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Exergy Analysis of Bioethanol Production from Rice Residues

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Abstract

Biofuels production is one of the industrial sectors with greater growth in the last years. This sector is focused on the energetic self-sustainability of the regions through the replacement of fossil fuels. The use of residual biomass for the production of second generation biofuels generates opportunities for strengthening the agricultural sectors, at the same time as it offers greater opportunities for the growth of bioethanol production. However, some of these processes must be evaluated to verify that the productive processes proposed from waste biomass represents energy and environmental suitable alternatives. In this paper, exergy analysis of a bioethanol production plant from rice husks was performed. Ethanol production through simultaneous saccharification and co-fermentation (SSCF) of lignocellulosic residues was simulated through Aspen Plus software. Also, production pathways were analyzed using exergy tools in order to evaluate the process performance.

Keywords: Bioethanol, exergy, rice, agricultural wastes, SSCF

1. Introduction

Fuels of fossil origin are the primarily energy supply of the world. One of the unfavorable aspects of the use of fossil fuels lies in their non-renewable nature, in addition to the negative environmental impacts produced by the combustion of this type of substances [11]. The importance of biorefineries lies in transforming biological material, in biofuels, chemical derivatives with applications in different types of industries, and power generation [13]. Biorefineries offer comparative advantages over other types of industries. However, the processes have very demanding water and energy supply requirements. Therefore, current research aims to make optimal biofuels, like bioethanol, applying process analysis methodologies to the process design to transform agricultural waste into value-added products [9]. Agroindustrial waste represents a major concern due to its final disposal. Therefore, coupling agricultural production chains together with the operation of biorefineries, which would take the agroindustrial waste to transform them into valuable products, implies a solution to the problem of solid waste management generated in these industries, in addition to the rural economic growth by the joint operation of the biorefinery [2]. The selection of raw materials coupled with the process routes is an important aspect, since it conditions the viability of biofuel production [3].

On the other hand, exergy is a property described by thermodynamics that refers to the energy potential of a certain source. It can be defined as the maximum profitable work that can be extracted from a system that is in interaction with the environment. As the system evolves towards equilibrium with the environment, the possibility of producing work is reduced. The environment refers to a part of the environment where its intensive properties do not change significantly as a result of any process that is considered [5]. The exergy content of a material stream is the amount of work which would be produced by bringing this stream in thermal, mechanical and chemical equilibrium with a reference state by a sequence of reversible operations. Application of exergy analysis for accounting both for materials use and waste residuals constitutes is effective in generating and screening design alternatives to sustainable development [9]. Therefore, in this work, exergy analysis was applied as a tool to evaluate the efficiency of the proposed stages in a bioethanol production process from rice husks.

2. Bioethanol Production

The simulation in Aspen Plus software was adjusted to have a capacity to transform 1,795.8 t/year of rice chaff. Due to the structure of the carbohydrates that make up the lignocellulosic biomass, it is necessary to develop a pre-hydrolysis stage to facilitate the formation of five and six carbons sugars. For this design, an acid pre-treatment was simulated, with H_2SO_4 diluted to 0.5% w/w, and a concentration of solids in the reactor of 22%. The reaction system operates at 190 °C and 13 atm [7]. The outlet stream was sent to a neutralization reactor with lime, according to the concentration of sulfuric acid, to reduce the pH of the system. After neutralization, the main flow was de-lignified and sent to a flash cooler to reduce the pressure as low as 1 atm. In this equipment an important amount of HMF, furfural, and acetic acid was separated, and finally after neutralization and delignification the stream was sent to a SSCF stage [12].

In the fermentation reaction was used *Zymomona mobilis* as biocatalyst, this microorganism can degrade carbohydrates with yields of ethanol production of 95% for glucose, and 85% for xylose. The fermentation broth, with a high content of carbon dioxide and water, was sent to the column to remove a significant portion of gas. Finally the bottom of the column with an approximate ethanol concentration of 8% w/w, was sent to a distillation stage, until reaching the azeotrope concentration [4]. In the literature are reports of purification using molecular sieves to purify ethanol up to 99.7% w/w [6].

