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A self-sustaining advanced lignocellulosic biofuel production by integration of anaerobic digestion and aerobic fungal fermentation

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HIGHLIGHTS

- A combined hydrolysis can synergistically treat solid digestate and corn stover.
- *M. isabellina* can efficiently accumulate lipids on the combined hydrolysate.
- A novel self-sustaining advanced lignocellulosic biofuel production is concluded.
- A positive net energy of 57 MJ/L biodiesel is achieved by the system.

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ABSTRACT

High energy demand hinders the development and application of aerobic microbial biofuel production from lignocellulosic materials. In order to address this issue, this study focused on developing an integrated system including anaerobic digestion and aerobic fungal fermentation to convert corn stover, animal manure and food wastes into microbial lipids for biodiesel production. Dairy manure and food waste were first anaerobically digested to produce energy and solid digestate (AD fiber). AD fiber and corn stover were then processed by a combined alkali and acid hydrolysis, followed by fungal lipid accumulation. The integrated process can generate 1 L biodiesel and 1.9 kg methane from 12.8 kg dry dairy manure, 3.1 kg dry food wastes and 12.2 kg dry corn stover with a positive net energy of 57 MJ, which concludes a self-sustaining lignocellulosic biodiesel process and provides a new route to co-utilize corn stover and organic wastes for advanced biofuel production.

1. Introduction

Energy crops and agricultural residues represent an enormous untapped reservoir of lignocellulosic biomass that has great potential as feedstocks for the production of renewable bio-based fuels/chemical products. It has been estimated that approximate 194 million dry tons of lignocellulosic material are produced annually from agricultural activities in the United States (Perlack et al., 2005). Corn stover and animal manure with a total amount of 95 million dry tons per year (60 million dry tons for corn stover and 35 million dry tons for animal manure) are the two major resources among the agriculture-based lignocellulosic materials. Current biorefining research and development on these feedstocks have mainly focused on alcohol production to date. Yue et al. demonstrated a new biorefining concept to convert animal manure into ethanol and methane (Yue et al., 2010). Lau et al. developed an integrated biorefining concept to improve the efficiency of corn stover ethanol production and enhance the economic performance of the biorefinery (Lau et al., 2012). Tao et al. compared corn stover biorefining of isobutanol, n-butanol, and ethanol production, and concluded that n-butanol and ethanol have better energy return on investment than isobutanol (Tao et al., 2014). In order to fully utilize the potential of lignocellulosic materials and diversify our energy portfolios, there is an urgent need of developing new biorefining processes to produce advanced fuels besides bio-alcohols from these feedstocks. Therefore, this study focused on simultaneously using animal manure and corn stover to produce lipid based fuel – biodiesel.

In spite of numerous studies on converting corn stover into biofuels (Aden, 2002; Borrion et al., 2012; Lau and Dale, 2009; Lau et al., 2008), utilization of animal manure is mostly limited to methane production through anaerobic digestion technology (Lv et al., 2013; Nasir et al., 2012; Zhang et al., 2014). It is well known that anaerobic microbes can only convert around 40–60%

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of carbon into methane during animal manure anaerobic digestion, there is a large amount of carbon still remained in the digestate in the forms of cellulose, hemicellulose, lignin, and protein. Several recent studies discovered that the solid digestate has similar fiber quality with corn stover and switchgrass, and can serve as a suitable biorefining feedstock, which makes anaerobic digestion a dual-functional unit operation of generating methane and pretreating manure fiber (Teater et al., 2011; Yue et al., 2010).

Lignocellulosic biodiesel production includes feedstock pretreatment, carbohydrate saccharification, aerobic fungal fermentation, and lipid extraction and transesterification. Some of these unit operations are energy and chemical intensive. Many efforts have been devoted to address this issue. Two new processes of co-hydrolysis and combined hydrolysis have been recently developed to simplify the pretreatment of corn stover for fungal lipid accumulation (Ruan et al., 2014, 2013). However, even though simplified pretreatment reduce a significant amount of total energy demand for the process, the net energy is still not balanced due to the high energy demand of aerobic fungal fermentation. Therefore, other renewable energy sources must be systematically and synergistically incorporated to satisfy the energy demand of aerobic fermentation, and realize self-sustaining biodiesel production.

