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Environmental sustainability of bioethanol produced from sweet sorghum stem on saline–alkali land

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HIGHLIGHTS

- Bioethanol from sweet sorghum stem on saline–alkali land can produce net energy.
- Most significant environmental impacts were eutrophication and acidification.
- Contributors of energy consumption and environmental impacts were identified.
- Uncertainty of the life cycle assessment results was analyzed.
- Key points to improve environmental sustainability were discussed.

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ABSTRACT

Life cycle assessment was conducted to evaluate the energy efficiency and environmental impacts of a bioethanol production system that uses sweet sorghum stem on saline–alkali land as feedstock. The system comprises a plant cultivation unit, a feedstock transport unit, and a bioethanol conversion unit, with 1000 L of bioethanol as a functional unit. The net energy ratio is 3.84, and the net energy gain is 17.21 MJ/L. Agrochemical production consumes 76.58% of the life cycle fossil energy. The category with the most significant impact on the environment is eutrophication, followed by acidification, fresh water aquatic ecotoxicity, human toxicity, and global warming. Allocation method, waste recycling approach, and soil salinity significantly influence the results. Using vinasse to produce pellet fuel for steam generation significantly improves energy efficiency and decreases negative environmental impacts. Promoting reasonable management practices to alleviate saline stress and increasing agrochemical utilization efficiency can further improve environmental sustainability.

1. Introduction

Given its rapid economic and social development, China has experienced increasing energy demand and energy-related carbon emissions for a particularly long period. In an effort to offset fossil fuel-related negative impacts on energy safety and environmental health, its government has established the process of blending liquid biofuels with fossil fuels. Therefore, bioethanol based on energy crop has been promoted to substitute gasoline in many provinces, and 10 Mt bioethanol is being planned to be blended into gasoline annually by 2020 (NDRC, 2007). However, the development of bioethanol fuel is constrained by the increasing concern over food safety (Qiu et al., 2010). This concern has prompted the government and enterprises to cultivate energy crops in marginal lands that are not suitable for agriculture and to identify nongrain crops, including cassava, sweet potato, sugar cane, and sweet sorghum, as feedstock for bioethanol fuel production (Wang et al., 2013; Ren et al., 2014).

Sweet sorghum is relatively more adapted than corn to marginal growing conditions, such as water deficit stress, water logging, salinity, alkalinity, and other edaphic constraints; however, maximum sweet sorghum yields are typically obtained in deep, well-drained soils with good fertility (Regassa and Wortmann, 2014). Given its adaptability and resilience, sweet sorghum stem is often more suitable for biofuel production than other feedstock crops on marginal land. Therefore, sweet sorghum stem has attracted attention as a promising nonfood feedstock crop for bioethanol production in China. During the last decade, farmers in China have been organized to demonstrate the feasibility of establishing sweet sorghum plantations for bioethanol fermentation on saline–alkali regions (Ren et al., 2012). In addition,

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Bioethanol produced from energy crop should be evaluated for its environmental sustainability, that is, whether or not it can produce positive net energy and whether or not it is environmental friendly (Papong and Malakul, 2010; Amigun et al., 2011; Liang et al., 2012). Life cycle assessment (LCA) is a useful tool to analyze these two issues (Leng et al., 2008; Hou et al., 2011; Wang et al., 2014). However, little information is available about the energy efficiency and environmental impacts of bioethanol produced from sweet sorghum stem on saline–alkali land.

Thus, this study aims to evaluate the fossil energy consumption, energy gain, and energy efficiency associated with bioethanol produced from sweet sorghum stem on saline–alkali land and to assess its environmental impacts through LCA. The uncertainty level of the evaluation results was also discussed. This study provides insights into the reasonable use of sweet sorghum stem on saline–alkali land as feedstock for bioethanol production.

2. Methods

The purposes of LCA are to compare alternative products, processes, or services; to compare alternative life cycles for a particular product or service; and to identify the parts of the life cycle where the greatest improvements can be achieved. Hence, LCA was conducted in this study to evaluate the life cycle of bioethanol produced from sweet sorghum stem on saline–alkali land.

2.1. System description

A product system comprises unit processes that are connected by flows of intermediate products that perform one or more defined functions. 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. In this study, the product system is subdivided into three units, namely, plant cultivation, feedstock transport, and bioethanol conversion. The system boundary of bioethanol production system in this study is shown in Fig. 1. A functional unit (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, the evaluation was conducted with 1000 L of bioethanol as FU.

