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EMERGY EVALUATION OF BIO-OIL PRODUCTION USING SUGARCANE BIOMASS RESIDUES AT FAST PYROLYSIS PILOT PLANT IN BRAZIL

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ABSTRACT

Fast pyrolysis can directly produce a liquid fuel from biomass named bio-oil. It can be readily stored or transported. This liquid fuel can be a substitute for fuel oil in any static heating or electricity generation application and can also be used to produce a range of commodities and chemicals, such as phenol and its derivates. Brazilian sugar and ethanol are taking on considerable importance in the negotiation in the Free Trade Area of Americas. In 2003/2004, Brazil produced 389 millions metric tons of sugarcane that means about 250 millions metric tons of biomass residues. The yield of commodities production from biomass fast pyrolysis is, approximately: bio-oil (60-70 %), powder charcoal (20%) and gas (10-20%). Starting from the economical information, it is carried out an emergy evaluation of the system for bio-oil production in Brazil**.** This research presents the preliminary emergy analysis of a typical fluidized bed reactor for bio-oil production pilot plant at State University of Campinas (UNICAMP), located in Piracicaba, São Paulo. This paper identifies the tendencies that will affect the bio-oil production, from energy, environmental, economic and social points of view. Emergy ratios obtained for bio-oil production were: transformity (69,700), emergy yield ratio (3.36), environmental loading ratio (0.45), renewability (68%), emergy investment ratio (0.42), emergy exchange ratio (1.08) and emergy sustainability index (7.46).

1. INTRODUCTION

The process of bio-oil production from sugarcane biomass through fast pyrolysis has been already investigated in developed countries. During the 80's the Waterloo University in Canada was engaged in researches on the process and Canadian companies such as Dynamotive and Ensyn. The process to obtain bio-oil through fast pyrolysis is a thermo-chemical conversion consisting a fast transmission of heat to biomass, its degradation and subsequent and immediate cooling in an environment that is suitable for the separation of pyrolysis products. Through this process it is possible to avoid the destruction of the polymeric chains and undesirable secondary reactions involving the products obtained through the heating of biomass at a temperature of 400-500 ^{o}C and very short residence times. Although fast pyrolysis is a common process it has not been completely described yet since there are not accurate methods to allow its immediate reproduction without going through the previous scale-up and experiment processes.

Different researches have been carried out in Latin America since the last decade to investigate the use of a wide range of native residues, mainly in the sugarcane industry. Countries such as Brazil, Cuba and Argentina have outlined plans and projects to develop and improve technologies related to biomass fast pyrolysis. Brazil has made significant progresses in the fast pyrolysis studies due to the expansion of its sugarcane industry. It is clear that the production of bio-oil as a substitute for fossil fuels can be justified from an environmental point of view, but its environmental loading ratio, emergy sustainability and renewability have not been evaluated or sufficiently studied yet. Though many types of biomass to bio-oil production have been investigated, the sugarcane trash is the better choice from the economical point of view [3]. This work intends to make an emergy analysis of the production of bio-oil from sugarcane biomass. This analysis is considered of great importance since the literature on the subject does not present an evaluation of the ecological sustainability of products resulted from the fast pyrolysis process, its environmental impact and its energy input/output production benefits ratio.

2. MATERIALS AND METHODS

Experiments were conducted in Unicamp's fast pyrolysis pilot plant which has a capacity of 200kg/h for biomass conversion into pyrolysis´s products. Figure 1 shows the bio-oil production scheme that describes the process used currently by BIOWARE, a company of the University of Campinas, Núcleo Interdisciplinar do Planejamento Energético (NIPE) /UNICAMP, and carried out at the COPERSUCAR Technological in Piracicaba, São Paulo.

