was concentrated from 5% to 20% w/w of lactose using evaporation equipment at 40°C (V-101). X-100 is ideal equipment for adequate concentration in the hydrolysis reactor. For the lactose hydrolysis stage, a continuous tank reactor (CSTR-101) with a kinetic model of first-order Arrhenius-type was used. The pre-exponential factor and the activation energy were of 7.61×10^9 (s^{-1}) and 46.861 kJ/mol respectively, valid in the range 25-40°C [24]. Galactose and glucose were obtained for this reaction with a conversion grade of 99.95%.

The “Biomass” stream (with a mass flow of 28.89 t/h) was heated from a room temperature (20°C) to the reaction temperature (140°C). The "biomass" composition was defined by the main sugars that made up the rice husk, hemicellulose, and cellulose with the fractions of 2.3% w/w and 97.7% w/w, respectively. Mass fractions resulting from the optimal pre-treatment experimentally studied by Dagnino et al. [25] were used for rice husk simulation. A continuously stirred tank reactor type (CSTR-100) operating at a temperature of 140°C and slightly above atmospheric pressure was designed. A homogeneous kinetic model Arrhenius-type of pseudo-first-order was applied. The pre-exponential factor and the activation energy were respectively of 4.74×10^7 (s^{-1}) and 64.350 kJ/mol [26]. This reactor was fed with biomass, hydrolyzed whey, and drained water from the whey concentration step, obtaining a conversion of 96.95% of cellulose to glucose and 81.95% of hemicellulose to xylose. The resulting stream (rich in fermentable sugars) was fed into a conversion reactor (CRV-100). In this reactor, operating at a temperature of 37°C and under atmospheric pressure, where the reactions of ethanol and carbon dioxide formation from glucose, xylose, and galactose were considered. The xylose and galactose reactants were defined as hypothetical components. Table 1 shows the parameters employed.

Table 1. Hypothetical component parameters

Parameter	Xylose [27]	Galactose [28]
Molecular weight	150.1	180.2
Normal boiling point	329.9 °C	436.8 °C
Critical temperature	617.3 °C	737.9 °C
Critical pressure	6578 kPa	6200 kPa
Critical volume	0.342 m^3/kgmol	0.416 m^3/kgmol

For both reactions of glucose and galactose, the conversions were set at 97% because typical values hovered between 90% and 100%. While xylose was fixed at 85% [21,29-32]. From the reactor mentioned above (CRV-100), two streams were obtained: "CO2 to washing at 37°C", constituted mainly of carbon dioxide, and "To Absorption Tower 2", whose major component was ethanol. Two parallel absorption steps were included to vent carbon dioxide and recover ethanol. An absorption Column T-100 was designed to separate the CO_2 produced in the bioreactor "CRV-100" present in the stream "CO2 to washing at 37°C". This gas stream, consisting mainly of CO2 with traces of water and ethanol, was washed with water (tap "Water to Absorption Tower 1") in the Absorption Column "T-100". This column was designed in 10 stages where ethanol was absorbed in water (current "Ethanol recovered"). Meanwhile, CO_2 venting occurred in the gaseous stream "Venting CO2". The stream "To Absorption Tower 2" coming out of the Fermenter reactor "CRV-100", consisting of a dilute solution of ethanol with traces of other compounds, was treated in the Absorption Column (T-102) designed in 10 stages to remove water, yielding the ethanol (stream "Bioethanol") from the top of the column. From the simulation of the process designed up to this point, it was possible to obtain a bioethanol production of 7.52 t/h with a purity of 91.9% w/w. Later, purification stages (not addressed in this work) would be necessary to meet quality requirements. Energy optimization was performed using the Pinch Method. The Pinch is a critical point in HEN design that divides the network into two zones in which essential design criteria are established, such as no heat transfer across the Pinch, no heating below the Pinch, and no cooling above the Pinch [14,33,34]. Three important points for the design of heat exchange networks are the minimum amount of heat required for heating supplied by external utility (Qh), the minimum amount of heat to be extracted for cooling (Qc), and the Pinch at the temperature at which the heat flux is zero [33]. The basic rules of the method are presented in Laborde et al. [14].