The plant cultivation unit includes field preparation, plowing, sowing, fertilization, crop protection, harvesting, packaging, and storage. In this study, data were collected by interviewing farmers from a sweet sorghum cultivation pilot base for bioethanol production in Wendeng County, Shandong Province, North China. It is located in typical coastal saline–alkali zones, which are recognized as promising regions for sweet sorghum production in China. The fertilizers were applied at 160 kg of N, 69 kg of P_2O_5, and 60 kg of K_2O per hm^2. Approximately 0.76 kg/hm^2 of pesticides was applied to control pests and diseases. The average yield of sweet sorghum stem and grain reached 46 and 2.03 t/hm^2, respectively.

The feedstock transport unit includes the transport of sweet sorghum stem from planting fields to bioethanol plants. The sweet sorghum stem was assumed to be transported first to a nearby collection center and then to the bioethanol processing plant with diesel–fueled trucks with a load of 5 t.

The bioethanol conversion unit includes six operation processes, namely, smashing feedstock, yeast inoculation, continuous solid-state fermentation, continuous solid-state distillation, bioethanol purification, and residual vinasse treatment (Shen et al., 2012; Li et al., 2013). Aside from sweet sorghum stem, bioethanol conversion also consumes electricity and auxiliary materials, such as H_2SO_4, NaOH, alpha amylase, glucoamylase, and yeast. Sweet sorghum stems were smashed into pieces and preheated. 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. One half of the vinasse was used to produce crude protein as cattle feed, and the other half to produce pellet fuel as energy for steam generation. Wastewater was used to produce biogas, which was also utilized for steam generation.

2.2. Life cycle inventory (LCI)

In the plant cultivation unit, input and output data related to sweet sorghum cultivation were obtained by interviewing farmers. In particular, these data include fertilizer, pesticide, electricity, and diesel inputs for sweet sorghum cultivation and sweet sorghum stem and grain outputs. The emission factors of nitrogenous pollutants, such as N_2O, NH_3, and total nitrogen (TN) drainage loss caused by nitrogen fertilizer application, were estimated in accordance with the respective methods described by Xing and Zhu (2010), Zhang et al. (2011), and Zheng et al. (2004). Total phosphate (TP) drainage loss was estimated to be 1.5% of the phosphate fertilizer input by employing the method described by Ma et al. (2012) and by considering local field management practices, soil conditions, and climate conditions. Pesticide emissions to air, fresh water, and soil were estimated following the method of Birkved and Hauschild (2006). Data related to air emissions caused by fossil energy combustion and agrochemical production were mainly obtained using the GREET model developed by Argonne National Laboratory (ANL, 2012). Data related to water pollutant emissions were referenced from the environmental standards for chemical fertilizers and pesticides by the China Environmental Protection Ministry. Data on heavy metal emissions from fossil energy combustion were obtained from Di et al. (2005).

In the feedstock transport unit, the transportation distance of sweet sorghum stem from the planting farms to the bioethanol processing plants was estimated using the process described by Huang et al. (2009). The diesel consumption and emission related to transport were determined using the GREET model (ANL, 2012).

In the bioethanol conversion unit, the energy input and output data were collected from the pilot plant. The direct emissions of air and water pollutants from the bioethanol conversion unit were calculated in accordance with the cleaner production and environmental standards for ethanol industries in China by the China Reform and Development Commissions. Air emission factors of biogas combustion and pellet fuel combustion were referenced from Jury et al. (2010) and Fantozzi and Buratti (2010), respectively. Data related to air emissions resulting from fuel combustion and auxiliary material production were mainly obtained using the GREET model (ANL, 2012).

Allocation of energy consumption and emission data between the main product and the co-products is a critical issue in LCI analysis. Energy balance, mass balance, market value, and replacement methods are the main approaches used in most studies (Leng et al., 2008; Hou et al., 2011; Wang et al., 2014). In the present study, the market value allocation method with 2-year average market prices was used. In the plant cultivation unit, sweet sorghum stem was used as feedstock for bioethanol production, and the co-product was sweet sorghum grain, which is available in the market. In the bioethanol conversion unit, the main product is bioethanol and the co-product is protein feed. The CO_2 generated in biogas and pellet fuel combustion was carbon neutral; thus, it was not included in the inventory of emissions. The average