Applied Thermal Engineering 62 (2014) 90–104

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

An oil palm-based biorefinery concept for cellulosic ethanol and phytochemicals production: Sustainability evaluation using exergetic life cycle assessment

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HIGHLIGHTS

- Thermo-environmental sustainability of palm-based biorefinery was assessed.
- OPFs' exergy content was degraded when converted into bioethanol and phytochemicals.
- Exergy efficiency (59.05%) and TSI (2.44) were recorded for the biorefinery
- Global warming potential of 2265.6 kg CO_2 eq. was recorded for the whole biorefinery.

ARTICLE INFO

Article history:
Received 28 June 2013
Accepted 12 September 2013
Available online 25 September 2013

Keywords:
Exergetic life cycle analysis
Bioethanol
Oil palm fronds
Biorefinery
Sustainability
Aspen plus

ABSTRACT

In this study, thermo-environmental sustainability of an oil palm-based biorefinery concept for the co-production of cellulosic ethanol and phytochemicals from oil palm fronds (OPFs) was evaluated based on exergetic life cycle assessment (ExLCA). For the production of 1 tonne bioethanol, the exergy content of oil palm seeds was upgraded from 236 MJ to 77,999 MJ during the farming process for OPFs production. Again, the high exergy content of the OPFs was degraded by about 62.02% and 98.36% when they were converted into cellulosic ethanol and phenolic compounds respectively. With a total exergy destruction of about 958,606 MJ (internal) and 120,491 MJ (external or exergy of wastes), the biorefinery recorded an overall exergy efficiency and thermodynamic sustainability index (TSI) of about 59.05% and 2.44 per tonne of OPFs' bioethanol respectively. Due to the use of fossil fuels, pesticides, fertilizers and other toxic chemicals during the production, the global warming potential (GWP $=$ 2265.69 kg CO_2 eq.), acidification potential (AP $=$ 355.34 kg SO_2 eq.) and human toxicity potential (HTP $=$ 142.79 kg DCB eq.) were the most significant environmental impact categories for a tonne of bioethanol produced in the biorefinery. The simultaneous saccharification and fermentation (SSF) unit emerged as the most exergetically efficient (89.66%), thermodynamically sustainable (TSI $=$ 9.67) and environmentally friendly (6.59% of total GWP) production system.

1. Introduction

Every year, the oil palm industry generates large amounts of liquid and solid residues of which only a small portion is utilized commercially for value-added bio-products like biofuels and phytochemicals. The utilization of oil palm wastes (OPWs) for diverse marketable bio-products would help manage uncontrollable wastes generation and add economic value to the oil palm industry [1]. In an oil palm-based biorefinery, palm biofuels, biochemicals etc. could be co-produced from OPWs and this strategy would help improve the sustainability of the biorefinery. Cherubini et al. [2] have listed a number of pilot and commercial plants that are effectively running as biorefineries for the production of fuels and biochemicals in most parts of the world. For instance in Malaysia,

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Abbreviations: AETP, aquatic ecotoxicity potential; AP, acidification potential; EIP, exergy improvement potential; EP, eutrophication potential; ExLCA, exergetic life cycle assessment; FFBs, oil palm fresh fruit bunches; GHG, greenhouse gas; GWP, global warming potential; HTP, human toxicity potential; LCA, life cycle assessment; LCI, life cycle inventory; LCIA, life cycle impact assessment; NRTL, Non-Random Two Liquid; ODP, ozone depletion potential; OPFs, oil palm fronds; OPLs, oil palm leaves; OPWs, oil palm wastes; POCP, photochemical oxidant potential; RKS-EOS, Redlich–Kwong–Soave Equation of State; SHF, Separate hydrolysis and fermentation; SSF, simultaneous saccharification and fermentation; TETP, terrestrial ecotoxicity potential; TSI, thermodynamic sustainability index.

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http://dx.doi.org/10.1016/j.applthermaleng.2013.09.022

Nomenclature

Ex_{total}	total exergy (MJ)
$Ex^{0}_{ch,k}$	standard chemical exergy of *k*th component (MJ/kg)
$Ex_{ch,k}$	chemical exergy of *k*th component (MJ)
$Ex_{ph,k}$	physical exergy of *k*th component (MJ)
ΔG_{fo}	standard Gibbs free energy of formation (kJ/mol), (kJ/kg)
$Ex_{destruction}$	total exergy destroyed (MJ)
Ex_{out}	total exergy output (MJ)
Ex_{in}	total exergy input (MJ)
Ex_i	exergy of *i*th component (MJ)
m_i	mass of *i*th component (kg)
$Ex_{mass,in}$	exergy of entering material resource (MJ)
$Ex_{mass,out}$	exergy of exiting material resource (MJ)
Ex_{heat}	exergy due to heat interactions (MJ)
Ex_{work}	exergy due to work interactions (MJ)
Q	amount of heat produced (MJ)
$S_{generation}$	entropy generation (MJ/K)
I	irreversibility (MJ)
T	temperature (K)
T_0	reference temperature = 273.15 K
p_0	reference pressure = 1 atm = 101.3 kPa
N_k	number of moles of component *k*
H	specific enthalpy (kJ/kg)
H_0	specific enthalpy at T_0, p_0 (kJ/kg)
S	specific entropy (kJ/kg K)
S_0	specific entropy at T_0, p_0 (kJ/kg K)
η	exergetic efficiency (%)
c_i	concentration of *i*th organism (g/l)
β	weighting factor