3. Exergy Analysis

The exergy analysis uses thermodynamics principles (like the second law of the thermodynamics), that allows us to assess the energetic performance of the processes. Exergy is known as the maximum amount of exploitable work that can be extracted from a physical system by exchange of matter and energy [10]. The balance of energy and exergy of a system is:

$$Energy_{in} - Energy_{out} = Energy_{accumulated}$$

$$Exergy_{in} - Exergy_{out} - Exergy_{consumption} = Exergy_{accumulated}$$

The exergy consumed is the product of entropy generated and environment temperature. The exergy of a system can be written as the equation 1.

$$E = S(T - T_0) - V(p - p_0) + \sum_i n_i(\mu_i - \mu_{i_0}) \quad (1)$$

When standard environmental conditions are set as a reference, the exergy balance is:

$$E = H - H_0 - T_0(S - S_0) + \sum_i n_i(\mu_i - \mu_{i_0}) \quad (2)$$

Where H is enthalpy, S is entropy, n_i is the number of moles of species i, and μ_i is the chemical potential. The chemical exergy is calculated from the thermodynamic data of the substances. Table 1 reports the specific chemical exergy of some substances [10].

Table 1. Specific Chemical Exergy of the substances involved in the process

Component	**Specific Exergy (MJ/kmol)**	**Component**	**Specific Exergy (MJ/kmol)**
Ethanol	1,250.9	Lignin	3,449.5
Water (l)	0.9	Enzyme	145.6
Water (g)	9.49	Acetic Acid	908.0

Table 1. (Continued): Specific Chemical Exergy of the substances involved in the process

Carbon dioxide	**19.1**	**Succinic Acid**	**1,609.4**
Glucose	2,793.2	Furfural	2,338.7
Xylose	1,835.6	Hemicellulose	2,826.4
Cellulose	3,404.4	Sulfuric Acid	2,826.6
Calcium sulfate	6.8		

The transfer of exergy associated with a flow of heat that arrives or starts at a reference point at a certain temperature, refers to the maximum work that could be obtained from that flow when it interacts with the environment. Equation 3 shows the mathematical expression of the concept described above [8].

$$E_q = W_{util,max} = \int \left(1 - \frac{T_o}{T}\right) dQ \tag{3}$$

Where E_q is the exergy, T_o is the reference temperature, T is the system temperature, and Q is heat transferred.

For the measurement of the degree of resource and the thermodynamic characteristics of the process, the exergy efficiency is a valid parameter to determine how much exergy of a system is used and it is defined as follows in the equation 4.

$$\tau = \frac{Effective\ exergy\ obtained}{Exergy\ consumed\ in\ the\ process} \tag{4}$$

Exergy analysis is a useful tool that allows us to know the energy losses of a process, identifying the areas that require technological improvements to obtain processes with better energy performance [1].

4. Results and Discussion

The simulation was developed to receive an input stream of 1,795.8 t/year of rice husks, with a fractional mixture concentration of 0.5 (wet basis).
The biomass was pretreated at 190 ° C and dilute sulfuric acid as catalyst. Then, the stream was sent to a neutralization reactor where gypsum was precipitated and removed from the process with the lignin. Figure 1 and 2 illustrates the main pathways:

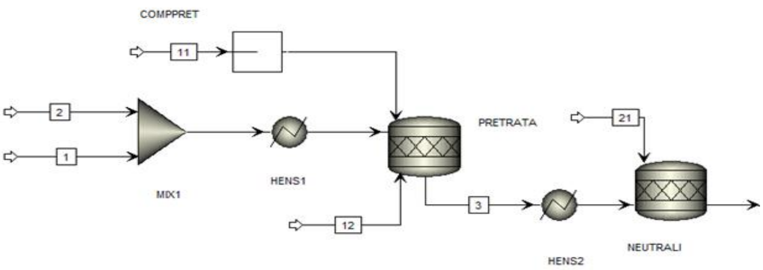

Figure 1. Acid pre-treatment pathway

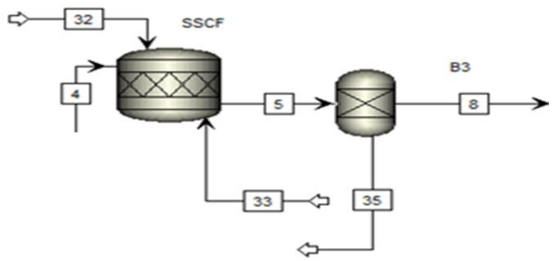

Figure 2. SSCF Pathway

Bioethanol obtained in the SSCF process was purified using azeotropic distillation and molecular sieves to a concentration of 99.7%. Thus, 0.149 kg of ethanol was produced per kg of biomass (rice residues) as raw material.