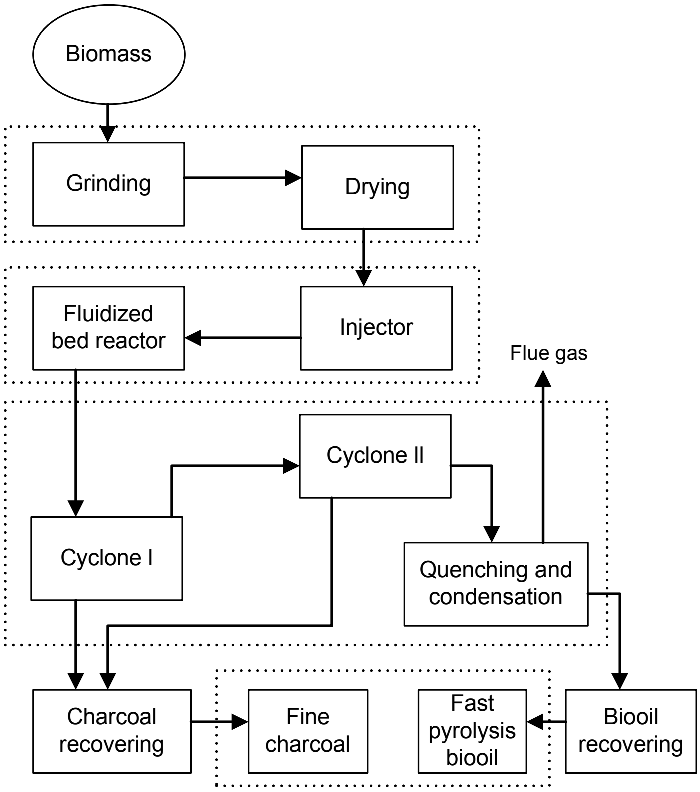

Figure 1. Biomass fast pyrolysis scheme

The main operational characteristics of pilot plant process conditions are summarized in Table 1. Knowing the values for the biomass consumption per year in the plant, the bio-oil yield (approximately 60%) and the charcoal production (between 15 and 20%), it is possible to determine the emergy for the biomass input, previously defined as sugarcane trash. Sugarcane trash accounts for approximately 25% of the harvested sugarcane total weight [1]. The values for sugarcane emergy have already been calculated in Brazil and Cuba [2, 3]. Analyzing the information of the Table 1 it is possible to deduce that for a yearly production of 81 tons of charcoal and 244.8 tons of bio-oil it is necessary 408 tons of sugarcane biomass. For the sugarcane trash, that presents a Low Heat Value (LHV) with a moisture content of 10-12% is Pci_{paja}=3772 kcal/kg [4] the biomass necessary energy quantity is calculated (see foot notes), resulting in: Biomass yearly energy = 6.44 E+12 J/yr .

Table1. Fluidized Bed Reactor Operational Conditions

Operational Conditions	Quantity	Unit
Yield	20	(% average)
Hours/Day	8	Hours
Days/Week	5	Days
Weeks/Year	52	Weeks
Hours/Year	2080	Hours
Maintenance Hours/Year	40	Hours
Operation Hours/Year	2040	Hours
Biomass Average Consumption	0.2	Tons/Hour
Biomass Consumption/Year	408	Tons/Year
Charcoal Production/Year	81.6	Tons/Year

2.1 Energy flow diagram for the bio-oil production plant

The method employed was developed by H.T. Odum [5] and comprise an energy flow chart and the corresponding spreadsheet containing the emergy analysis data (Table 2).

Table 2. Emergy Analysis

Notes		Energy (J/y) Mass (kg/y) Money ($/y)		Transformity sej/J sej/kg	Emergy Flows		Em$
Natural Resources					sej/year	%	2004 US$
Renewable					**1.7E+17**	**68**	**5.37E+04***
1	Sugarcane Biomass	6.44 E+12	J/y	24600	1.58 E+17	63	4.98E+04
2	Water (cooling system)	1.56 E+10	J/y	6.66E+05	1.04E+16	4	3.28E+03
3	Charcoal	1.71E+10	J/y	107000	1.83 E+15	1	5.77E+02
Non Renewable					**6.59E+15**	**2.6**	**2.08E+03**
4	Sand	3.29E+8	J/y	20000000	6.58E+15	2.6	2.08E+03
5	Ceramic Material	1.02E-6	Kg/y	330.0E+11	3.37E+7	0	1.06E-05
Materials from Economy					**7.32E+16**	**29**	**2.31E+04**
6	Equipments (carbon steel)						
	Reactor	1900	Kg/y	18E+11	3.42 E+15	1	1.08E+03
	Quench	250	Kg/y	18E+11	4.5 E+14	0	1.42E+02
	Vessels	325	Kg/y	18E+11	5.85 E+14	0	1.85E+02
7	Electricity kwh	4.07E+11	J/y	165000	6.71E+16	27	2.12E+04
8	Chemicals						
	ISOPAR	445	Kg/y	38.0E+11	1.69 E+15	1	5.33E+02
Services					**1.43E+15**	**0.6**	**4.50E+02**
9	Labor		J/y				
	Technicians	2.5E+8	J/y	4E+06	1.0E+15	0.4	3.15E+02
	Mechanics	2.5E+8	J/y	1200000	3.0E+14	0.1	9.46E+01
	Workers	3.2E+8	J/y	400000	1.28E+14	0.1	4.04E+01
Total Emergy					**2.51E+17**	**100**	**7.92E+04**

