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Ethanol Production from Banana Fruit and its Lignocellulosic Residues: Exergy and Renewability Analysis*

Velásquez Arredondo, H. I[**1,2], Ruiz Colorado A. A[1], Oliveira Junior, S[2]

[1]Grupo de Investigación en Bioprocesos, Universidad Nacional de Colombia, Sede Medellín
[2] Mechanical Engineering Department, Polytechnic School, University of São Paulo, Brazil
E-mail:[1] hivelasq@unal.edu.co

Abstract

Tropical countries such as Brazil and Colombia have the possibility of using their lands for growing vegetable products to produce biofuels such as biodiesel and ethanol. The objective of this work is to apply exergy analysis to evaluate the renewability of anhydrous ethanol production from surplus banana fruit production and its residual biomass. The study takes into account all production stages: growing, feedstock transport, hydrolysis, fermentation, distillation, and dehydration. It also considers the cogeneration plant and residues treatment. Four production routes were analyzed according to the biomass used as feedstock: banana pulp, banana fruit, hanging cluster or banana skin. Based on the exergy concept, performance indicators are proposed and calculated. In order to quantify the renewability of the ethanol production processes, a new indicator called "Renewability Performance Indicator" is defined and applied to the four ethanol production routes studied. The results show that when amilaceous material is used, better results than lignocellulosic material are obtained and four production processes studied must be classified as non-renewable.

Keywords: *Exergy analysis, renewability analysis, ethanol production, banana fruit, hydrolysis.*

1. Introduction

Global warming, urban pollution and reserves depletion of fossil fuels have been the driving forces for current research on the use of alternative energy sources, especially those derived from biomass. In this sense, ethanol produced from different renewable or organic feedstocks constitutes an alternative fuel for spark ignition engines.

Using ethanol as a fuel decreases fossil fuel consumption and increases energy supply security. It can be used neat or blended with gasoline. Additionally, it is considered biodegradable and sulphur free. Its carbon content has a vegetable origin and as a consequence, when it is released during the combustion process, it does not contribute to the increase of CO_2 in the atmosphere, reducing global warming (Hsieh, et al., 2002; Kadam, 2002; Wang, et al., 1999).

Banana fruit and its associated residual biomass are amilaceous and lignocellulosic compounds; therefore, they must be initially hydrolyzed to be converted into glucose which can be used as a feedstock to produce ethanol by fermentation and distillation.

A primary tool to analyze the ethanol production process from an integrated point of view is offered by exergy analysis. Exergy is defined as the maximum (theoretical) work that can be extracted from a mass or energy stream when it flows from a given thermodynamic state to one in chemical, mechanical and thermal equilibrium with the environment in a reversible way, interacting only with the components in the environment. Therefore, any deviation from the environmental reference can be assumed as exergy content (Szargut, et al., 1988). When an exergy analysis is performed, the thermodynamic irreversibility can be quantified as destroyed exergy, which is a wasted potential for producing work (Bejan, et al., 1996).

Exergy analysis has two key attributes for being used from an environmental standpoint: as the environment is used as a reference state, exergy is a measure of any thermodynamic deviation. Further, it allows comparisons between inflows and outflows, independently if they are mass or energy streams, using the same physical basis – exergy (Wall, 1977).

Exergy analysis has been used to evaluate biodiesel production from cooking oils (Talens, et al., 2007). A similar study using palm oil as a raw material was presented by Velasquez, Benjumea and Oliveira Jr (2007). For evaluating the combined production of sugar, ethanol and electricity, exergy analysis has been used (Pellegrini, et al., 2007; Pellegrini and Oliveira, 2007).

In Colombia, banana fruit surplus production amounts to 850.000 t/year and it generates 1.150.000 t/year of associated residual biomass. (Bohórquez and Herrera, 2005). This material is considered biomass waste. In some farms it is treated in a composting plant, but generally there is not an adequate practice for its use leading to environmental problems.

Looking for solving this problem it has been proposed to use the banana fruit surplus and residual biomass to produce ethanol and the objective of this work is to apply exergy analysis to evaluate its behavior and the renewability of its production process.

The study takes into account the production stages of: growing, feedstock transport, hydrolysis, fermentation, distillation and dehydration. It also considers the utility plant and residues treatment. Four production routes were analyzed according to the biomass used as feedstock: banana pulp, banana fruit, hanging cluster and banana skin.