Exergy balance was applied to each process. In the exergy analysis performed in this paper, the irreversibility generation and the exergetic efficiency were calculated for each case. For the exergetic analysis, the chemical exergy of each substance was initially calculated from the specific chemical exergy data of the compounds involved in the process. The reference temperature was 298.15 K, the relative humidity of atmospheric air was 70%, and the chemical exergy of ash was neglected. The control volume was divided into the pre-treatment, SSCF, and purification steps. The exergetic flow is determined as the sum of the physical exergy, chemical exergy, and exergy by heat transport, which was calculated with the help of the Carnot factor:

$$E^Q = Q\left(1 - \frac{T_o}{T}\right) \tag{5}$$

Where T is the temperature at which the heat Q is available and T_o is the reference temperature. Table 2 shows the exergetic flows for the process stages. Figures 3 and 5 show total irreversibilities and exergy efficiency for each stage of the bioethanol production process.

Table 2. Total exergy flow for stages

Variable	Pretreatment	SSCF	Purification
Total Exergy input (MJ/h)	3,677.99	1,389.28	1,118.60
Total Exergy output (MJ/h)	3,098.80	1,275.65	1,095.82
Total Irreversibility (MJ/h)	579.19	113.63	22.79

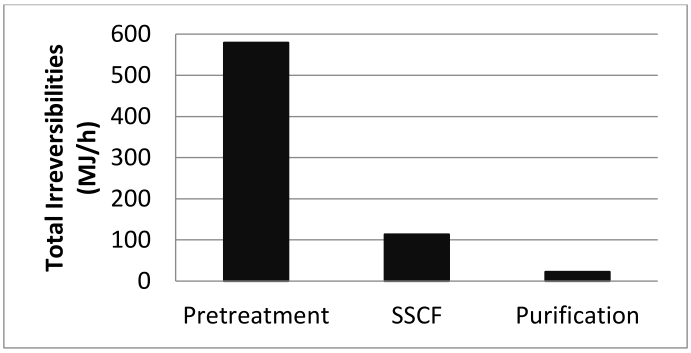

Figure 3. Irreversibilities for the bioethanol production pathways

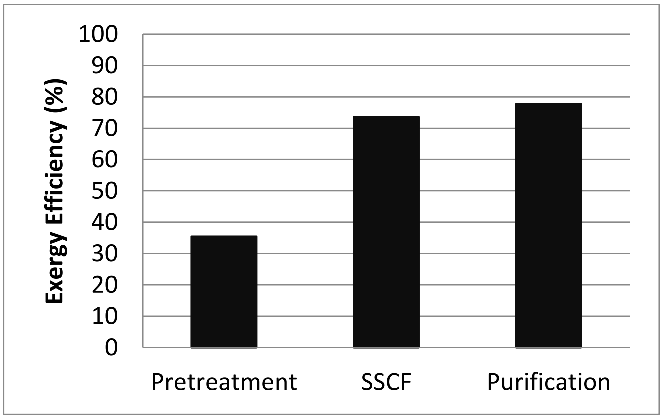

Figure 4. Exergy efficiency for the main stages

The results show that the stage with the least exergy efficiency is the pretreatment (35.48%). This fact indicates that in this sub-process has potential to make technological improvements to obtain better energy performance and to optimize the available resources. The efficiency for the SSCF and purification were relatively high (73.63% and 77.73%, respectively) indicating that the process has a good energy performance in these stages. The irreversibilities were calculated for each stage, which shows the loss of mass and quality energy by dissipation.

To improve the exergy performance, it is suggested to implement methodologies for energy integration of processes or to adjust cogeneration systems which will reduce the need for external energy supply.

5. Conclusions

In this study a bioethanol production plant from rice residues was simulated and analyzed. The exergetic analysis shows that the process that has the greatest potential for improvement is the pretreatment stage, since it has the lowest exergetic efficiency and the highest irreversibilities, which indicates that many resources are needed, either energy or mass, to obtain the product of the process.

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