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Hierarchical economic potential approach for techno-economic evaluation of bioethanol production from palm empty fruit bunches

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HIGHLIGHTS

- 4-Level economic potential (EP) for the evaluation of techno-economic feasibility.
- Case studies on bioethanol production from EFB with and without jet fuel.
- Bioethanol production with jet fuel shows higher economic viability.
- 4-Level EP can be a systematic approach for techno-economic analysis.

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ABSTRACT

A hierarchical four-level approach to determine economic potential (4-level EP) is proposed for preliminary techno-economic analysis of new processes. The 4-level EP includes input/output structure, process flow structure, heat integration (HI), and economic feasibility. Two case studies on a 30.2 t/d (or 12.7 million l/yr) bioethanol plant with and without jet fuel production from palm empty fruit bunches (EFB) were investigated by applying the 4-level EP. The plant flowsheet was established based on experiments in a 0.1 t/d pilot plant, including sequential dilute acid and alkali pretreatment, and separate hydrolysis and fermentation (SHF). EP approached a more reliable value through the hierarchical 4-level EP. The heating energy was reduced considerably by HI. The product value was estimated at \$0.8–\$1.3/kg of equivalent bioethanol. It was suggested through sensitivity analysis that a large plant size, enhanced production yields, and capital cost reduction were necessary for the lignocellulosic bioethanol production to be profitable.

1. Introduction

The depletion of fossil fuels along with environmental concerns has necessitated our society to search for renewable and sustainable energy sources. The fundamental challenges with renewable energy are viable technology and economics. Breakthroughs in the fields of chemistry, biology, and engineering have been reported, showing great potential toward providing energy alternatives (Upadhye et al., 2011). The abundance and relatively low cost of lignocellulosic materials make them attractive as renewable feedstocks for bioethanol production (Sassner et al., 2008).

Lignocellulosic materials may be divided into six groups: crop residues, hardwood, softwood, cellulose wastes, herbaceous biomass, and organic solid wastes (Quintero et al., 2013). Empty fruit bunches (EFB), a main residue of the palm oil industry, are one of the most recent renewable energy resources (Cheng et al., 2014; Chiesa and Gnansounou, 2014; Do et al., 2014a; Kim and Kim, 2013; Piarpuzán et al., 2011). Many experimental studies have addressed bioethanol production from EFB using different pretreatment and fermentation methods (Cheng et al., 2014; Chiesa and Gnansounou, 2014; Jeon et al., 2014; Kim and Kim, 2013; Kim et al., 2012; Piarpuzán et al., 2011; Tan et al., 2013; Zhang et al., 2012). Pretreatment with dilute acid or alkali has led to wide variations in the ethanol yield from 5.3 to 19.2 wt% of dry EFB (Cheng et al., 2014). However, the dilute alkali pretreatment showed limited performance in bioethanol production from EFB because of its relatively high lignin content (Chiesa and

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Nomenclature

Abbreviations

4-level EP	four-level hierarchical economic potential
ASR	annual sales revenue, \$/yr
ATC	annualized total cost, \$/yr
CEPCI	chemical engineering plant cost index
CF	cash flow, \$/yr
EFB	empty fruit bunches
EP	economic potential, \$/yr
ERW	electrolyzed-reduced water
FCI	fixed capital investment, \$
GP	gross profit, \$/yr
HI	heat integration
IC	indirect cost, \$
IRR	internal rate of return, %
L_p	plant life, yr
NP	net profit, \$/yr
NPV	net present value, \$
NRTL	non-random two-liquid
PBP	payback period, yr
PC	project contingency, \$
PEC	purchased equipment cost, \$
PFD	process flow diagram
PV	product value, \$/kg
REC	renewable energy certificate
ROI	return on investment, %
SHF	separate hydrolysis and fermentation
SSF	simultaneous saccharification and fermentation
TCI	total capital investment, \$
TDIC	total direct and indirect cost, \$
TEA	techno-economic analysis
TIC	total installed cost, \$
TPC	total production cost, \$/yr
TUC	total utility cost, \$/yr
WC	working capital, \$

Symbols

a_j	installation cost factor for equipment j
b	indirect cost factor
c	project contingency factor
d	working capital factor
F_k	mass flow rate of product k, t/yr
p_k	market price of product k, \$/t
α	rate of return on investment
β	rate of corporation income tax
γ	ratio of renewable energy certificate price to product price

Gnansounou, 2014). A high ethanol yield was obtained by sequential acid/alkali-pretreatments followed by simultaneous saccharification and fermentation (SSF) (Kim and Kim, 2013).