A comparison of mutually exclusive alternatives was made between the process with HEN and without HEN. The most straightforward comparison technique is to determine each alternative's net present value (NPV) based on the total investment and to select the one with the lowest negative NPV or the highest positive value [19,35,36]. A Class 4 cost estimate (Study Estimate) was performed in this project since this estimate used a list of the leading equipment in the process. However, a differential estimation between the different alternatives was performed. For this differential analysis, only those units that differed in the alternatives studied were considered. Capital costs were estimated using the module costing technique [37-40]. According to Ulrich and Vasudevan [41], utility costs were estimated by considering the Hot Water and Cooling Water equations.

3. Results and Discussion

The 2G bioethanol production process (Figure 1) required 9,473 MJ/h as a cooling utility and 20,843 MJ/h as a heating utility. From the simulation in Aspen HYSYS®, it was determined that the streams with the possibility of energy exchange in the process of obtaining 2G bioethanol were "Whey", "2", "5", "Galactose+Glucose", "Biomass", "Glucose+Xylose" and "CO2 to washing at 37°C". Table 2 shows the inlet and outlet temperatures (T) and the product of the streams' mass flow and heat capacity (W Cp) mentioned above. These parameters, obtained from the simulation in Aspen HYSYS®, and the constant heat capacity reported by the simulator for each stream were considered. The network was designed with the Pinch method establishing a ΔTmin of 10°C.

Table 2. Temperatures of streams possible to take part in HEN

Stream		T in (°C)	T out (°C)	W Cp (MJ/(h °C))
Whey (E-106)	C1	20	40	358.6
2 (E-103)	H1	106	40	10.1
5 (E-104)	C2	100	140	201.5
Galactose+Glucose (E-101)	C3	40	140	6.7
Biomass (E-105)	C4	20	140	41.1
Glucose+Xylose (E-100)	H2	140	37	75.2
CO2 to washing at 37°C (E-102)	H3	37	30	140.7

Applying the Pinch method to this process made it possible to obtain the heat exchange network and the required heaters and (or) coolers. The result indicated the need for four heat exchangers located above the Pinch. The obtained HEN is shown in Figure 2.

Figure 2 shows that C1, H1, H2, and H3 satisfied their energy requirement. Stream C2 after the exchange with H2 required heating utility. Streams C3 and C4 did not participate in the HEN, so they needed heating utility. Therefore, with the application of HEN, cooling utility was not used, and 11,370 MJ/h of heating utility was required. With this HEN, the heating utility was reduced by 45.45% and the cooling utility by 100%.

The differential NPV of these alternatives was calculated between the process options with and without HEN. Table 3 shows an "x" the equipment belonging to both processes for obtaining bioethanol without and with HEN. There is standard equipment in both designs; this is not considered for the differential economic analysis. Therefore, the different equipment included heat exchangers, heaters, and coolers.

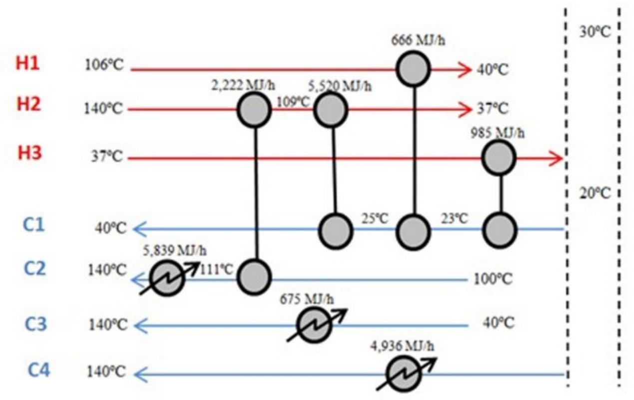

Fig. 2. Exchange network obtained from the pinch method

Table 3. Process equipment with and without HEN

Equipment	Without HEN	With HEN
E-106	x	
V-101	x	x
E-103	x	
X-100	x	x
MIX-100	x	x
E-104	x	x (< area)
CSTR-101	x	x
E-101	x	x
E-105	x	x
CSTR-100	x	x
E-100	x	
CRV-100	x	x
E-102	x	
T-100	x	x
T-102	x	x
Exchanger H3-C1		x
Exchanger H1-C1		x
Exchanger H2-C1		x
Exchanger H2-C2		x

The areas required to calculate the cost estimate of such equipment were calculated using equation (1).

$$Q = A\ U\ LMTD \qquad (1)$$

where: Q: heat quantity exchanged, MJ/h
A: heat transfer area, m^2
U: total heat transfer coefficient, MJ/(h °C m^2)
LMTD: Logarithmic mean of the temperature difference, °C.