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**Corresponding Author

2. Ethanol Production Processes

Ethanol production stages are shown in Figure 1. Banana planting and growing require the use of fertilizers, pesticides and fungicides which are quantified in this work. The feedstock used to produce ethanol are the banana fruit and the hanging cluster support. They are transported to the production facility where they are washed and classified. Four producing routes for hydrolysis reaction are evaluated:

- The banana fruit is exposed to acid hydrolysis, or it is peeled and the banana pulp is submitted to acid hydrolysis, availing of amilaceous material.
- The hanging cluster support or the banana skin is submitted to enzymatic hydrolysis, taking advantage of lignocellulosic material.

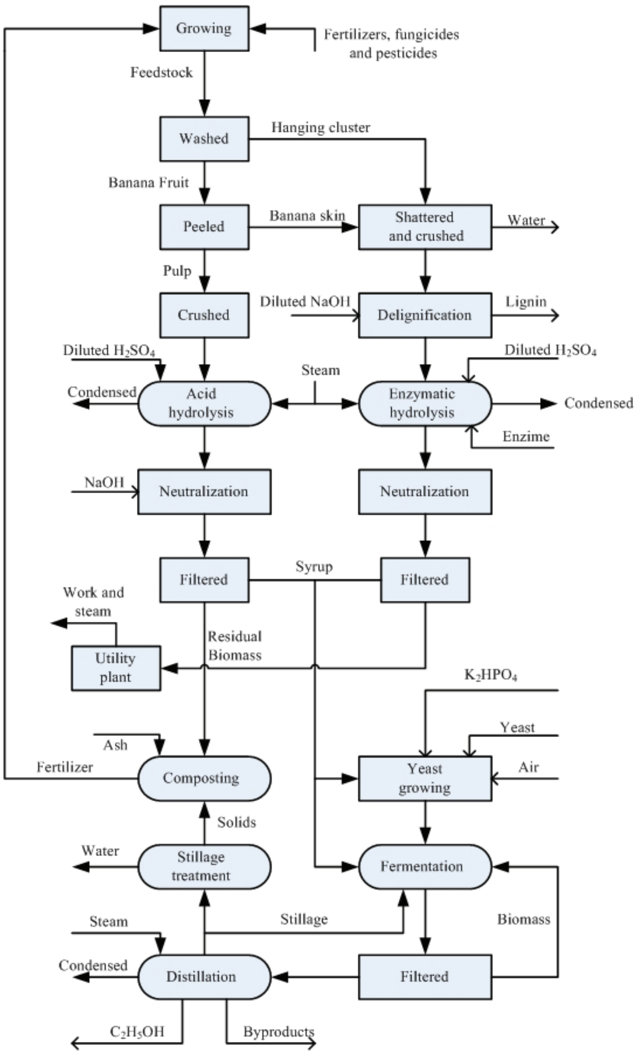

Figure 1: Scheme of the Ethanol Production Process from BF and its Biomass Residuals.

During the acid hydrolysis diluted H_2SO_4 is used for reducing the pH of the mixture which is shaken and heated by steam up to 100°C. After 6 hours, about 95% of the starch chains are transformed into glucose (Bohórquez and Herrera, 2005). The corresponding chemical reaction is presented in Eq. (1):

$$(C_6H_{10}O_5)n + nH_2O \rightarrow n(C_6H_{12}O_6) \quad (1)$$

The syrup obtained must be neutralized until reaching the pH for fermentation; this is achieved by adding NaOH. The mixture is filtered in order to separate the residues that can be used as fuel or fertilizer. On the other hand, the lignocellulosic material is shattered and crushed before being passed through the delignification process. NaOH is used in delignification process increasing the pH. The lignin is a by-product that can be sold as an agglutinative agent or food for the animal industry.

During enzymatic hydrolysis organic enzyme is used as an agent for obtaining glucose and diluted H_2SO_4 is employed for reducing the pH of the mixture which is shaken and heated until 50°C. After 10 hours of treatment, approximately 70% of cellulosic material is transformed into glucose.

The mixture is also neutralized and filtered before being prepared for fermentation. The syrup can be marketed as a sweetener or used as a raw material to produce ethanol. During the fermentation process about 2% of the syrup is used for yeast growing in aerobic conditions. The remaining syrup is used to produce ethanol.

