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Computer-Aided Design of a Local Biorefinery Scheme from Water lily (*Eichhornia Crassipes*) to Produce Power and Bioproducts

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ABSTRACT

Water lily (*Eichhornia crassipes*) has been identified as an invasive exotic plant with high proliferation in Mexico, affecting aquatic bodies, such as lakes. After extraction, the water hyacinth biomass can be used as raw material for the production of bioproducts and bioenergy, however, the majority of them not covered the region's needs, and their economic profitability decreases significantly. Also, few reports present its use as raw material inside a biorefinery scheme. In this work, we propose a local biorefinery scheme to produce power and bioproducts from water lilies, using Aspen Plus V.10.0, per the needs of the Patzcuaro Lake community in Michoacán, Mexico. The scheme has been designed to process the harvested and sun-dried water lily from 197.6 kg/h of total wet harvested biomass, according to the extraction region schedule. The biomass is separated: root (RT) and stems-leaves (SL). The processing scheme involves the RT combustion to produce electric power, and two processes to SL; the first one, anaerobic digestion to produce fertilizer and biogas, while, pyrolysis and gasification as second one. The biogas is converted to electricity, while, the pyrolysis products are separated in bio-oil and biochar; the last one is inserted to gasification reactor to produce syngas, and then, electric power. According with results, this scheme produces 35.6 % of fertilizer, 1 % of bio-oil, and 3.5 kWh of electric power. The scheme requires energy efficiency tools to improve its energetic performance, however, is a potential solution for the use of water lily in the region.

Keywords: Water hyacinth, local-biorefinery scheme, modelling and simulation, Aspen Plus.

INTRODUCTION

The conservation of aquatic bodies is a priority issue worldwide, due their ecosystems provide essential services such as, biodiversity maintenance, nutritious soils, climatic regulation, carbon sequestration and recreational activities. However, some have been affected by high resource exploitation, changing climatic patterns, or alien plant invasions (API), which contribute to deteriorating their ecological functions and causing the loss of native species. In accordance with [1], in Mexico have been identified 665 invasive exotic plants, among them the Water lily (*Eichhornia crassipes*) stands out due to its rapid proliferation, which enables it to cover several aquatic bodies, mainly lakes, across the country. The invasive plant impacts local ecosystems and human communities, making its management a pressing environmental and economic concern. In this sense, various strategies have been proposed to control and utilize *E. crassipes*, aiming to mitigate its negative effects while exploring its potential applications [2]. After extraction, the water hyacinth biomass has been used as raw material for the production of some bioproducts and bioenergy in the form of individual processes [3-6]; nevertheless, most of these products have not covered the region´s needs or have not been produced into an integral use framework, such as a biorefinery scheme, thus, in the most of cases their technical performance and economic profitability have not been reached. Few works have reported the use of water hyacinth into a biorefinery scheme [7-10]. In this work, we propose the modelling and simulation of a local biorefinery scheme to produce electric power and bioproducts from water lilies, using Aspen Plus V.10.0, per the needs of the Patzcuaro Lake community in Michoacan, Mexico.

METHODOLOGY

The methodology followed for carrying out this work is presented next. As first step, the conceptual design of biorefinery scheme was proposed from physical and chemical composition of water lily, and taking account the energetic needs of Patzcuaro community. Then, the proposed biorefinery was modelled from literature information to describe the reactive systems and obtain operational conditions for each processing zone; next, the simulation was carried out using Aspen Plus V.10.0. Finally, in order to analyze the proposed scheme, two performance indicators were constructed and applied.

Conceptual Design

Patzcuaro, small municipality of Michoacan, Mexico is a fertile region, which include a famous lake called Patzcuaro´s lake. The economy of this region includes agriculture, fishing, crafts and tourism activities around the lake. However, the water lily invasion on the lake has been a recurrent issue since long time ago. In accordance with [11], the lake posses a defined extraction schedule and the appropriate machinery to do it. According with the extraction program an average of 197.6 kg/h of water lily are extracted every year. This biomass is composed by two main compounds: root (RT, 47 wt % of total plant) and steams-leaves (SL, 53 wt % of total plant) with high moisture content, 93 % and 91.8 %, respectively. Usually the wet biomass is sun dried and its final disposal is not regulated. For this reason, in this work is proposed a biorefinery scheme from the extracted and sun-dried water lily, assuming 1 % of water content for both biomass components; its block diagram is presented in Figure 1. The processing scheme starts with RT conversion by a combustion device to obtain electric power. Then, the SL are separated in two streams with 50 wt % each one; the first one enters to an anerobic digestion process, while the second one is inserted to a pyrolysis and gasification zone. Biogas and fertilizer are obtained from anaerobic digestion, then, the biogas is used to produce power; on the other hand, pyrolysis bio-oil and biochar are obtained from pyrolysis, next, the biochar is processed by gasification to obtain syngas, which is converted to electricity.