*3,17E+12 sej/US

Figure 2 shows the energy flow diagram for the bio-oil production plant. This diagram was made based on the production scheme for charcoal and bio-oil as main products of the fast pyrolysis process used in this plant. The ash production percentage of sugarcane biomass is 1-3 % that can be negligible compared to the main products.

Considering that the thermo-conversion processes are ongoing processes, once we would have heavy heat losses in a discontinuous operational mode, it were adopt eight-hour work shifts.

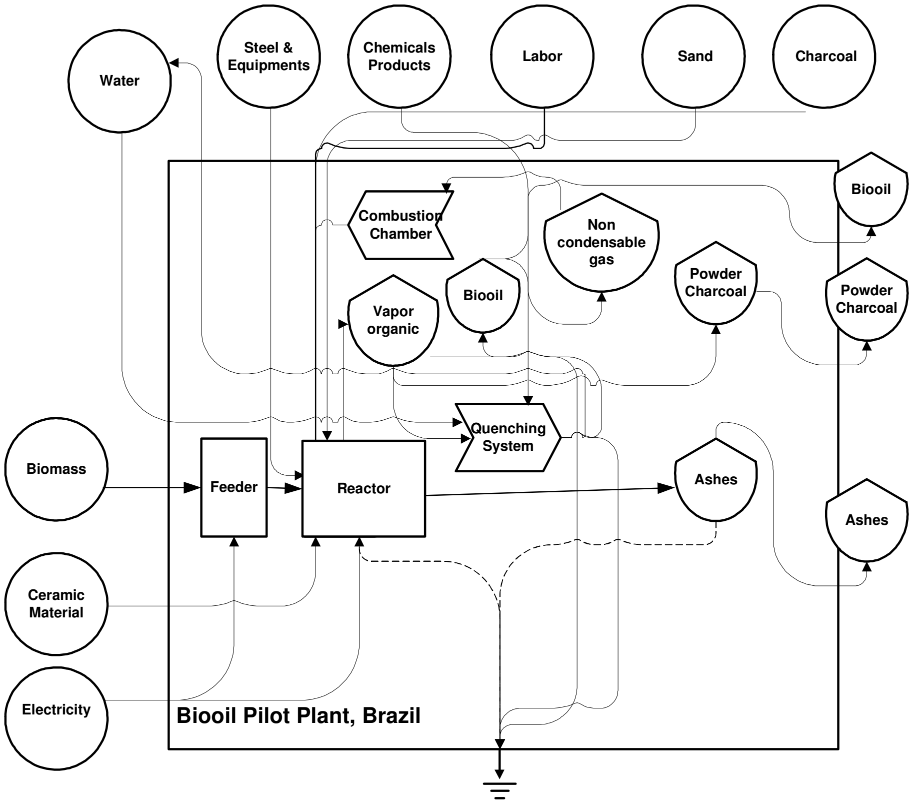

Figure 2. Bio-oil production energy flow diagram

3. RESULTS

Based on the powder charcoal and bio-oil yearly quantities, it was possible to calculate the main resources, the transformities and the main emergy ratios of the charcoal and bio-oil production (see Tables 3 and 4).

Table 4 presents the main emergy ratios. The 244.8 tons bio-oil yearly production with a LHV lower than 15 MJ/kg is the energy quantity [7].

$Q_{pbio\text{-}oil}$= 244.8 ton*15 MJ/kg=244.8x1000xkgx15MJ/kg=3.67E+12 J
Then $Tr_{bio\text{-}oil}$=2.51E+17 sej/3,67E+12 J= 6.97E+04 sej/J
For the fine charcoal:
$Q_{pcarbón}$=81Tons*7600kcal/kgx4186J/kcal=81x1000x7600kcal/kgx4186J/kcal= 0.3E+12 J
$Tr_{charcoal}$=2.51E+17 sej/0.3E+12 J=8.37E+05 sej/J
The price for the bio-oil is 300 US$/ton. The price for the charcoal is 83.3 US$/ton [6].