biodiesel and phytochemicals are co-produced on pilot scale whereby about 2.41 kg of phytochemicals are recovered from every tonne of palm oil biodiesel produced, and this plant is able to generate about US$ 970 as profit [3]. This study assesses the sustainability of an oil palm-based biorefinery concept in which cellulosic ethanol and phenolic compounds are recovered simultaneously from oil palm fronds (OPFs).

OPFs form the largest group of OPWs whose global total generation capacity amounts to nearly 92.4 million tonnes (by dry weight) annually [4]. However, currently, OPFs are not been utilized commercially for value-added bio-products like bioethanol and phenolic compounds in a biorefinery though they have good chemical characteristics for such purposes. Nonetheless, there are few reports on the utilization of OPFs for animal feed, biofertilizers, pulp and paper, activated carbon, concrete materials, to mention but a few. Lee and Ofori-Boateng [5] have detailed numerous potential bio-products that could be obtained during the sustainable transformation of OPFs into ‘wealth’.

Bioethanol has been used extensively as gasoline substitute in most parts of the world. From 2002 to 2007, the costs of grains in the USA attained about 30% increment due to the production of corn and wheat-based bioethanol [6]. Second-generation feedstocks such as OPFs are better alternatives to the first-generation feedstocks (e.g. corn) that are used for bioethanol production because they help reduce the competition of food for fuel in the world.

The sustainability of biofuels has become paramount in designing energy conversion processes, because most of the production stages involve the heavy use of fossil fuels and other toxic chemicals, which are detrimental to the environment. In as much as great emphasis must be placed on socio-political sustainability of biorefineries for equitable, diverse, democratic and provision of good quality of life for all [7], their thermo-environmental sustainability dimension must also be critically evaluated as their consequences could be a long-term damage to the environment.

Exergy is a measure of energy quality or useful energy of a resource available to perform work [8,9]. Uihlein and Schebek [10] have assessed the sustainability of biorefineries based on exergy analysis and life cycle assessment (LCA). However, the limitations from most of these studies involve the exclusion of the feedstock production units in the system boundary. This study combines exergy analysis with LCA to evaluate the thermo-environmental sustainability of an oil palm-based biorefinery for cellulosic ethanol and phenolic compounds production with the inclusion of the OPFs' cultivation unit in the system boundary. Though LCA and exergy analysis have similar methodology, LCA measures the environmental performances of energy systems based on the heating values of the input and output resources (using the first law of thermodynamics) whilst exergy analysis considers the quality of energy of the resources based on both the first and second law of thermodynamics. Because LCA is unable to characterize the quality of energy in a resource, the combination of exergy analysis with LCA would bring out a better view of the degradation of the quality of energy (called exergy) simultaneously with the emissions associated with the system under consideration. Exergetic life cycle analysis (ExLCA) is able to evaluate the exergy destruction, exergy efficiency and environmental impacts associated with a product over its life cycle [11]. However, Meyer et al. [12] have proposed another tool called exergoenvironmental analysis, which is tantamount to ExLCA except that the exergoenvironmental analysis tool assigns each exergetic stream with an environmental impact. Exergy destruction in a process is directly related to greenhouse gas (GHG) emissions (part of global warming potential in this study) and thermodynamic sustainability index (TSI) which largely depends on the type of input resources to the system [13]. Thus, a better idea of how detrimental a system may be in terms of environmental and thermodynamic performances can be obtained using ExLCA.

2. Methodology

2.1. Process description and system boundary

Fig. 1 summarizes the configuration for the ExLCA of the oil palm-based biorefinery concept under consideration in this study. The process description for each subsystem is given in the subsequent sections. The production processes of utilities like electricity, water, steam etc. were not considered as part of the system boundary. A functional unit of 1 tonne anhydrous cellulosic ethanol was considered in this study.

2.1.1. Cultivation of oil palm fronds (Sys 1)

Almost all the current researches on exergy analyses of biorefineries for the production of biofuels and biochemicals have centered on only the units that convert the feedstocks into the bio-products. However, this article performs a full ExLCA of palm bioethanol and phytochemicals production beginning from the feedstock extraction stage to the bio-products purification stages with the aim to evaluate the systems' thermo-environmental sustainability.

From normalized data from published researches [14–16] on oil palm nursery and plantation based on Malaysia's conditions, this