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Energy efficiency and environmental performance of bioethanol production from sweet sorghum stem based on life cycle analysis

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HIGHLIGHTS

- Bioethanol based on sweet sorghum stem can produce positive net energy.
- Most negative environmental impacts were human toxicity and eutrophication.
- Main factors contributed to fossil energy consumption and emissions were analyzed.
- Vinasse treatment and inventory allocation exerted significant effects on results.
- Key points to better energy efficiency and environmental performance were discussed.

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ABSTRACT

Life cycle analysis method was used to evaluate the energy efficiency and environmental performance of bioethanol production from sweet sorghum stem in China. The scope covers three units, including plant cultivation, feedstock transport, and bioethanol conversion. Results show that the net energy ratio was 1.56 and the net energy gain was 8.37 MJ/L. Human toxicity was identified as the most significant negative environmental impact, followed by eutrophication and acidification. Steam generation in the bioethanol conversion unit contributed 82.28% and 48.26% to total human toxicity and acidification potential, respectively. Fertilizers loss from farmland represented 67.23% of total eutrophication potential. The results were significantly affected by the inventory allocation methods, vinasse reusing approaches, and feedstock yields. Reusing vinasse as fuel for steam generation and better cultivation practice to control fertilizer loss could significantly contribute to enhance the energy efficiency and environmental performance of bioethanol production from sweet sorghum stem.

1. Introduction

China is currently the largest fossil energy consumer and greenhouse gases (GHGs) emitter worldwide (Gregg et al., 2008; IEA, 2010). The increasing dependence on imported oil and excessive GHGs emission has resulted in the emergence of renewable energy as an important energy and environmental concern in China. Bioethanol based on energy crop has been promoted by the Chinese government in many provinces. However, the development of bioethanol fuel is constrained by the increasing concern over food safety (Qiu et al., 2010), prompting the government and enterprises to identify non-grain crops, which include cassava, sweet potato, sugar cane, and sweet sorghum, as feedstock for bioethanol fuel production.

Bioethanol produced from various feedstocks using different technologies faces several controversial issues, such as energy efficiency, environmental impact and cost-effectiveness. A highly controversy issue of first-generation biofuels (produced from food and feed crops) frequently involves their negative impacts on food safety and environmental performance (Papong and Malakul, 2010; Mueller et al., 2011; Liang et al., 2012). Although the second-generation bioethanol (produced from lignocellulosic biomass) does not have such disadvantages (Sánchez and Cardona, 2008; Roy et al., 2012), the main controversy of second-generation bioethanol is the high cost for the establishment of cellulosic ethanol infrastructure (Gómez et al., 2011; Giarola et al., 2012).

Sorghum is a fast growing C4 plant native to tropical zones, but it can adapt to different environmental conditions. This plant grows in tropical, subtropical and temperate zones (Zegada-Lizarazu and Monti, 2012). Sweet sorghum has attracted attention as one of the most promising non-food feedstock crop for

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bioethanol production in China because of its rich germplasm resource, high biomass yield, rapid growth, wide adaptability, and rich sugar content in stem, as well as clean and relatively low production cost. Therefore, bioethanol from sweet sorghum is regarded as a 1.5-generation biofuel (Li et al., 2013). China has launched numerous research projects and pilot production activities involving sweet sorghum, especially on alkaline and saline lands, as feedstock for bioethanol production. For instance, several International Scientific and Technological Cooperation projects and National Key Technology R&D programs have been funded by the Ministry of Science and Technology of China (Li et al., 2013).

However, bioethanol production from sweet sorghum stem is also confronted with two controversial issues: whether the bioethanol produces positive net energy, and whether it is environmental friendly. The net energy efficiency and environmental performance of different biofuels depend on the type of feedstock, production process, and amount of nonrenewable energy required (Amigun et al., 2011; Liang et al., 2012). Life cycle assessment (LCA) is a useful tool to analyze these two issues. LCA is a technique to evaluate environmental impacts associated with all the stages of a product's life cycle from cradle to grave, so it has been extensively used to evaluate the energy efficiency and environmental performance of bioethanol and biodiesel (Jury et al., 2010; Hou et al., 2011). Several studies have assessed the productive potentials, conversion technology, energy balance, GHGs, and economic performance of bioethanol production from sweet sorghum stem (Zhang et al., 2010; Tao et al., 2011; Liang et al., 2012; Li et al., 2013; Yu et al., 2014). However, few studies have evaluated the energy efficiency and environmental performance of sweet sorghum from the life cycle perspective.