Table 3. Emergy ratios for the charcoal and bio-oil production

Resources	Bio-oil +Charcoal (sej/year)
Renewable **(R)**	**1.70E+17**
Non renewable **(N)**	**6.59E+15**
Total of Natural Resources **(I=R+N)**	**1.77E+17**
Materials from Economy **(M)**	**7.32E+16**
Services **(S)**	**1.43E+15**
Feedback (**F=M+S)**	**7.46E+16**
Total Emergy	**2.51E+17**

Table 4. Emergy Ratios

Index	Value	Type
$T_{rbio\text{-}oil}=Y/Q_{pbio\text{-}oil}$	**6.97E+04 sej/J**	Bio-oil Transformity
$T_{rcarbón=}Y/Q_{pcarbón}$	**8.37E+05 sej/J**	Charcoal Transformity
EYR=Y/F	**3.36**	Emergy Yield Ratio
EIR=F/I	**0.42**	Emergy Investment Ratio
ELR=(N+F)/R	**0.45**	Environmental Loading Ratio
%R=R/Y	**68%**	Renewability (%)
EER=Y/E$	**1.08 bio-oil;1.17 charcoal**	Emergy Exchange Ratio
ESI=EYR/ELR	**7.46**	Emergy Sustainability Index

Table 5 summarizes the transformity values for fast pyrolysis products and presents a comparison of those values to the corresponding diesel and charcoal values.

Table 5. Fast Pyrolysis Products Transformity

	Bio-oil	Diesel	Charcoal Fines	Charcoal
Transformity Sej/J	69,700	66,000	837,000	107,000

The transformity value obtained for bio-oil was 6.97E+04 sej/J and 8.37E+05 sej/J for charcoal. The transformity value for bio-oil and diesel were similar. This means that the bio-oil production system is significantly efficient. The transformity value for charcoal fines obtained in the fast pyrolysis process in a fluidized bed was eight times greater than the transformity value for the charcoal obtained from wood, an unavoidable sub-product in the production process, meaning that the process was not efficient.

The emergy yield ratio (EYR) was 3.36. The Middle East oil EYR is 13,1 while Alaska oil EYR is 11, and the EYR for USA oil in 1991 was 6 [5]. Generally, depending of its concentration rate and prices, fossil fuels present an EYR varying from 3 to 15 [8]. In fact, the greater the EYR for a product the greater its emergy ratio and its recommendation as a primary source of energy. A value lower than 6 indicates that from the emergy point of view, the bio-oil is not an ideal source of primary energy in comparison to fossil fuels. On the other hand, no fuel or any energy carrier obtained from biomass through chemical conversion or thermo-chemical process can reach the yield levels of a product created by nature during millions of years. In spite of this ratio in the bio-oil production indicates that the best application for the bio-oil is as a substitute for oil by-products in the chemical and petrochemical industries.

The emergy investment ratio (EIR) is 0.45 and it indicates that the bio-oil production process requires a relatively low economy inputs considering that the industrial production processes usually present an average value of 0.7. This indicates that the process is feasible and competitive as the possibility of development and market competition is high.

The high renewability (%R) of 68 % together with the emergy sustainability index (ESI) of 7.46 indicates that the process is sustainable. These are very good values for an industrial process.

The environmental loading ratio (ELR) of 0.45 indicates that the system produces low and pressure on the environment.

The emergy exchange ratio (EER) calculated for bio-oil production was 1.08 and for charcoal was 1.17, indicating that the system delivers almost the same emergy to buyers of its products than the value received by sales. The system is operating in a fair trade.

4. CONCLUSIONS

1. The non-condensed gases recirculation in the bio-oil production process through fast pyrolysis in a fluidized bed together with the charcoal fines utilization are important elements which turn the process more sustainable and avoid the production of great quantities of waste which in this case are the biomass ashes.
2. The bio-oil production energy rate was acceptable if considering that the bio-oil lower heat rate per volume is approximately 55% of the diesel heat rate.
3. From the emergy point of view, the bio-oil production process is sustainable and its application as a substitute for oil byproducts is a very promising choice.