When the yeast is submitted to anaerobic conditions, its metabolic route is deviated to produce ethanol and CO_2 as shown below (Correa and Levaza, 2006):

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 \quad (2)$$

The theoretical fermentation reaction yield is 51%, however it reaches about 91% of this theoretical conversion. Furthermore, during the fermentation process other compounds such as aldehydes, heavy alcohols, fatty acids, and residual biomass are produced.

Ethanol at 96% w/w is produced in the distillation process. Normally two distillation columns are used and some by-products such as aldehydes and heavy alcohols are recovered. Stillage that is a mixture of water and other by-products is separated, and then about 70% of this liquid mixture is sent again to the fermentation process for increasing the process efficiency. Finally, the stillage is carried to the stillage treatment plant, the solids are separated and sent to the composting plant, where they are mixed with ashes and residual biomass to obtain an organic fertilizer. At the end of the process the product is dehydrated using molecular sieves to produce anhydrous ethanol at 99.8% w/w.

Residual biomass generated during the hydrolyze process is sent to the cogeneration plant to produce steam to be used in backpressure turbines. This equipment is responsible for supplying the electromechanical demands of the plant. The cogeneration plant consists of a boiler that generates steam at 22 bar and 333°C, that is expanded in a backpressure turbine until 2.6 bar with an isentropic efficiency of 70%. The electromechanical energy produced is for internal use only. A boiler working at 10 bar is used to fulfill the thermal requirements of the process and the condensate returns to the boilers.

3. Exergy Analysis

The exergy balance for a control volume at steady-state condition, taking into account the concepts of physical exergy (b^{ph}) and chemical exergy (b^{ch}), is given by Eq. (3) (Kotas, 1995):

$$\left(\sum_i \dot{m}_i\left(b^{ch}+b^{ph}\right)_i\right)_{in} + \dot{B}^Q = \left(\sum_j \dot{m}_j\left(b^{ch}+b^{ph}\right)_j\right)_{out} + \dot{W} + \dot{I} \tag{3}$$

The left side of Eq. (3) represents the exergy associated with mass entering the system ($\dot{m}_i$) and the heat transferred ($\dot{B}^Q$). On the other hand, the right side accounts for the exergy associated with the mass leaving the system ($\dot{m}_j$), the work transferred ($\dot{W}$) and the exergy destroyed due to irreversible processes ($\dot{I}$).

The physical exergy (b^{ph}) of the mass flows is calculated according to Eq. (4):

$$b^{ph} = \left(h - h_0\right) - T_0\left(s - s_0\right) \tag{4}$$

For a given environment reference, the values of b^{ch} for many substances are tabulated (Szargut, Morris and Steward, 1988). If the mixture is a real solution its b^{ch} can be calculated according to Eq. (5).

$$b^{ch}_{mix} = \sum_i y_i b_i^{ch} + RT_0 \sum_i y_i Ln\left(\gamma_i y_i\right) \tag{5}$$

For organic compounds whose elemental compositions are known, b^{ch} is calculated as a function of the lower heating value (LHV) and the elementary composition (Szargut, Morris, and Steward, 1988) as in Eq. (6):

$$b_{ch} = \beta LHV \tag{6}$$

For a solid material having exclusively atoms of carbon, hydrogen and oxygen, the value of β can be calculated according to Eq. (7):

$$\beta = \frac{\left(1.0438 + 0.1882\frac{H}{C} - 0,2509\left(1 + 0.7256\frac{H}{C}\right)\right)}{\left(1 - 0.3035\frac{O}{C}\right)} \tag{7}$$

The developed model aims at simulating the steady state operation of a pilot plant, using 1000 kg of wet biomass as a basis for presenting the results. It is composed of mass, energy and exergy balances, heat and mass transfer equations, and correlations of thermodynamic properties such as those for ethanol-water mixtures (Modesto and Nebra, 2005).

The elemental composition of the biomass and their higher and lower heating values (HHV and LHV) necessary to develop the exergy analysis were obtained by experimental analysis developed at the Thermal Laboratory of National University of Colombia, and they were analytically corroborated (Channiwala and Parikh, 2002; Hugot, 1986). The models were implemented in EES software, using its thermodynamic properties library for substances such as steam, Ethanol and ideal gases, for instance, CO_2, H_2O and O_2 (Klein and Alvarado, 2007).