Since the fluids in this work were aqueous solutions, the heat transfer coefficient was established as corresponding to water. The total heat transfer coefficient, tabulated by Kern [42], is 500 Btu/(°F h ft^2) (equivalent to 10.2 MJ/(°C h m^2)) for considered fluids. Table 4 shows the parameters and areas of each heater, cooler and heat exchanger for the processes (with / without HEN), their cost, and the total investment in US$. The cost constants proposed by Turton [37] for Heat Exchanger Double Pipe and Multiple Pipe with transfer areas between 1 to 10 m^2 and 10 to 100 m^2, respectively, were considered. The Chemical Engineering Index used to update costs was the "Heat Exchanger and Tanks" of April 2022 (856.8).

Table 4. Capital investment of different equipment in the processes with and without HEN

	Equipment	Q (MJ/h)	LMTD (°C)	A (m^2)	Cost (US$)	Total Investment (US$)
Without HEN	E-106	7,172	120	6	40,482	291,774
	E-103	666	42	2	29,861	
	E-104	8,06	25	32	130,315	
	E-100	675	50	1	65,362	
	E-102	4,936	116	4	25,754	
With HEN	E-104'	5,839	21	27	110,144	290,029
	Exchanger H3-C1	1,064	12	9	43,760	
	Exchanger H1-C1	666	41	2	30,038	
	Exchanger H2-C1	5,441	33	16	48,735	
	Exchanger H2-C2	2,301	17	13	57,352	

(“'” equipment with a smaller area than the original without HEN)

Table 5 shows the cost of external utilities for the differential process with and without HEN. The required heat quantity (QH), temperature (T), and flow rate (q) data were obtained or calculated from simulation data. The temperatures of utilities were established according to the heuristic rules proposed by Seider [43]. These are 150 °C for heating utility and 20 °C for cooling utility. These costs were updated with Chemical Engineering's CE Index of April 2022 (785.9).

Table 5. External utility costs in the process with and without HEN

	Equipment	T (K)	q (m^3/s)	CS,u (US$/year)	CS,u Total (US$/year)
Without HEN	E-106	423	-	1,075,173	4,476,014
	E-103	-	0.01	761,721	
	E-104	423	-	1,123,984	
	E-100	-	0.01	761,721	
	E-102	-	0.01	753,414	
With HEN	E-104'	423	-	995,272	995,272

(“'” equipment with a smaller area than the original without HEN)

As shown in Table 6 about the differential costs of the alternative with and without HEN, the capital and external cost utilities investment with HEN was found smaller than the process without HEN, achieving an annual saving of 0.6% and 77.8%, respectively.

Table 6. Differential costs

Concept	Without HEN	With HEN	Difference (With HEN - Without HEN)
Investment in exchangers (US$)	291,774	290,029	-1,745
Cost of services (US$/year)	4,476,014	995,272	-3,480,741

Table 7 shows the 10-year differential background flow. It is called as differential fund flow because it is made from differential costs; that is, the mutual costs of both alternatives are not considered. From this flow of funds, a NPV of US$ 31,679,003 was obtained. Since it was a differential cash flow, the parameters common to the alternatives were not considered. A rate in Dollars of 1.75% (according to Argentine Nation Bank, August 2022) was used.

Table 7. Differential cash flow

Concept	Año 0	Año 1	…	Año 10
Investment	1,745	0	…	0
Income	0	0	…	0
Expenses	0	-3,480,741	…	-3,480,741
Cash flow	1,745	3,480,741	…	3,480,741

4. Conclusion

In this work, the technical-economic analysis of the bioethanol process from rice husks and whey was carried out. A heat exchange network (HEN) was designed using the Pinch method between the streams of the production process that required cooling and heating. This technological alternative reduced the consumption of external services by 45.07% for heating and 100% for cooling. The alternatives with / without HEN were economically compared, resulting in lower capital investment and lower cost of utilities for the with HEN process. A 10-year differential cash flow was performed, obtaining an NPV of US$ 31,679,003. Therefore, this project with HEN is a viable economic alternative, and concerning the environment, it is a "friendly" system since the reduction of energy consumption means to reduce environmental damage.

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