Acknowledgement

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Foot Notes

1. -Biomass energy calculation

$$408 \cdot \frac{\text{tonne}}{\text{yr}} \cdot 3772 \cdot \frac{\text{kcal}}{\text{kg}} \cdot 4186 \cdot \frac{\text{J}}{\text{kcal}} = 6.442 \cdot 10^{12} \circ \frac{\text{J}}{\text{yr}}$$

2. - Water energy calculation

The system recycles 360 liters of water per hour or 0.36 m^3 /h. Considering a yearly recirculation time of 8640 hours, 3110 m^3 of water are recycled in a year and a corresponding loss of 2% per meter of recycled water which must be replaced, the loss is equivalent to 62 m^3 of water. The total water used in the plant in a year equals to 3172 m^3

3172 m^3 x the water density x Gibbs energy (4.94J/gm)

$$3172 \cdot m^3 x 997.1 \tfrac{kg}{m^3} x 4.94 \tfrac{J}{gm} = 1.562 \cdot 10^{10} J$$

3. - Preheating charcoal energy calculation

Monthly charcoal consumption 45 kg

Yearly consumption 540 kg

Lower charcoal heat value 7600 kcal/kg

$$540 \cdot \tfrac{kg}{y} \cdot 7600 \cdot \tfrac{kcal}{kg} \cdot 4186 \cdot \tfrac{J}{kcal} = 1.718 \cdot 10^{10}$$

4. -Energy calculation for the inert bed sand. The consumption of siliceous sand is 45 kg /month and 540 kg /year.

$$540 \cdot kg \cdot 611 \cdot \tfrac{J}{gm} = 3.299 \cdot 10^8$$

Chemical energy of sand 611 J/gm[5].

5. -Refractory materials energy calculation.

The reactor volume of refractory ceramics is 0.23 m^3. The refractory ceramics are formed by a mix of aluminum silicates. The density of a typical asbestos-cement is 1.4 kg/liter. Assuming a Gibbs energy value 65J/g for the alloys [5].

Then:

$$0.23 \cdot \tfrac{m^3}{yr} x 1.4 \tfrac{kg}{lier} = 1.02E - 6 \cdot kg / yr$$

6. - Energy calculation for steel equipment and parts.

The reactor was build of carbon- steel weighted 1.9 tons. The carbon-steel transformity is 18 E11 sej/kg

Carbon- steel quenching system weighted 250 kg ,

Carbon- steel pipeline system weighted 325 kg,

$$(1900 + 250 + 325) \cdot kg = 2475 \cdot kg$$

7. - Electricity power installed 13.1 kw. Yearly work time is 24hours x 360 days 8640 hours; Yearly energy is 113184 kwh/year.1 kwh=3600000J

$$113184 \cdot \tfrac{kwh}{y} \div 3600000 \cdot \tfrac{J}{kwh} = 4.07 \cdot 10^{11} \cdot \tfrac{J}{y}$$

Hydro electricity energy transformity in Brazil is 165000 [5].

8. - Chemicals. ISOPAR oil sub-product for the bio-oil separation.

500 liters/year. The ISOPAR is basically a compound of oil paraffin. The paraffin density is 0.89 gm/cm^3, and the ISOPAR mass is calculated.

$$500 \cdot liters \cdot 0.89 \frac{gm}{cm^3} = 445 \cdot kg$$

9. - Work calculation

There are three work shifts in the plant. Each shift is staffed by:
1 a technician
1 a mechanic
1 an assistant

The plant employs a total of 9 workers being three technicians, three mechanics and three assistants. This means three professionals for each category. Assuming a consumption of 3200 kcal for the assistants and a consumption of 2500 kcal respectively for the technicians and the mechanics, we have:

$$\frac{3\,pers}{360\,dias}\, x \frac{8\,hrs}{pers}\, x \frac{360\,días}{y}\, x3200 \frac{kcal}{día}\, x4186 \frac{J}{kcal} = 3.2E+8$$

for the assistants

$$\frac{3\,pers}{360\,dias}\, x \frac{8\,hrs}{pers}\, x \frac{360\,días}{y}\, x2500 \frac{kcal}{día}\, x4186 \frac{J}{kcal} = 2.5E+8$$

respectively for the technicians and the mechanics.