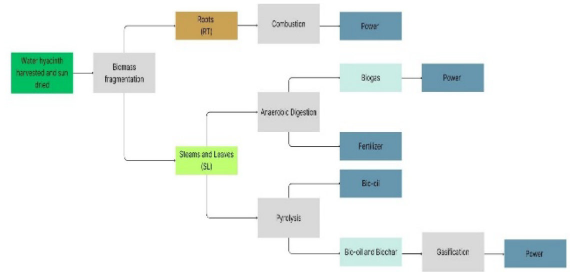

Figure 1. Block diagram for conceptual design of biorefinery scheme from water lily.

Modelling and Simulation

The RT composition involves 24.53 wt % fiber, 12.31 wt % protein, 36.94 wt % carbohydrates, 5.65 wt % lipids and 20.57 wt % ash; while the SL composition is 21.44 wt % fiber, 18.90 wt % protein, 34.69 wt % carbohydrates, 8.16 wt % lipids and 16.9 wt % ash [12-13]. To model the biomass, the majority compounds (3 or 4) of each fraction for RT and SL were selected and normalized to be inserted into the simulation sheet. The flow diagram for the biorefinery scheme from Aspen Plus is presented in Figure 2. The ROOTS stream enters to mixer (MIX-1) along with 30 % excess air to carry out the combustion. The mixed stream is inserted to combustion reactor (R-COMBUS) modelled with R-Stoic module; the operational conditions were 550 °C, 1 bar and a fractional conversion for set combustion reactions of 85 %, in accordance with experimental information provided by [14]. Then, the out-stream from combustion enters to CYCLONE module to separate the solid fraction, next, the condensable compounds traces into the gas fraction (GAS-COMB) were separated by SEP module (SEP-1); the cleaned gas fraction is converted to electric power by a turbine using the COMPRESSOR module (TURB-COM). This process was modelled using the Peng-Robinson model [15].

Regarding to SL, the STE+LEAV with SL composition enters to SPLIT module (SPLIT-1) to get two streams: 50 wt % for anaerobic digestion process (SL-AD) and the other one for pyrolysis and gasification train (SL-PY-G). The SL-AD stream enters to anaerobic digestion reactor (R-AD) modelled by R-STOIC module at 38 °C and 1 bar, adding water as digestion medium (1:10, biomass to water, mass ratio) [16-17]. The out-stream from R-AD is inserted to simple separator (SEP-2, SEP module) to obtain BIOGAS and FERTILIZER. Then, the BIOGAS stream is converted to electricity by a turbine (TURBI-AD, COMPRESSOR module). In accordance with [15], the thermodynamic models used for this process were NRTL and Peng-Robinson. On the other hand, SL-PY-G stream enters to pyrolysis reactor, modelled by R-BATCH module (R-PIRO) at 329.7 °C and 1 bar, using a first order kinetic model provided by [18], specifying as stop criteria 5 h of operation. The out-stream from R-PIRO (PIRO-OUT) is

