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Life-cycle energy efficiency and environmental impacts of bioethanol production from sweet potato

Mingxin Wang [a,*], Yu Shi [a], Xunfeng Xia [b], Dinglong Li [a], Qun Chen [a]

[a] *College of Environmental & Safety Engineering, Changzhou University, Changzhou 213164, China*
[b] *China Environmental Science Research Institute, Beijing 100012, China*

HIGHLIGHTS

- ▶ The net energy ratio and net energy gain values were 1.48 and 6.55 MJ/L, respectively.
- ▶ The most significant environmental impacts were eutrophication and acidification.
- ▶ The main sources contributing to energy consumption and environmental impact were analyzed.
- ▶ Sensitive factors were identified, and improvement measures were discussed.

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ABSTRACT

Life-cycle assessment (LCA) was used to evaluate the energy efficiency and environmental impacts of sweet potato-based bioethanol production. The scope covered all stages in the life cycle of bioethanol production, including the cultivation and treatment, transport, as well as bioethanol conversion of sweet potato. Results show that the net energy ratio of sweet potato-based bioethanol is 1.48 and the net energy gain is 6.55 MJ/L. Eutrophication is identified as the most significant environmental impact category, followed by acidification, global warming, human toxicity, and photochemical oxidation. Sensitivity analysis reveals that steam consumption during bioethanol conversion exerts the most effect on the results, followed by sweet potato yields and fertilizers input. It is suggested that substituting coal with cleaner energy for steam generation in bioethanol conversion stage and promotion of better management practices in sweet potato cultivation stage could lead to a significant improvement of energy and environmental performance.

1. Introduction

National crude oil consumption in China reached 461.8 million t, with imported crude oil constituting approximately 54.8% in 2011 (BP, 2012). The amount of imported crude oil continuously increases because of the rapidly rising demand for oil in the flourishing economy. In addition, China is currently the top CO_2 producer worldwide (Gregg et al., 2008). Increasing reliance on imported oil, high crude oil prices, and heavy environmental burdens have prompted the Chinese government to conduct a serious review of the country's energy policy.

Development of renewable energy becomes a critical strategy for China to maintain its rapid economic growth and improve its environmental sustainability. China's first Renewable Energy Act took effect on January 1, 2006. The government attempted to increase renewable energy to 10% of the total energy consumption in 2010. Currently, China aims to increase renewable energy to 16% of the total energy consumption by 2020.

Bioethanol is an important factor in China's Renewable Energy Development Plan. The government planned to raise bioethanol consumption as a fuel blending component from 1 million t in 2005 to 2 million t by 2010. The government remains intent on raising bioethanol consumption as a fuel blending component to 10 million t by 2020. However, the development of bioethanol fuel is constrained by the rising concern over food safety, prompting the government and the industry to identify non-grain feedstock such as sugar cane, cassava, sweet potato, and sweet sorghum for bioethanol fuel production.

Several publications are already available on LCA studies conducted to identify the energy efficiency and environmental performance of bioethanol production from different feedstocks by using first-generation technologies (produced from food and feed crops). Leng et al. (2008) found that the energy conversion efficiency of E10 bioethanol fuel production from cassava is 1.28 and that energy consumption from denatured bioethanol conversion contributes 70% of the total energy consumption. Papong and Malakul

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* Corresponding author. Tel.: +86 13912345364.
E-mail address: wmxcau@163.com (M. Wang).

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(2010) indicated that cassava-based bioethanol in Thailand has a negative net energy value with an energy ratio of less than 1, indicating a net energy loss. The conversion stage of cassava-based bioethanol also significantly contributes to environmental burdens because of the consumption of coal for power and steam production in bioethanol plants. Amigun et al. (2011) argued that the net performance of different biofuels in reducing non-renewable energy consumption and greenhouse gas emission depends on the type of feedstock, production process, and amount of non-renewable energy required. Liang et al. (2012) argued that corn- and wheat-based bioethanol in China exhibited higher negative economic, energy, and environmental impacts, whereas bioethanol production from sweet sorghum, cassava, sugar beet, and sugarcane showed better economic performance, increased negative energy efficiency, and higher environmental impacts. A strong controversy surrounds the first-generation biofuels, frequently referring to their negative impacts on food safety and the environment (Mueller et al., 2011). Second-generation bioethanol (produced from lignocellulosic biomass) are not as exposed to such disadvantages (Sánchez and Cardona, 2008; Roy et al., 2012; Wang et al., 2012); however, high costs hinder the establishment of cellulosic ethanol infrastructure (Giarola et al., 2012). Consequently, the use of first-generation technology for the commercial production of liquid biofuels continues (Gómez et al., 2011).

