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Sustainability assessment of sugarcane biorefinery and molasses ethanol production in Thailand using eco-efficiency indicator

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HIGHLIGHTS

- Sugarcane biorefinery in Thailand is evaluated using the eco-efficiency concept.
- Green cane along with cane trash use for electricity yields highest eco-efficiency.
- Proposed biorefinery system increases eco-efficiency by 20–70%.

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ABSTRACT

The study aims to evaluate the sugarcane biorefinery and molasses ethanol production in Thailand using the combined environmental and economic sustainability indicator, so called "Eco-efficiency". Four sugarcane biorefinery scenarios in Thailand are evaluated. The total output values (US$) and the life cycle greenhouse gas (GHG) emissions (kg CO_2eq) are selected as the indicators for characterizing economic and environmental performance, respectively. The results show that the biorefinery system of mechanized farming along with cane trash utilization for power generation yields the highest eco-efficiency. The benefits come from the increased value added of the biorefinery together with the decreased GHG emissions of the biorefinery system. As compared to the base case scenario, the new systems proposed result in the eco-efficiency improvement by around 20–70%. The biorefinery concept induces reduction of GHG emissions attributed to molasses ethanol. Green cane production and harvesting results in further lowering of the GHG emissions. Integration of sugarcane biomass utilization across the entire sugarcane complex would enhance the sustainability of the sugarcane production system.

1. Introduction

The promotion of biomass utilization for energy is become one of the key energy strategies in many countries due to the increased concerns on energy and climate security [1,2]. This is especially so for the developing countries including Thailand whose economies rely highly on agriculture and are thus rich in biomass resources. Based on the recent 10-Year Alternative Energy Development Policy (AEDP 2012–2021), the Royal Thai Government (RTG) has set an ambitious target to establish renewable energy at 25% of the country's total energy consumption by 2021 [3]. Energy from biomass, biogas, municipal solid wastes as well as the first generation biofuels from indigenous feedstocks like molasses and cassava and advanced generation biofuels from agricultural residues are therefore gaining attraction and being expanded. Sugarcane is recognized as a promising crop for energy because of the high proportion of biomass in the form of readily fermentable sugars allowing for easy and commercially viable production of biofuels, especially bioethanol. The whole production system of sugarcane is complex and comprises various products and by-products e.g. sugar, bagasse, sugarcane trash, sugarcane molasses, and filter cake. To enhance the benefits of sugarcane biomass utilization, the establishment of biorefinery is therefore gaining attention worldwide [4–6].

Biorefinery generally refers to the production system that integrates biomass conversion processes to produce fuels, heat, electricity and value-added products e.g. materials or chemicals from biomass [4,7]. A variety of sugarcane biorefinery configurations have been proposed. The first generation sugarcane biorefineries are the sugar–ethanol–electricity mills [8,9]. Later, thanks to the development of technology, other sugarcane biorefineries have

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been proposed e.g. the integrated first and second generation ethanol production from sugarcane [8,10,11], integrated sugar mill with ethanol and methanol production plants [5], and the sugar chemistry route via butanol production integrated with sugar and first generation ethanol production [12]. These proposals are to maximize benefits from sugarcane biomass resources in terms of the value added creation of business.

Sugarcane is a staple crop playing an important role in the Thai economy. In 2013, the sugarcane planted area in Thailand was around 1 million ha producing about 60 million tonnes cane [13]. Selling and export of sugar products contributed about US$ 2462 million to the country's economy. The Thai sugarcane and sugar industry involves more than 600,000 small holders in the rural sector [14]. One of the by-products of sugar milling, bagasse, is mainly used for power generation due to the promotion of Independent Power Producers (IPP) and Small Power Producers (SPP) [15]. Sugarcane molasses, another by-product from sugar milling, is nowadays used as the major feedstock for bioethanol production; about 60% of the total bioethanol production in 2013 was from molasses. Because of the profit sharing requirement between farmers and millers under the Cane and Sugar Act, sugar millers are discouraged from producing ethanol directly from sugarcane juice which is recognized as the more efficient option, as practiced in Brazil. Although bioethanol production in Thailand has now developed into a relatively mature industry, there are still issues of concern on the environmental sustainability in view of life cycle assessment (LCA) [4,9]. Moreover, LCA studies in Thailand so far have been limited on the specific impact categories e.g. energy and greenhouse gas (GHG) emissions for the specific sugarcane bioenergy e.g. ethanol and electricity [16–19]. Those studies lack consideration on the whole system of sugarcane biorefinery and the integration of the economic and social indicators in the assessment. This study therefore aims to evaluate the sustainability of sugarcane biomass utilization in view of sugarcane biorefinery for molasses ethanol production by using the combined environmental and economic sustainability indicator, so called "Eco-efficiency".