4. Performance Indicators

For assessing the ethanol production performance several efficiency criteria have been proposed. One of them is the "Mass Performance" (η_m) (Wang et al., 1999), defined by Eq. (8):

$$\eta_m = 1000\frac{V_p}{m_{DB}} \qquad [\text{l/t}] \tag{8}$$

where V_p is the volume of produced ethanol and m_{DB} is the mass of the dry biomass used.

Another indicator is defined as "Growing Density (ρ_g)" (Lechón et al., 2005) and is defined in Eq. (9).

$$\rho_g = \alpha\frac{V_p}{m_{DB}} \qquad [\text{l/ha}] \tag{9}$$

The α factor is the biomass produced per land hectare (see Table 1).

The "Exergetic Density (ρ_B)" is a new indicator which is defined using a similar relation for the energy density (Society, 2008). The proposal made here is to change the use of the LHV for the b^{ch} in the indicator, as shown in Eq. (10).

$$\rho_b = \alpha\frac{\sum_p m_p b_p^{ch}}{m_{DB}} \qquad [\text{kJ/ha}] \tag{10}$$

where b_p^{ch} is the chemical exergy of the biofuel produced.

The global efficiency of ethanol production will be evaluated according to Eq. (11):

$$\eta_b = \frac{B_{products}}{B_B + B_{RM} - B_{emissions}} \tag{11}$$

where B_p is the products exergy, B_B is the exergy of the biomass used, B_{RM} is the exergy of the raw material used and $B_{emissions}$ is the exergy of wastes produced.

In order to evaluate the environmental performance along with the energy conversion processes, many indicators have been proposed. It is agreed that an environmental indicator must have certain features: it must be easy to calculate and interpret, allow comparisons between different products and at different times, and be calculated in a scientific form eliminating subjectivities (Gong and Wall, 2001).

Some exergy methodologies proposed to evaluate the environmental performance of process production are "Life Cycle Exergy Analysis" (Gong and Wall, 1997), the "Cumulative Exergy Consumption" (Szargut, 2005; Szargut et al., 1988), "Exergetic Life Cycle Analysis" (Cornelissen, 1997), "Net Exergy Consumption" (Berthiaume et al., 2001) and "Ecological Cost" that quantifies the exergy cumulative consumption of non-renewable resources (Szargut, 2002; Szargut et al., 2002).

Different exergy environmental indicators have been defined such as: "Renewability Indicator" (Berthiaume et al., 2001); "Ecological eficiency" (Toxopeus et al., 2006); "The Environmental Loading Ratio" (Bakshi, 2002); "Sustainability index" (Rosen et al., in press; Szargut, 2005).

For evaluating any energy conversion process, especially those related to the conversion of biomass into biofuels, this paper introduces the "Renewability Performance Indicator" (λ) defined by Eq. (12). This indicator is based on the reversible process concept. This means that renewability is understood as the possibility to return the environment to its initial conditions, or the conditions before the process occurred.

$$\lambda = \frac{\sum B_{product}}{B_{fossil} + B_{destroyed} + B_{de-activation} + \sum B_{emissions}} \qquad (12)$$

where:

- $B_{product}$ represents the net exergy associated with the products.
- B_{fossil} is the non-renewable exergy consumed in the production process chain. For biofuels production this considers growing, transport and the processing plant.
- $B_{de\text{-}activiation}$ is the deactivation exergy for treating wastes, when they are carried to equilibrium conditions with the environment. It accounts for exergy required for passing the streams leaving the system, considered as wastes, to no harmful environmental conditions.
- $B_{emissions}$ is the exergy of wastes that are not treated or deactivated.
- $B_{destroyed}$ is the exergy destroyed inside the system, punishing the process for its inefficiencies.

The renewability evaluation based on this indicator implies that:

- Processes with $0 < \lambda < 1$ are considered non-renewable indicating that the exergy of the products is insufficient to return the environment to its initial conditions;
- For internally and externally reversible processes with nonrenewable inputs, $\lambda = 1$;
- If $\lambda > 1$, the process is considered renewable and it implies that the exergy in products could be used to restore the environment to its initial conditions and obtaining the remaining exergy;
- For an internally and externally reversible process with only renewable inputs, $\lambda \to \infty$.

