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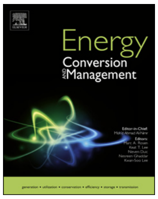

A new insight into sugarcane biorefineries with fossil fuel co-combustion: Techno-economic analysis and life cycle assessment

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ABSTRACT

In this study, alternative lignocellulosic biorefineries annexed to a typical sugarcane mill were investigated, to produce ethanol, lactic acid or methanol, or co-production of ethanol and lactic acid, all with surplus electricity for sale by conversion of sugarcane bagasse and harvesting residues (brown leaves) as accessible feedstock. In order to meet the energy demand of the sugar mill and biorefinery, burning a portion of feedstock or fossil source (coal) along with residues in the centralized combined heat and power unit were assumed as energy supplement strategies. A thorough Aspen Plus simulation was developed for each biorefinery scenario considering all required process units and supplementary units (i.e. combined heat and power, waste water treatment and evaporation). Furthermore, mass and energy balances along with costing data were applied to carry out techno-economic analysis, Monte Carlo finical risk study and life cycle assessment, in a multi-criteria desirability matrix. The lactic acid production biorefinery was found to be the most energy intensive process with highest chemical consumption and the highest conversion of biomass carbon input to products. Consumption of coal as an alternative source of energy enhanced the available biomass for valorization. Biorefineries with coal combustion producing ethanol or ethanol-lactic acid showed better environmental performance than methanol producing biorefineries, based on 1 ton of product. Although, the co-production of ethanol and lactic acid showed the largest likelihood of economic success, Methanol producing scenarios had a zero likelihood of an economic viability without substantial financial incentives or enhanced market prices.

1. Introduction

The fossil fuel depletion, the necessity for climate change mitigation, as well as the growing global population and its effect on world food security, are issues that encourage technological, social and political innovations in exploitation of natural resources [1]. Previously high oil price rises and price volatility for complex hydrocarbons derived from crude oil has opened a market gap for bio-based chemicals [2]. Various government initiatives have been launched at international, national and regional levels to support the biofuel, bioenergy and other biochemicals production, such as mandated biofuel blending targets in the United States (USA), Brazil, Canada and several EU member states [3].

Among a range of potential natural resources, lignocellulosic biomass has gained increasing attention as a result of its widespread availability, restricted competition with food crops and potential applicability as a sustainable source of energy and material [4]. Different technologies for processing such biomass are generally classified into three broad categories, i.e. thermochemical, chemical and biochemical [5]. Bioethanol is the most common biofuel product from the biochemical pathway, with the largest market ($58 billion a year sales market) followed by much smaller, but still significant markets for n-butanol, acetic acid and lactic acid [6]. The global demand for lactic acid (including polylactic acid, PLA, derived from it) is estimated at 472 kilo tonnes (kt/y), with revenues of around $685 million, based on market prices for bio-lactic acid of 1300–1600 $/tonne [6]. Approximately 45% of lactic acid is used for industrial applications (including lactic acid for PLA), with the more conventional food additive, pharmaceutical and cosmetic markets demanding around 260 kt/y. Demand for more environmentally-friendly packaging products, and the use of PLA in starch-based plastics is expected to drive demand for PLA over the next few years [7]. Further incentives include renewable energy targets and a shift to renewable feedstocks, as well as health concerns related to chemical toxicity [8].

Methanol is the simplest organic liquid that acts as a hydrogen carrier or storage compound, with the total annual worldwide production capacity of 50 million tonnes per annum, of which 75% is produced from natural gas [9]. Nowadays, methanol is used as primary

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Nomenclature

Acronym

AD	Anaerobic digestion
aLCA	attributional life cycle assessment
CHP	combined heat and power
CML	centre of Environmental Science
DM	dry matter
El	electricity
Et	ethanol
Et-b	ethanol production scenario with biomass co-combustion
Et-c	ethanol production scenario with coal co-combustion
EtLA-b	multi production of ethanol and lactic acid scenario with biomass co-combustion
EtLA-c	multi production of ethanol and lactic acid scenario with coal co-combustion
EtOH	ethanol
EU	European Union
GHG	greenhouse gas
GWP100	global warming potential
IRR	internal rate of return
LA	lactic acid
LA-b	lactic acid production scenario with biomass co-combustion
LA-c	lactic acid production scenario with coal co- combustion
LCA	life cycle assessment
LCIA	life cycle impact assessment
LCI	life cycle inventory
Me	methanol
Me-b	methanol production scenario with biomass co-combustion
Me-c	methanol production scenario with coal co-combustion
MeOH	methanol
M$	millions of United States of America dollar
MSP	Minimum selling price
ODP	ozone depletion
OPEX	operating costs
POCP	photochemical oxidation
R3N	trimethylamine
SA	South Africa
SScF	simultaneous saccharification and co-fermentation
TCI	total capital investment
USA	United States of America
WT	water treatment
WWT	waste water treatment

