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Effect of solids loading on ethanol production: Experimental, economic and environmental analysis

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HIGHLIGHTS

- Hydrolysis and fermentation were conducted at 19%, 30%, and 45% solids.
- Corn stover at 45% (CS45) solids loading released 205 ± 25.8 g/L glucose
- Ethanol release for CS45 was 115.9 ± 6.7 g/L after 60 h of fermentation.
- Techno-economic analysis revealed an ROI of 8% at 45% solids loading.
- Global warming potential for CS45 was −37.8 gCO_2 eq./MJ ethanol.

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ABSTRACT

This study explores the effect of high-solids loading for a fed batch enzymatic hydrolysis and fermentation. The solids loading considered was 19%, 30% and 45% using wheat straw and corn stover as a feedstock. Based on the experimental results, techno-economic analysis and life cycle assessments were performed. The experimental results showed that 205 ± 25.8 g/L glucose could be obtained from corn stover at 45% solids loading after 96 h which when fermented yielded 115.9 ± 6.37 g/L ethanol after 60 h of fermentation. Techno-economic analysis showed that corn stover at 45% loading yielded the highest ROI at 8% with a payback period less than 12 years. Similarly, the global warming potential was lowest for corn stover at 45% loading at −37.8 gCO_2 eq./MJ ethanol produced.

1. Introduction

The need for liquid fuels is increasing the global oil consumption expected to reach 100 million barrels by 2019 (US Energy Information Administration, 2017) and ethanol is one of the promising alternatives to replace fossil fuels. Though the in-field feedstock availability is high between 10 and 50 billion tons (dry weight) (Rajendran and Taherzadeh, 2014; Zhao et al., 2009) the challenges range from harvesting and transportation logistics, process challenges such as complexity of biomass structure and overall hydrolysis efficiency. Several attempts were made in the past decades to produce ethanol at an economically competitive prices however, there are several hurdles such as increasing the efficiency of the enzymes, efficient release of glucose during hydrolysis, decreasing the energy consumption during pretreatment step, and availability of commercial scale equipment (Mussatto et al., 2010). Considerable efforts were made with respect to the conversion of lignocelluloses to ethanol including developing various pretreatment methods, studying the enzyme interactions with cellulose and lignin, increasing the solids loading during enzymatic hydrolysis and several types of process integration improvements such as separate hydrolysis and fermentation (SHF) and simultaneous saccharification and fermentation (SSF) (Brodeur et al., 2017; da Silva Martins et al., 2015; Hahn-Hägerdal et al., 2006; Jin et al., 2017; Liu et al., 2015; Margeot et al., 2009).

Solids loading during enzymatic hydrolysis is usually in the range of 10–20% w/w basis (Humbird et al., 2011) however some studies considered a higher solids loading between 25% and 40% (Jørgensen et al., 2007; et al., 2010; Zhu et al., 2011). Few concerns with the high-solids loading are that the mixing of the materials

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becomes very difficult beyond 20% solids due to unavailability of free water, dead zone formation due to improper mixing, available free water decreases with time as the sugar concentration increases and the product inhibition of the cellulases has a significant effect on the hydrolysis efficiencies (Zhang et al., 2010). To address these concerns, fed-batch methods were proposed where solids were loaded at regular intervals so that the mixing is not impacted and can yield more glucose at high-solids loaded (da Silva Martins et al., 2015; Liu et al., 2015). To the best of our knowledge, no previous work reported solids loading exceeding 40%.

The overall goal of this study was to provide a holistic view of the effect of solids loading for the lignocellulosic ethanol production through experimental, economic and environmental perspectives. The first objective of this study was to evaluate the effect of solids loading (19%, 30%, and 45%) on lignocellulosic biomass (Corn stover and wheat straw) for enzymatic hydrolysis and ethanol fermentation. The second objective was to use the experimental data from this work in conjunction with other reported literature and develop process models to analyze the techno-economic feasibility of a biomass processing facility with a capacity of 60,000 dry MT/year. Sensitivity analysis was performed on the several factors including, capacity, ethanol price, biomass cost, and enzyme cost. The third objective was to use the mass and energy balance data from the techno-economic studies to investigate environmental impacts through a life cycle assessment.