Figure 2 shows the control volume used for λ calculations considering: growing, feedstock transport, processing production residues treatment, the irreversibility and the terms that cross the frontier: renewable and non-renewable resources, deactivation exergy, net products, emissions and residues.

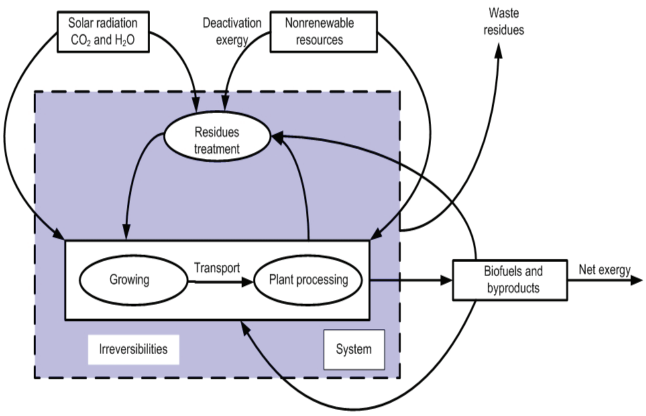

Figure 2: Control Volume for λ Calculation.

In the indicator calculation there is a clear distinction between organic (renewable) and inorganic (non-renewable) resources. The renewable exergy used in the process is not taken into account because it is considered non-environmentally harmful (Berthiaume et al., 2001; Cornelissen and Hirs, 2002; Gong and Wall, 1997&2001; Toxopeus et al., 2006). The non-renewable exergy used in equipment and plant construction is considered negligible (Malça and Freire, 2006; Shapouri et al., 2002; Kaltschmitt, et al., 1997)

In ethanol production some specific considerations are given: the obtained products are ethanol and their by-products (aldehydes and heavy alcohols). Raw materials such as NaOH, $(NH_2)_2CO$, KCl, H_2SO_4, KH_2PO_4 and $(NH_4)_2SO_4$, diesel oil and gasoline, are inorganic materials, and their b^{ch} values are taken from (Szargut, 2005; Szargut et al., 1988).

The residual biomass surplus is mixed with the solid stillage and boiler ashes to produce an organic fertilizer, decreasing the use of mineral fertilizers. This process is done in a composting plant and the consumed fossil fuels are taken into account in the calculations. The CH_4 produced in the composting plant is burned, without any use. It could be utilized to generate electricity. The stillage treatment consumes 1.73 kJ/kg-stillage as deactivation exergy to concentrate the solid material in stillage (Villegas, 2008). This exergy is taken into account in cogeneration plant.

As residual biomass ash leaves and other lignocellulosic material are left on the field as protecting material they are not considered as wastes consuming deactivation exergy. The water contaminated by fertilizer and pesticides is not taken into account because there is no available data for water treatment. The exergy of CO_2 emissions in fermentation process and combustion gases in boilers are considered as wastes.

5. Results

The raw materials consumed in farming and the dry biomass produced are shown in Table 1.

Table 1. Raw Materials Used for Farming and Dry Biomass Production (Bohórquez and Herrera, 2005).

Fertilizers	kg/ha year	α (kg dry biomass /ha-year)	
CH_4ON_2	625	Banana fruit	12972
KCL	850		
$(NH_3)_2PO_4$	100		
NH_3SO_4	75	Hanging cluster	372
B	2		
Zn	3		
Mg	18	Stem and leaf	4670
$C_{19}H_{39}$ NO	10		
Oil	120	Total	18014
Gasoline	14		

The fruit composition is 73.3% pulp and 26.7% skin. The stem and leaf are left on the field as protecting material. The diesel consumed in biomass transport and composting plant is evaluated as 0.0003 kg/kg-wet biomass.

The mass inputs, and steam and work consumed in the ethanol production plant are shown in Table 2.

An energy balance for the different steps of the process was done in order to quantify the required steam and work consumed in shakers and pumps. The steam is supplied at

2.6 bar after having been expanded in a back pressure turbine.

Table 2. Mass Inputs, Steam and Work Consumed for Ethanol Production (kg/t-wet biomass).