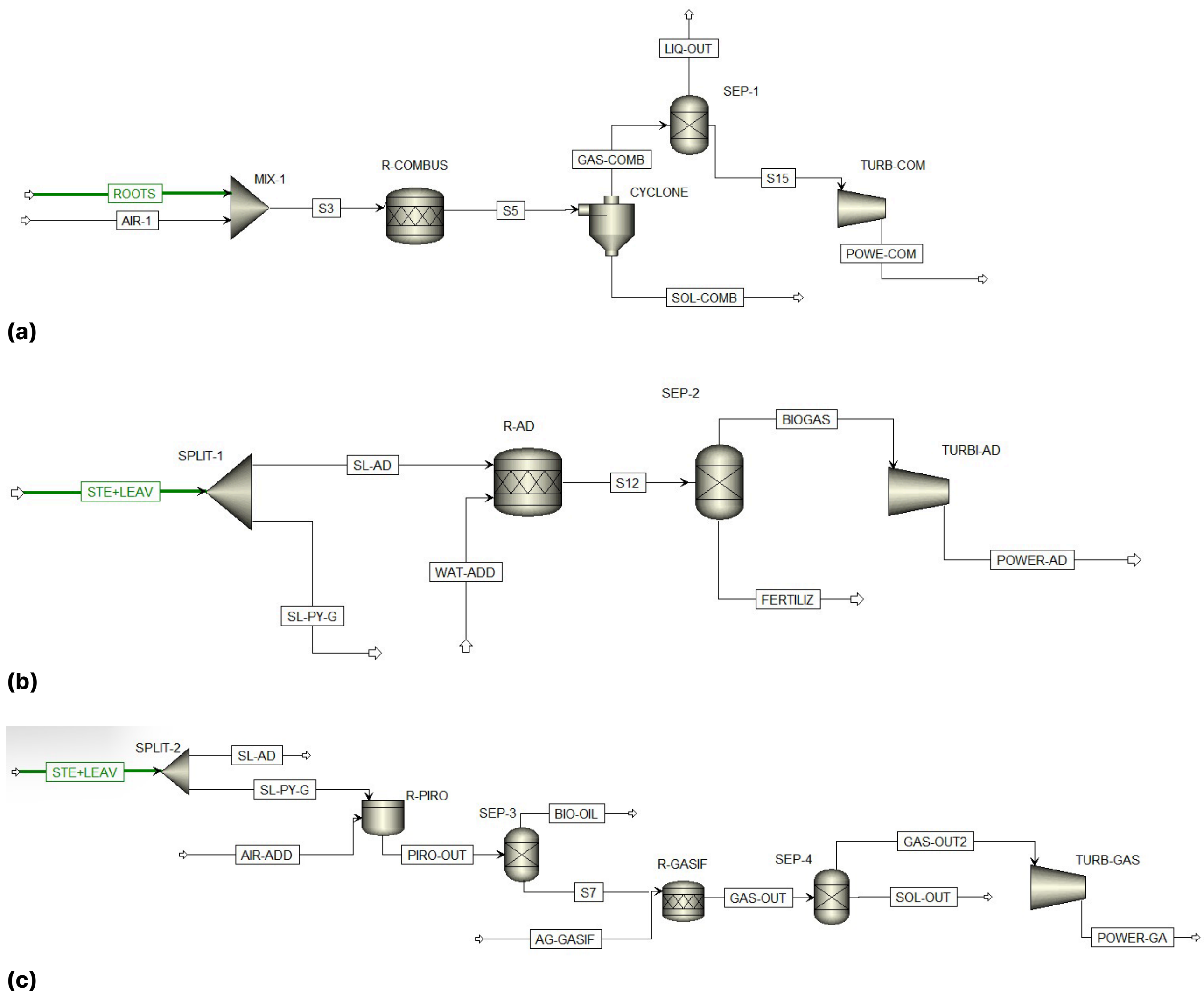

Figure 2. Aspen Plus flow diagram of biorefinery scheme from water lily: a) RT processing, b) SL for anaerobic digestion processing, and c) SL for pyrolysis and gasification train.

separated to remove the condensable products (BIO-OIL) using a SEP module (SEP-3); the remaining non-condensable gases and biochar were inserted to gasification reactor, modelled by R-STOIC module (R-GASIF). The operational parameters for R-GASIF were 700 °C and 1 bar, adding steam at 200 °C as gasifying agent (10 wt %, regarding the S7 stream mass) [19]. The out-stream from R-GASIF (GAS-OUT) was inserted to SEP module (SEP-4) to clean the syngas. Then, the syngas stream (GAS-OUT2) is converted to power by a turbine (TURB-GAS) using the COMPRESSOR module. The reactions set for each processing zone is provided at supplementary information section.

Performance Indicators

To analyze the technical performance of the biorefinery scheme, two indicators are proposed next.

1.- EI-EP defined as the relation between the invested energy for the processing (reactor heating and electrical needs), regarding to the energy provided by the products.

For this case, the products considered by this indicator include the electric power provided by turbines, and pyrolysis bio-oil.

2.- PM-EM defined as the relation between total product mass generated by the scheme, including combustion gases, biogas, fertilizer, pyrolysis bio-oil and syngas, regarding to the water lily mass (RT and SL).

It is worth mentioning that according to the definition of these indicators, both are dimensionless.

RESULTS

In this section are presented the results and their analysis from water lily biorefinery scheme. In Table 1, 2 and 3 is presented the product distribution for out-streams after R-COMBUS, R-AD and R-PIRO+R-GASIF, respectively. As it can be observed, the proposed processes have low conversion efficiency, thus the amount of non-converted biomass is high.

Table 1: Mass flow at the exit of the combustion process.