feedstock for a large variety of chemicals such as formaldehyde (70% of the total methanol produced), methyl-tert-butyl ether (MTBE, 20%), acetic acid and dimethylether and a variety of intermediates employed in manufacturing of chemicals and materials [10]. Mixtures of methanol and gasoline are already being marketed as an attractive automotive fuel because of its physical and chemical characteristics. In China, national fuel blending standards of M85 (85% methanol, 15% gasoline) and M100 (100% methanol) have being effective since 2009, and a M15 standard is in adoption stage [10]. The methanol economy, based on green-methanol synthesis pathways, has been proposed in contrast to the hydrogen economy, which requires a deep change in energy storage and transportation means. The thermochemical pathway for conversion of biomass, particularly municipal solid waste (MSW), to methanol has been commercialized in Canada since 2014 [11].

A number of economic assessments have been published on biofuel production from lignocellulosic biomass, considering biochemical or thermochemical technologies as well as the co-production of value-added chemicals [3]. However, research and development continue to be necessary on economic and environmental aspects of co-producing biochemicals along with biofuel.

Apart from economic viability, environmental impact is another important factor underpinning sustainable development of biorefinery systems, with Life Cycle Assessment (LCA) widely recognised as an evaluation approach [12] and formalized by the International Organization for Standardization [13]. LCA has been applied in a few cases for biorefineries assessment [14], while the majority of the studies focused on GHG emissions and energy balances, with less attention paid to the wider range of environmental impact categories [15].

The environmental burdens of ethanol and electricity co-production was investigated previously [16]. Several impact categories of environmental performance of methanol production from sugarcane bagasse was studied by Reno et al. and Khoo et al. [17]. LCA of lactic acid production has only been investigated in a limited number of instances where studies focused predominantly on the environmental performance of PLA, and specifically consequences from GHG emissions and energy utilisation of PLA production from sugarcane [18].

The overall objective of this work is to assess the viability of lignocellulosic biorefineries utilizing lignocellulosic residues of a typical sugar mill (bagasse and trash), in terms of economics and environmental impacts. In this regard four potential biochemical/thermochemical biorefineries for production of bioethanol, methanol or lactic acid, or the co-production of bioethanol and lactic acid, were simulated and assessed, to explore sustainable biorefinery design. The current research differs from other studies, not only in the developed biorefinery scenarios, but also in considering the source of energy used to meet the energy demands of combined complex (existing sugar mill and new biorefinery). Two approaches were compared including (i) bioenergy self-sufficient scenarios by directing a portion of lignocellulosic feedstock to centralized combined heat and power (CHP) unit, and (ii) coal co-combustion with biomass residues, where the whole biomass feedstock is processed to final products. In fact, the supply of process energy with a combination of lignocellulose residues (zero bypass of untreated lignocellulose) and coal is an economically attractive option since the total lignocellulose feed can be converted to value-added products [19].

As discussed, there is a large number of literature studies on Techno-economic evaluations and Environmental impacts of biomass conversion into biofuels and bioproducts. However, it is imperative to understand the implications of the technology choice on the economic viability and environmental sustainability. Very few studies had considered the comprehensive integrated analyses with techno-economic analysis and LCA of the biochemical/biofuel lignocellulosic biorefineries using multi-product platform strategy [20]. Furthermore, coal co-combustion can work as a double-edged sword to improve the economic viability and worsen environmental burden. The effect of coal co-combustion on lignocellulosic ethanol production has been previously studied by authors of this research as a pilot research [19]. This work widens the scope not only on product diversification, but also multi-product/co-product strategy and coal co-combustion energy supplement approach.

2. Materials and methods

Sugarcane is one of the most important agricultural products, with 97% of it planted in developing countries, such as Brazil, India, China and Southern Africa. Sugarcane residues (bagasse and trash) is a high volume agriculture residue with global production estimated more than 800 million tonnes per year [21]. The current practice of sugarcane harvesting in African countries mostly includes burning the sugarcane plant on-field prior to harvesting, for ease of manual harvesting. The