The ethanol yield is reduced by the inefficient utilization of xylose (Cheng et al., 2014). Xylose, being a major component of hemicellulose in EFB, was separated during the dilute acid pretreatment step (Zhang et al., 2012). Xylose can be used as a raw material for production of high value products such as xylitol, furfural, hydrogen, ethanol, and jet fuel (Xing et al., 2010). A four-step process including acid hydrolysis and xylose dehydration, aldol condensation, low-temperature hydrogenation, and high-temperature hydrodeoxygenation was proposed to produce jet fuel-range alkanes (C_8–C_{13}) from xylose. In a preliminary techno-economic analysis (TEA), it was reported that jet fuel can be produced from xylose at \$0.68–\$1.47/kg (Xing et al., 2010). Nevertheless, there remains a need for a complete TEA of bioethanol production with jet fuel starting from a raw feedstock such as EFB.

TEA is a type of value engineering that includes process design, modeling and cost analyses for innovative product design, and competitive production (Gnansounou and Dauriat, 2010). TEA is often performed using the following procedures: process design and modeling on the technological side, total capital investment (*TCI*) and total production cost (*TPC*) evaluation on the economical side, and sensitivity analysis for uncertainty and viability (Do et al., 2014a,b; Gnansounou and Dauriat, 2010; Humbird et al., 2011; Piccolo and Bezzo, 2009; Sassner et al., 2008). The *TCI* was estimated from the sum of the purchased equipment cost (PEC) multiplied by appropriate factors, which is known as the factorial method (Do et al., 2014a,b; Peters et al., 2003).

In lignocellulosic bioethanol production, the key factors that affect the techno-economic feasibility are the plant capacity, feedstock cost, product yield, and process configuration (Gnansounou and Dauriat, 2010; Sassner et al., 2008). The production cost was estimated for 200 million l/yr of bioethanol from \$0.71 to \$0.98/kg depending on the feedstock (Gnansounou and Dauriat, 2010). The production cost as the minimum selling price was \$0.72/kg in 2011 for 230 million l/yr of bioethanol produced from corn stover (Humbird et al., 2011). The bioethanol production cost from EFB was reported in the range of \$0.62 to \$0.73/kg for 33 million l/yr (Quintero et al., 2013). The feedstock price was one of the biggest costs, accounting for 37–56% of the total bioethanol production cost in 2010 (Littlewood et al., 2013). Unfortunately, these TEAs neglected heat integration (HI) that is required for a cost efficient process in biofuel projects. Furthermore, few researchers have addressed the effect of the ethanol price in the TEA. Since the oil price has sharply declined recently, the sensitivity analysis of the ethanol price on the economic viability is necessary.

Diverse assumptions and approaches make it intractable to compare techno-economic evaluations (Gnansounou and Dauriat, 2010). A systematic approach to TEA that can be used as a standard strategy would be helpful in the analysis of bioethanol processes. A systematic method was presented to evaluate and develop renewable energy technologies (Upadhye et al., 2011). The method breaks down the conceptual process design (CPD) into six hierarchical levels (Douglas, 1988) in which economic potential (EP) is evaluated as an engineering decision indicator. HI is involved in the 6-level hierarchical approach. The CPD identifies the steps within a process that are the most expensive, providing insight into how costs can be reduced, and guiding where future research efforts should be directed (Upadhye et al., 2011). However, the 6-level approach focuses on the development of process flowsheets in the preliminary process design stage, and does not include detailed economic analyses such as *TCI* and *TPC*.

This study presents a four-level hierarchical approach to determine economic potential (4-level EP) for techno-economic evaluations in a systematic way. The 4-level EP is applied to a 30.2 t/d (or 12.7 million l/yr) bioethanol plant with and without jet fuel production from EFB. The process flowsheet is based on experiments obtained from a pilot plant (0.1 t/d of 99.5% bioethanol without jet fuel) including a sequential dilute acid and alkali pretreatment and separate hydrolysis and fermentation (SHF). This study aims to assess the techno-economic feasibility of bioethanol production with jet fuel from EFB by using the 4-level EP, and to suggest some solutions during a low oil price period.