Component	Description	Mass Flow (kg/hr)
Unreacted biomass[a]	Non-converted biomass in the combustion process	1.6753
Combustion gases	O2	2.8022
	N2	13.5634
	CO2	1.6454
	CO	0.3901
	CH4	0.2224
	NH3	0.0007
	NO2	0.0018

[a] Crude fiber, proteins, carbohydrates, lipids and ashes contents in the biomass that doesn't react during the process.

Table 2: Mass flow at the exit of the anaerobic digestion

Component	Description	Mass Flow (kg/hr)
Unreacted biomass[b]	Non-converted biomass in the combustion process	0.059
Biogas	CO2	0.6047
	CH4	0.2695
	NH3	0.0012

[b] Crude fiber, proteins, carbohydrates, lipids and ashes contents in the biomass that doesn't react during the process.

Table 3: Mass flow at the exit of pyrolysis process and gasification.

Component	Description	Mass Flow (kg/hr)
Unreacted biomass[c]	Non-converted biomass in the combustion process	0.7010
Bio-oil	C7H8	0.0909
	C6H6O	0.1128
	C10H14O	0.1483
Biochar	C6H5O2	0.1077
Gases	CO	0.0148
	CO2	0.0280
	N2	13.0114
	O2	4.0261
Syngas	H2	0.01394
	CO	0.07537

[c] Crude fiber, proteins, carbohydrates, lipids and ashes contents in the biomass that doesn't react during the process.

Then, in Table 4 are presented the mass flows of each product derived from scheme. It is worth to mention that, the combustion gases, biogas and syngas were cleaned before the turbines, in order to avoid operational troubles and get electric power. In Table 5 are presented the power data derived from scheme. As it can be observed, the combustion process and pyrolysis-gasification train produce the majority of electricity. It is due to conversion aim for both processes are gaseous products with high energetic content. Also, it is noticeable that the combustion gases and fertilizer represent roughly 90 % of total obtained products.

Table 4. Mass flow total of products.

Process	Product	Mass Flow (kg/hr)
Combustion	Combustion gases	18.6261
Anaerobic	Biogas	0.8755
Digestion	Fertilizer	11.059
Pyrolysis	Bio-oil	0.3520
and Gasification	Syngas	0.0893

Table 5. Power produced by processing scheme.

Process	Equipment	Power (KW)
Combustion	TURB-COM,	1.5194
Anaerobic Digestion	TURB-Dal	0.035
Pyrolysis and Gasification	TURB-GA	1.944

Finally, in Table 6 are presented the results derived from EI-EP and PM-EM indicators. According with these results, the energy invested to processing is extensively high in comparison with the energy delivered by the products, which means that this scheme must be improved to enhance its energy efficiency. Energy efficiency tools, such as mass and energy integration or process intensification must be implemented. It is worth to mention that the EP was calculated from enthalpy values provided by simulation. On the other hand, regarding to second indicator, the products obtained from the scheme are almost 4-times less than the total mass available for processing; which means low conversion efficiency. This value must be improved by analyzing the operational conditions and using specific kinetic models to represent each processing unit.

Table 6. Evaluation Indicators

Indicator	Factor	Value
EI - EP	EI (kW) = 2.6783E+16 EP (kW) = 5.6979	4.7006E+15
PM – EM	PM (kg/h) = 51.0423 EM (kg/h) = 196.5502	0.2597

CONCLUSIONS

In this work, a biorefinery scheme from water lily has been proposed, modelled and simulated using Aspen Plus V.10.0. This proposal attends to specific needs of Patzcuaro´s lake community located in Michoacan, Mexico, wherein the water lily infestation is a huge problem, affecting the natural ecosystem and local human society. The biorefinery scheme was designed to process the harvested and sun-dried biomass, in accordance with the local extraction program; also, the integrated processes into the scheme were included to generate mainly power, current demand in the region. According with results, this scheme produces 35.6 % of fertilizer, 1 % of bio-oil, and 3.5 kWh of electric power. It is important to mention that, the bio-oil can be integrated as biofuel in the combustion process to get more energy. On the other hand, regarding the indicators results, EI-EP demonstrates the need of implementing energy efficiency tools on the scheme to improve its energetic performance, while the PM-EM is almost 4-times less than the total mass available for processing, which means low conversion efficiency, thus kinetic values for each processing unit must be added to get better performance of the scheme. This proposal represents a first and integrated option to produce local bioenergy at the study region; also, in accordance with the opportunity areas detected from scheme, technical improvements could be implemented, representing a potential solution for the sustainable use of water lily in the region.

DIGITAL SUPPLEMENTARY MATERIAL

The supplementary material for this contribution can be founded in in the next link https://acortar.link/vY7NFV.

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