2. Methodology

Eco-efficiency was introduced by the World Business Council for Sustainable Development (WBCSD) in 1995 and has become widely recognized as one of the indicators to promote the sustainable development of industry [20,21]. The concept of eco-efficiency is about creating more goods and/or services while using fewer resources and creating less environmental impacts. Assessing eco-efficiency requires indicators of both economic and environmental performance according to the eco-efficiency formula defined by WBCSD i.e. the ratio of "product or service value" to "environmental impact" [22]. The implementation of eco-efficiency indicators varies widely depending on the economic and environmental performance indicators of interest [22–25]. The use of eco-efficiency indicators is generally for a specific site or a specific production process to measure the progress towards economic and environmental sustainability. To apply the eco-efficiency concept therefore, the indicators and scope of comparison system should be clearly defined to ensure that it will be a fair comparison; such as comparing the different production options for a similar product.

In this study, the eco-efficiencies of different sugarcane biorefinery systems for sugar–electricity–ethanol production are evaluated using two important environmental and economic performance indicators i.e. life cycle GHG emissions and Gross Value Added (GVA), respectively. Life cycle GHG emission is recognized as an essential environmental sustainability indicator of bioenergy as indicated in the various sustainability schemes e.g. Global Bioenergy Partnership (GBEP), EU-RED [26–29]. Meanwhile, GVA is a measure in economics of the value of goods and services produced in an industry or an economy [30]. The total output values per unit of bioenergy product therefore indicate the economic performance of the bioenergy system. The eco-efficiency of the sugarcane biorefineries can be calculated using Eq. (1):

$$\text{Eco-efficiency}_{\text{biorefinery}} = \text{Gross value added (US\$)} / \text{Total GHG emissions (kg } CO_2\text{eq)} \quad (1)$$

The relative improvement of eco-efficiency of the base case biorefinery system and the new biorefinery systems can be calculated by Eq. (2). The advantage of calculating the relative indicator for eco-efficiency is that the problem of unknown unit of eco-efficiency like US$/kg CO_2eq can be avoided and the net efficiency of the new biorefinery systems can be determined by comparing with the base case [31,32].

$$\textit{Relative improvement of eco-efficiency} = \textit{Eco-efficiency}_{\textit{new system}} / \textit{Eco-efficiency}_{\textit{base case}} \quad (2)$$

2.1. Gross value added

GVA of the biorefinery refers to the total output value of the biorefinery system which can be calculated from Eq. (3):

$$\textit{Gross value added}_{\text{product}} = \textit{Selling Price}_{\text{product}} - \textit{Production cost}_{\text{product}} \quad (3)$$

In this study, the final products obtained from the sugarcane biorefinery consist of raw sugar, refined sugar, molasses ethanol, bioelectricity and organic fertilizer. For a fair comparison of the different sugarcane biorefineries, the GVA and GHG emissions are evaluated based on the same reference flow i.e. per tonne of sugarcane processed. Since the values or profits of the production system or the product are confidential, the market prices of products are used instead by assuming that the values of products will be finally reflected by prices and using the calculation of "Relative improvement of eco-efficiency" to indicate the performance of the base case and new scenarios. Table 1 shows the market prices of the final products. The total output value of a biorefinery is the summation of the values of all products generated per tonne of sugarcane input.

2.2. Life cycle GHG emissions

In the study, Life cycle assessment (LCA) has been used as a tool to evaluate the potential environmental impacts of different bio-ethanol production systems [9,12]. The "ReCiPe" impact assessment methodology is used in the assessment. The "ReCiPe" methodology is a recent life cycle impact assessment (LCIA)

Table 1
Prices of final products associated with sugarcane biorefinery.

Final products	Market prices[a]
Raw sugar	0.43 US$/kg
Refined sugar	0.55 US$/kg
Molasses ethanol	0.87 US$/l
Bioelectricity (from biomass)[b]	0.14 US$/kWh
Vinasse (for fertilizer)[c]	N.A.

Remark:
[a] Average exchange currency unit is 1 US$ = 32.5 Thai Baht (THB) [Year 2014].
[b] Electricity price is based on the 2015 feed-in-tariff schemes of Thailand.
[c] Vinasse is now given to sugarcane farmers free of charge through the Corporate Social Responsibility Program of the ethanol producers.