The objective of this study was to develop a novel energy-positive lignocellulosic biodiesel production concept by integrating anaerobic digestion and aerobic fermentation. Corn stover and animal manure were two main feedstocks. A small amount of food wastes was used to balance nutrient to enhance the anaerobic digestion performance. Fig. 1 demonstrates the studied self-sustaining advanced lignocellulosic biodiesel production concept. Dairy manure and food wastes were first fed into an anaerobic digester to produce methane biogas and solid digestate (AD fiber). Due to the alkalinity of AD fiber, it has been reported that alkali pretreatment was the preferred method to treat AD fiber (Teater et al., 2011), so that the AD fiber was pretreated with sodium hydroxide and mixed with acid pretreated corn stover to prepare the combined slurry for next step of saccharification. Cellulase and xylanase were added in the combined slurry to convert cellulose and xylan into mono-sugars. After enzymatic hydrolysis, the liquid hydrolysate containing glucose, xylose, and acetate was used as the medium for aerobic fungal fermentation of lipid accumulation. The fungal biomass was collected after the fermentation, and the fungal lipid was extracted and refined into biodiesel. The methane biogas generated from the anaerobic co-digestion was combusted to produce electricity and heat to power the entire system.

2. Methods

2.1. Feedstock characteristics

The dairy manure used for the experiments was taken from the Dairy Teaching and Research Center at Michigan State University. The food wastes were collected from a cafeteria at Michigan State University. The dairy manure and food waste were then mixed with water in a blender (Waring Commercial Laboratory, Model No. 34BL97(7012)) according to the experimental manure-to-food-waste ratio. The mixed feedstocks were stored in a −20 °C freezer prior to use. The corn stover was collected from the Crop and Soil Science Teaching and Research Agronomy Farm at Michigan State University, the corn stover was air-dried and grinded to 2 mm size using a hammer mill (Wiley Mill, Standard Model No. 3). The ground corn stover was stored in the airtight bags at the room temperature prior to use. The characteristics of the feedstocks were listed in Table 1.

2.2. Anaerobic digestion

Anaerobic digestion of dairy manure was compared with anaerobic co-digestion of dairy manure and food wastes (the ratio of manure-to-food-waste is 80:20). The digestion was carried out in 0.75 L bottles (reactor) with septa caps. The working volume for all reactors was 0.50 L, with a headspace of approximately 0.25 L. Rubber septa (VWR) were used to seal the reactors. Needles were used to penetrate the septa caps to release biogas. Duplicates were prepared for individual runs with a total of 4 reactors. The reactors were shaken on Innova 2000 shakers (New Brunswick Scientific, NJ) at 150 rpm. The shakers were placed in an incubator (Fisher Scientific, Model No. 650D), where temperature was set at 35 °C. The solid content for the digestion was 5% total solids (TS), and the hydraulic retention time (HRT) was 20 days. The pH for all reactors was controlled in the range between 6.70 and 6.90 by dosing 30% (w/w) sodium hydroxide (NaOH) solution. The biogas produced from each reactor was measured using a water displacement method.

Sampling and feeding of reactors was performed using an automatic atmosphere chamber (Plas Lab, Lansing, MI). The chamber was purged with a medical grade specialty gas from Airgas, composed of 85% nitrogen (N_2), 10% hydrogen (H_2) and 5% carbon dioxide (CO_2). A palladium catalyst heater was installed to make the chamber completely anaerobic. Fresh feeds at 5% TS were made

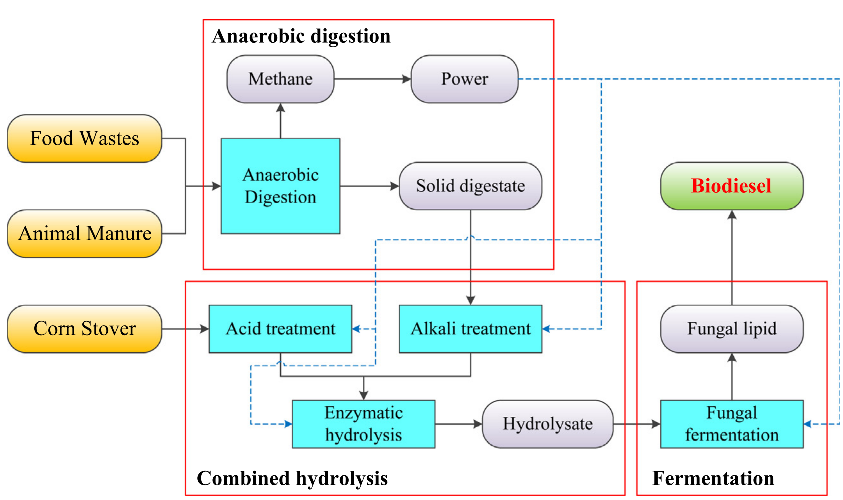

Fig. 1. Flowchart of a self-sustaining advanced lignocellulosic biofuel production. *Note:* Solid black lines are mass flow; red frames are unit operations; dash blue lines are energy flow. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)