	Banana pulp	Banana fruit	Hanging cluster	Banana skin
Dry biomass	260	211	64	109
H_2O	740	789	936	891
H_2SO_4	12.5	30.7	1.6	2.8
H_2O	517	67	-	-
NaOH	5.1	12.5	1.3	2.3
H_2O	-	-	106	187
Enzyme	-	-	0.8	1.4
K_2HPO_4	3.0	2.1	0.2	0.6
Anti-foam	0.7	1.2	0.1	0.2
Steam	457.5	324.7	36.1	41.5
W (kJ)	140043	103357	35930	58945

The outlet mass and condensate generated for the four production process are shown in Table 3.

Table 3. Outlets of the Ethanol Production Process (kg/ t-wet biomass).

	Banana pulp	Banana fruit	Hanging cluster	Banana skin
Ethanol	79.4	57.3	6.2	7.4
By-products	4.9	1.2	0.4	0.5
Residual biomass	216.6	207.8	51.5	122.5
H_2O	-	-	875	787
Lignin	-	-	10.9	18.6
Stillage	1152	816	248	421
CO_2	78.6	56.7	6.1	7.3
Condensate	457.5	324.7	36.1	41.5

The residual biomass is a mixture of biomass, glucose, Na_2SO_4 and water. The stillage composition is 97% water and 3% other materials. The CO_2 is produced during the fermentation process. When the steam required for processing the feedstock, shown in Table 2, is divided for the ethanol production shown in Table 3, the obtained values are 5.8 kg steam/kg ethanol for banana pulp, 5.7 kg steam/kg ethanol for banana fruit, 5.8 kg steam/kg ethanol for hanging cluster and 5.6 kg steam/kg ethanol for banana skin. For work transfer, the obtained values are: 1.763 kJ/kg-ethanol for banana fruit, 1.803 kJ/kg-ethanol for banana fruit, 5.795 kJ/kg-ethanol for hanging cluster and 7.965 kJ/kg-ethanol for banana skin.

When amilaceous material is used, the energy requirements are lower than lignocellulosic material. Nevertheless, for the studied feedstock the process energy required is smaller than the ethanol energy content. Therefore they are energetically favorable processes.

The exergy balance is carried out taking the different production steps as a control volume. Except steam, the streams involved in the process enter and leave the system at normal environmental conditions and so they do not have physical exergy. The results of the exergy balance taking the plant production as a control volume including the steps of hydrolysis, fermentation, and distillation, are presented in Table 4 for exergy inputs, and Table 5 for exergy outlet streams and the exergy destroyed (I), as a function of 1000 kg of wet biomass processed.

Table 4. Exergy Inputs for Ethanol Production (kJ/t-wet biomass).

	Banana pulp	Banana fruit	Hanging cluster	Banana skin
Biomass	5.161×10^6	4.093×10^6	1.183×10^6	2.041×10^6
Raw materials	90390	102246	13209	21162
Steam	318509	219270	20668	27776
Work	140043	103357	35930	58945
Total	5.71×10^6	4.415×10^6	1.253×10^6	2.149×10^6

The exergy in raw material considers the exergy of H_2SO_4, NaOH, K_2HPO_4, water for dilution, anti-foam and yeast ferment. The required exergy in growing and the cogeneration plant is not taken into account in the exergy balance of the ethanol plant production. Nevertheless, they are used to obtain the λ indicator.

Table 5. Exergy in Outlet Streams and Exergy Destroyed (kJ/t-wet biomass).

	Banana pulp	Banana fruit	Hanging cluster	Banana skin
Ethanol	2.343×10^6	1.691×10^6	182494	217564
By-products	114291	82513	8903	10615
Residual biomass	1.433×10^6	1.559×10^6	722.912	1.369×10^6
Lignin	-	-	194129	341405
Stillage	56484	39623	12251	20877
Steam condenser	21449	31064	2078	2587
I	1.742×10^6	1.209×10^6	130040	186944

When the residual biomass shown in Table 5 is divided for the ethanol produced shown in Table 3, the values obtained are 18.047 kg/kg-ethanol for banana pulp, 27.207 kg/kg-ethanol for banana fruit, 116.598 kg/kg-ethanol for hanging cluster and 185.000 kg/kg-ethanol for banana skin.