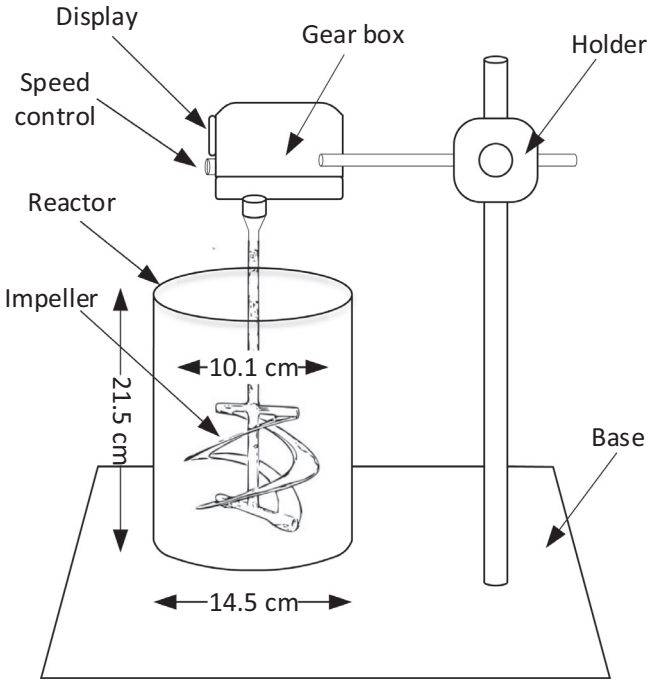

Fig. 1. Schematic diagram of the reactor used in this study to carry out enzymatic hydrolysis and fermentation.

2. Materials and methods

2.1. Biomass

Wheat straw (WS) and corn stover (CS) were considered for the enzymatic hydrolysis and fermentation studies including. The dilute acid pretreated biomass was obtained from a pilot facility at Boardman, Oregon. The composition of the pretreated biomass was measured according to the NREL procedures (Sluiter et al., 2008; Sluiter et al., 2012). The obtained biomass was washed with three folds' water (W/W) and the pH was adjusted to 5.5 using sodium hydroxide. The pH adjusted and washed biomass was squeezed with hand press to remove additional water and air dried at ambient temperatures until the moisture content was 30% (W/W) (Sluiter et al., 2008; Sluiter et al., 2012). This air-dried biomass was used for all the experiments and further analysis. All experiments were conducted in triplicates.

2.2. Reactor

A stainless reactor with 3 L working volume was used for enzymatic hydrolysis and fermentation. The overall volume was 3.5 L with an internal diameter of 14.5 cm and a height of 21.5 cm. A helical impeller with 10.1 cm diameter was used in the reactor to support complete mixing (Fig. 1). The helical impeller was driven by IKA impeller drive (model: EUROSTAR 60 CS1) which could control impeller speed. The impeller rotational speed was set at 150 rpm for hydrolysis process (He et al., 2014). The reactor was placed in a water bath at 50 °C for enzymatic hydrolysis, and 30 °C for the fermentation process.

2.3. Enzymatic hydrolysis

Three fed-batch enzymatic hydrolysis experiments were conducted for the two biomasses (WS and CS). The first experiment used WS with a final solid loading of 19% w/w. The experiment was started with 10% solids and remaining biomass was added in two increments of 4.5% w/w at 3 h intervals. For the second experiment, WS was initiated with 20% (W/W) solids and then remaining biomass was added in two increments at 3 h intervals to reach a final solids content of 30% (W/W). Third fed-batch enzymatic hydrolysis was conducted using corn stover initiated with 30% (W/W) solids. The remaining biomass was added at 4 h intervals to make up to 45% solids. The cellulose enzymes were donated by Novozymes (Ctec2) and were added at the rate of 20 mg protein/g glucan in a single dose at the start of the experiment. This was done to achieve high enzymatic hydrolysis rates initially to liquefy biomass and reduce the insoluble solids content. All the experiments were conducted in triplicates and samples were taken at every 3 h for the first 24 h; subsequently, the sampling frequency was decreased to one sample every 24 h. The samples were centrifuged at 10,000 rpm for 5 min and the supernatant was stored at −20 °C until further analysis using HPLC.

2.4. Fermentation experiments

Active dry yeast, *Saccharomyces cerevisiae*, from BIO-FERM® XR was inoculated at a concentration of 1.0 g/L to the enzymatically hydrolyzed slurry. Urea (1.0 g/L) was added to provide nitrogen requirements of the yeast. Tetracycline (stock solution: 5 mg in 70% ethanol) was added at a rate of 400 µl/L from the stock solution to limit the bacterial activity. After inoculation with yeast and other chemicals as described above the enzymatically hydrolyzed slurry was fermented at 30 °C for a maximum period of 120 h. The rotational speed of the impeller was reduced from the enzymatic hydrolysis experiments to 30 rpm. Samples were taken every 3 h for the first 24 h and subsequently once in a day. The samples were centrifuged and stored until further analysis as described above.

2.5. Analytical methods

The stored samples from enzymatic hydrolysis and fermentation experiments were analyzed for various sugars and ethanol concentration using HPLC. Biorad Aminex HPX-87H column was used for the analysis which was equipped with an appropriate