Thus, this study aims to evaluate the fossil energy consumption, energy gain, and energy efficiency associated with bioethanol production from sweet sorghum stem and to assess its environmental performances using attributional LCA method. In addition, the main sources of energy consumption and environmental impacts, as well as the uncertainty of the evaluation results were discussed. Hence, this study provides insight into the reasonable use of sweet sorghum stem as feedstock for bioethanol production.

2. Methods

2.1. System boundary and functional unit (FU)

The product system boundary used in the study is presented in Fig. 1. A product system is a collection of unit processes connected by flows of intermediate products that perform one or more defined functions. The system is subdivided into a set of units. Units are linked to one another through flows of intermediate products and waste, to other product systems through product flows, and to the environment through elementary flows. According to the above definition, the product system is subdivided into three units, namely, plant cultivation, feedstock transport and bioethanol conversion.

An FU primarily provides a reference to which the inputs and outputs are related. This reference is necessary to ensure the comparability of LCA results. In this study, FU is 1000 L of bioethanol produced from sweet sorghum stem.

2.2. Product system description

2.2.1. Plant cultivation unit

A plant cultivation unit includes field preparation, plowing, sowing, fertilization, crop protection, harvesting, and packaging. Many provinces in China are suitable for sweet sorghum production. The most suitable cultivation areas are in Northeast China, North China, Northwest China, and certain areas along the Yellow River Delta (Qiu et al., 2010). Sweet sorghum plantation is still of minor scale and widely dispersed in China. In present study, data were collected by interviewing farmers from a sweet sorghum cultivation pilot base for bioethanol production in Shangdong Province, North China. The pilot base has an area of 267 hm^2. The main cultivar was Chuntian 1. The average fresh weight of the sweet sorghum grain was 3.3 t/hm^2, and the fresh weight of stem reached 60 t/hm^2.

2.2.2. Feedstock transport unit

A feedstock transport unit includes the transport of sweet sorghum stem from planting fields to bioethanol plants. The sweet sorghum stem was transported either from the fields to markets and then from markets to bioethanol plants or was directly transported from the fields to bioethanol plants. The main assumptions regarding this unit included the following: only diesel-fueled trucks with a load of 5 t are used during the transport of sweet sorghum stem, and the average transport distance for sorghum stem is 20 km.

2.2.3. Bioethanol conversion unit

A bioethanol conversion unit includes six operation processes, namely, smashing feedstock, yeast inoculation, continuous solid-state fermentation, continuous solid-state distillation, bioethanol purification, and vinasse treatment (Shen et al., 2012; Li et al., 2013). Sweet sorghum stems were smashed into pieces and preheated. Then, the solid pieces were fed into a continuous solid-state fermenter. The fermented bagasse was distilled and condensed into crude bioethanol, and the remaining material was treated as residual vinasse. The crude bioethanol was purified to 99.5% (v/v), which is suitable for blending with gasoline and used as transportation fuel. Bioethanol was cost-effectively produced with the use of proprietary yeast that converted fermentable sugars in sweet sorghum stems into bioethanol in 24 h. The bioethanol yield reached 91% of the theoretical yield (Wang et al., 2010). Wastewater was used to produce biogas and partly substitute the coal in steam generation. The residual vinasse was refermented and a protein feed with 8% crude protein was obtained. The emitted CO_2 was also collected, and could be sold as a raw material in numerous industrial processes.

2.3. Life cycle inventory (LCI)

Based on the demonstrated enterprise investigation, interview with farmers, open LCI databases and public references, we obtained input and output data related to energy and raw material during plant cultivation, feedstock transport, and bioethanol conversion: (1) fertilizer, herbicide, electricity and diesel inputs for sweet sorghum cultivation, as well as the sweet sorghum stem and grain outputs; (2) transport distance and diesel consumption for sweet sorghum stem; and (3) fossil energy and auxiliary materials inputs, and the outputs of the main products and co-products in bioethanol conversion unit.

Background data related to air emissions resulting from fossil energy combustion (coal, diesel and natural gas) and auxiliary materials production (including chemical fertilizers, herbicide, alpha amylase, glucoamylase and yeast) in all units were mainly obtained using the GREET model developed by Argonne National Laboratory (ANL, 2012). The model was developed to fully evaluate the energy and emission impacts of advanced and new transportation fuels from well to wheel, containing a large quantity of inventory data of input materials for fuel production. However, the conditions of the processes (e.g., energy structure, energy efficiency, etc.) often varied. In such cases, we verified the data against the energy consumption conditions of these materials, which can