The higher values obtained when a lignocellulosic feedstock (hanging cluster or banana skin) is used comes from the low conversion efficiency in the enzymatic hydrolysis (70%) and low content of lignocellulosic material in the biomass used (41% in hanging cluster and 29% in banana skin).

The performance indicators proposed in Eq. (8) to Eq. (11) are shown in Table 6. The α factor used to calculate ρ_G and ρ_B was taken from Table 1, and b^{ch} value for ethanol is 29515 kJ/kg (Szargut, Morris and Steward, 1988).

Table 6. Performance Indicator Results.

Indicator	Banana pulp	Banana fruit	Hanging cluster	Banana skin
η_m (l/t-DB)	388.7	346.5	123.0	88.1
ρ_G (l/ha)	3696	4495	46	298
ρ_B (MJ/ha)	85700	104200	1061	6912

η_B (%)	43.5	39.6	15.3	10.6

The best η_m is obtained when banana pulp or banana fruit are used as feedstock. The highest ρ_G and ρ_B are achieved when banana fruit is used, due to its high α factor. Hanging cluster and banana skin are not attractive to be utilized due to its low performance. The best η_B results are obtained when amilaceous material is used as feedstock. The terms for λ calculation are shown in Table 7.

Table 7. Terms Considered for λ Calculations (kJ/kg-wet biomass).

		Banana pulp	Banana fruit	Hanging cluster	Banana skin
B_p		2458	1774	191	228
$B_{NR,G}$		126.3	126.3	126.3	126.3
$B_{NR,P}$		57.4	94.4	11.5	19.2
B_{DE}		11.77	12.46	1.4	1.7
B_w	B_{GP}	351.8	383.7	118.8	176.9
	B_{CP}	473.6	501.6	57.6	68.67
	B_F	35.5	25.6	2.8	3.3
I	I_P	1742	1209	130	187
	I_{GP}	3195	3513	1074	1600

The products are ethanol and also heavy alcohols and aldeydes. The non-renewable exergy consumed in growing ($B_{NR,G}$) is calculated based on data shown in Table 1. The non-renewable exergy consumed in plant production ($B_{NR,P}$) considers the use of H_2SO_4, NaOH and K_2HPO_4. The deactivation exergy (B_{DE}) includes the diesel oil used in stillage treatment and composting plant. The work used is not taken into account because it is generated in a cogeneration plant that utilizes biomass as fuel. The exergy in waste (B_w) considers the chemical and physical exergy of combustion gases in cogeneration plant (B_{GP}), the chemical exergy of CH_4 emissions in composting plant (B_{CP}), and of CO_2 emissions in fermentation process (B_F). The exergy destroyed is divided in two parts: the irreversibility in plant production (I_P) and cogeneration plant (I_{GP}).

The results of the renewability performance indicator, λ, and the exergy efficiency, η_B, are shown in Figure 3. According to the results for the production rout analyzed, there is a direct relation between η_B and λ. As all the obtained values for λ are lower than one, ethanol production processes must be considered non-renewable, since the exergy in products is insufficient to return the environment to its initial conditions. The main factor for the non-renewability of ethanol production process is the destroyed exergy. Nevertheless, some improvements can be done in the variable processes in order to upgrade the results. For example:

- The acid hydrolysis time could be reduced to three hours and temperature at 50°C, or six hours for enzymatic hydrolysis (half the current time). In this case, it will diminish both work and steam requirements.
- The water used for diluting the biomass for hydrolysis can be reduced by a factor of two. If this improvement could be done, it will reduce H_2SO_4, NaOH, work and steam consumptions.
- The steam consumed in distillation can be reduced from 3.7 up to 2.4 kg steam/kg ethanol.
- The conventional boiler used to generate steam for electromechanical work production could be changed for a boiler producing steam at 120 bar and 510°C.

These process modifications were made and the new λ and η_B values are shown in Figure 4.