China, the world's largest producer of sweet potato, supplies 80–85% of global production. The majority of China's sweet potato crop is grown in seasonal rotations with other staple crops. Currently, sweet potato is mainly used as processed food, feed, and feedstock for alcohol production in China. Sweet potato is rich in starch, and approximately 80% of its dry matter consists of carbohydrates. Starch and carbohydrates in sweet potato are readily and anaerobically converted into hydrogen and bioethanol. Moreover, sweet potato contains indigenous bacteria, which may aid in the bioconversion of starch into hydrogen and bioethanol. With the current technology, approximately 8 t of fresh sweet potatoes can produce 1 t of bioethanol (Qiu et al., 2010).

Sweet potato is considered a potential source of bioethanol feedstock by policymakers in China. Numerous pilot production bases of sweet potato are established with high-yielding cultivars and highly intensive cultivation practices to provide feedstock for commercial bioethanol production. Similar to other biomass fuels, bioethanol fuel derived from sweet potato is also confronted with two controversial issues: whether bioethanol fuel produces positive net energy and whether it is environment-friendly. LCA has been proven to be a valuable tool for analyzing energy and environmental considerations of product and service systems. No LCA study has been conducted to assess the energy efficiency and environmental impacts of bioethanol production from sweet potato.

Thus, this study aims to (1) evaluate the energy efficiency of a commercial sweet potato-based bioethanol production plant in China, with net energy gain (NEG) and net energy ratio (NER) as indicators of energy efficiency, and (2) assess the life-cycle environmental impacts associated with bioethanol production from sweet potato. LCA was performed for all stages in the production of 1000 L of bioethanol from sweet potato.

2. Methodology

LCA in this study comprises four steps: definition of goal and scope, inventory analysis, impact assessment, and interpretation (ISO, 2006).

2.1. Definition of goal and scope

This study aims to determine the environmental performance and energy efficiency of sweet potato-based bioethanol to identify opportunities for improving the environmental aspects at various points in the entire life cycle and aid in the decision-making process of the Chinese government regarding bioethanol development policy.

The study covers the holistic life cycle of sweet potato-based bioethanol, including the cultivation and treatment, transport, as well as bioethanol conversion of sweet potato. The system boundary is presented in Fig. 1.

A functional unit (FU) measures the performance of the functional outputs of a product system. 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. The FU of this study is 1000 L of bioethanol produced from sweet potato.

2.2. Product system description

A product system is a collection of unit processes connected by flows of intermediate products that perform one or more defined functions. Product systems are subdivided into a set of unit processes. Unit processes are linked to one another by flows of intermediate products and waste for treatment, to other product systems by product flows, and to the environment by elementary flows. According to life-cycle inventory, the product system is subdivided into three unit processes described below.

2.2.1. Sweet potato cultivation and treatment

Sweet potato is widely grown in almost every province in China. The Yangtze River Basin is the most important region for sweet potato production in China, providing approximately 60% of the national production. Sweet potato is primarily planted in hilly areas on loess and red soils. Sichuan and Chongqing have the largest sweet potato production in the Yangtze River Basin. The growing season in these regions continues for a period ranging from 140 days to 170 days beginning in late April, May, or June; the harvesting season is in late October or November. This unit process includes field preparation, plowing, sowing, fertilization, crop protection, harvesting, and packing.

Numerous high-yielding sweet potato cultivars have been developed and planted as feedstock for commercial bioethanol production in this region. This study investigated a sweet potato pilot base for a commercial bioethanol plant with an annual production capacity of 0.1 million t in western China. The cultivar was identified as Yushuwang, and the fertilizers were applied at 157.5 kg N, 81 kg P_2O_5 and 247.5 kg K_2O per hm^2, respectively. Approximately 1.8 kg/hm^2 of pesticides (such as phoxim) were applied to control underground pests. The average yield of the fresh sweet potato reached 45 t/hm^2.

2.2.2. Transport of fresh sweet potato

This unit includes the transport of fresh sweet potatoes from planting fields to commercial bioethanol plants. The fresh sweet potatoes were either transported from the farmers' houses to markets and then from markets to bioethanol plants or were directly transported from the farmers' houses to the bioethanol plants. The main assumptions regarding this unit process include the following: (1) only diesel–fueled trucks are used during the transport of fresh sweet potato, and (2) the average transport distance is 150 km.

2.2.3. Bioethanol conversion

This stage includes crushing, steam cooking, saccharification, fermentation, and distillation. Steam generation and waste treatment are also involved in this phase. Except for fresh sweet potatoes or dry sweet potato chips, bioethanol conversion also consumes coal, electricity, and auxiliary materials such as H_2SO_4, alpha amylase, glucoamylase, and yeast. The main product consists