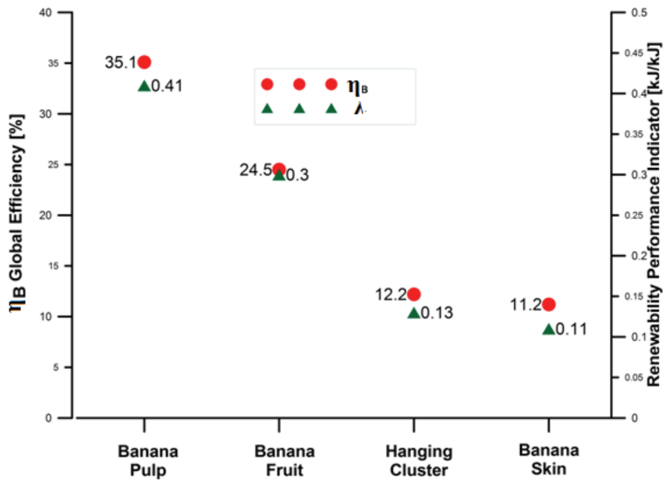

Figure 3. Global Efficiency and Renewability Performance Indicator.

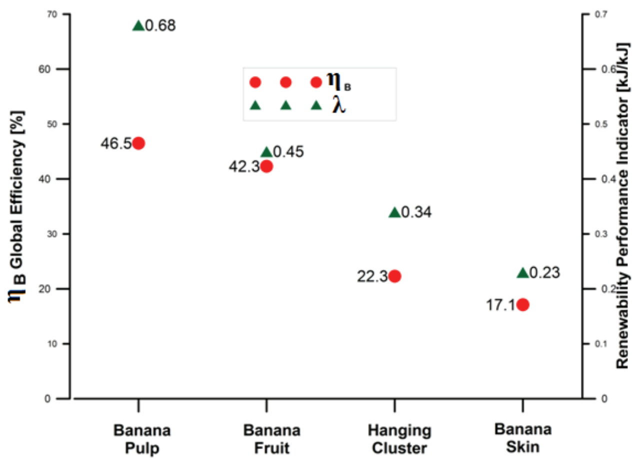

Figure 4. Global Efficiency and Renewability Performance Indicator for Improved Processes.

Although the results for the improved processes are better than the current results, the ethanol production processes are still non-renewable. It is interesting to notice that, using the same considerations and control volume for combining sugar and ethanol production from sugar cane, the λ indicator result is 0.56 kJ/kJ (Velásquez et al., 2008), showing that ethanol production processes need some improvements for being considered as renewable.

6. Conclusions

Banana fruit and its organic residues are feed stocks that can be used to produce ethanol through hydrolysis, fermentation and distillation.

The best performance indicators are obtained when amilaceous material are used as feedstock (banana pulp and banana fruit).

The four ethanol production routes have Renewability Performance Indicators lower than one. These results can be understood as the exergy in products is insufficient to restore the environment to its initial conditions, indicating that ethanol production processes can be considered as non-renewable. These results show also that although the main raw material used for ethanol production is biomass, the production process irreversibilities can render the production chain non-renewable.

Although η_B and λ have a similar behavior for the studied ethanol production routes, it must be pointed out that the definition of λ penalizes twice the processes that use nonrenewable inputs: by the use of fossil fuels and by the irreversibilities associated with the use of these fuels.

Future research must be carried out with the aim of optimizing the variables affecting the process performance and diminishing the exergy and raw materials requirements. This can be done by employing the renewability performance indicators as an objective function to be maximized.

Acknowledgments

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Nomenclature

Latin Letters

B: Exergy (kJ)
b: Specific exergy (kJ/kg)
h: Specific enthalpy (kJ/kg)
I: Irreversibility (kJ)
LHV Lower Heating Value (kJ/kg)
HHV Higher Heating Value (kJ/kg)
m: Mass (kg)
Q: Heat (kJ)
R: Ideal gas constant (kJ/kmol-K)
S: Specific entropy (kJ/kg-K)
T: Temperature (K)
V: Volume (l)
y: Molar fraction
W: Specific Work (kJ/kg)

Greek Letters

γ : Activity coefficient
λ : Renewability Performance Indicator (kJ/kJ)
η : Efficiency (%)
β : Exergy factor
ρ : Density
α : Dry biomass (kg/ha-year)

Subscripts and Superscripts

B,b: Exergy, biomass
ch: Chemical
CP: Composting plant
DB: Dry-biomass
DE: Deactivation
GP: Cogeneration plant
i: Component
In: Inlet
G: Growing
Mix: Mixture
O: Reference state
Out: Outlet
p: Product, production
NR: Non renewable
Ph: Physical
Q: Heat per mass unit (kJ/kg)
RM: Raw material
. Flux

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