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Research Article

Fermentation technology to improve productivity in dry grind corn process for bioethanol production

Deepak Kumar, Ankita Juneja, Vijay Singh*

Agricultural and Biological Engineering Department, University of Illinois at Urbana-Champaign, 1304 W. Pennsylvania Avenue, Urbana, IL, United States

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ABSTRACT

High solid fermentation during bioethanol production is a promising process engineering strategy to reduce total energy use and water requirements, and to improve productivity. However, ethanol toxicity at higher concentrations restricts the corn solids to 30–32% (*w*/w) during dry grind corn ethanol process. This work, using in situ ethanol removal, results in two big improvements in the fermentation process: 1) achieve complete fermentation of high solids slurries (up to 42%) at typical commercial enzyme dosages, and 2) fasten the fermentation process for currently used process with 32% solids. Application of vacuum at optimal times during fermentation (1 h at 12, 24, 36, and 48 h) of 40% corn solids resulted in complete fermentation, compared to about 12% residual glucose in the conventional process. The ethanol yield of 0.42 L/kg of dry corn with about 80% ethanol conversion efficiency was 88% higher than that of the conventional process at 42% solids (0.22 L/kg dry corn). Application of 1.5 h of vacuum at 18 and 24 h of fermentation with 32% solids resulted in high fermentation rates and decreased the fermentation time by more than 50%. Shorter fermentation times can allow processing of more material with the same equipment and allow smaller fermentation tanks in new plants, which would lead to both, lower capital and operating cost.

1. Introduction

The transportation sector is the second largest consumer of energy in the United States, and more than 95% of energy in this sector is derived from fossil fuels. Bioethanol, produced from either sugars, starch or plant fibers, is considered as promising alternative to fossil fuels, yields high net energy ratio and produce significantly less greenhouse gas emissions [1]. With about 15.25 billion gal production in 2016 (58% of the global total), United States is the biggest bioethanol producer in the world. Most of the bioethanol in the United States is produced from corn, and dry grind processing is the most commonly used method. In the year 2014, about 38% (137.1 million MT) of total corn produced in the United States was used by the dry grind process [2].

Conventional dry grind process includes size reduction, liquefaction, saccharification, fermentation, distillation, and coproduct recovery (Fig. 1). Cleaned corn is ground to reduce particle size and mixed with process water to form a slurry with desired solids content. The α-amylase enzymes are added to the slurry to convert starch into soluble dextrins at high temperatures (80–90 °C), during the liquefaction process. The liquefied slurry is cooled and transferred to fermentors. In the fermentors, glucoamylase enzymes convert dextrins to glucose, which is simultaneously fermented to ethanol by yeast. This combined process is known as simultaneous saccharification and fermentation (SSF). SSF avoids osmotic stress in as glucose is fermented to ethanol and not allowed to accumulate. At the end of fermentation, the resulting mixture of water, ethanol, and non-fermentable components is processed through series of distillation columns and molecular sieves to recover pure ethanol. The whole stillage from the bottom of the distillation column is processed in downstream operations (centrifugation, evaporation, and drying) to get a feed product marketed as distillers dried grains with solubles (DDGS).

As fuel ethanol demand is tied to oil prices, wholesale ethanol price has varied widely between $1.18 and $3.51 per gal (average $1.96/gal) in the last 10 years [3]. The price fluctuations, along with predictions of policy changes create uncertainty about the economic viability of bioethanol industry. Ethanol industrial and academic researchers have engaged in identifying technologies that can further save energy, improve productivity and maximize process economics to ensure commercial viability even with low ethanol selling prices ($1.44/gal in 2016) [4–8].

Fermentation is the core of the whole process and any improvement in this unit operation can benefit the plant productivity and economics. One of the major challenges and topic of research in corn fermentation

* Corresponding author.
E-mail addresses: kumard@illinois.edu (D. Kumar), ajuneja@illinois.edu (A. Juneja), vsingh@illinois.edu (V. Singh).

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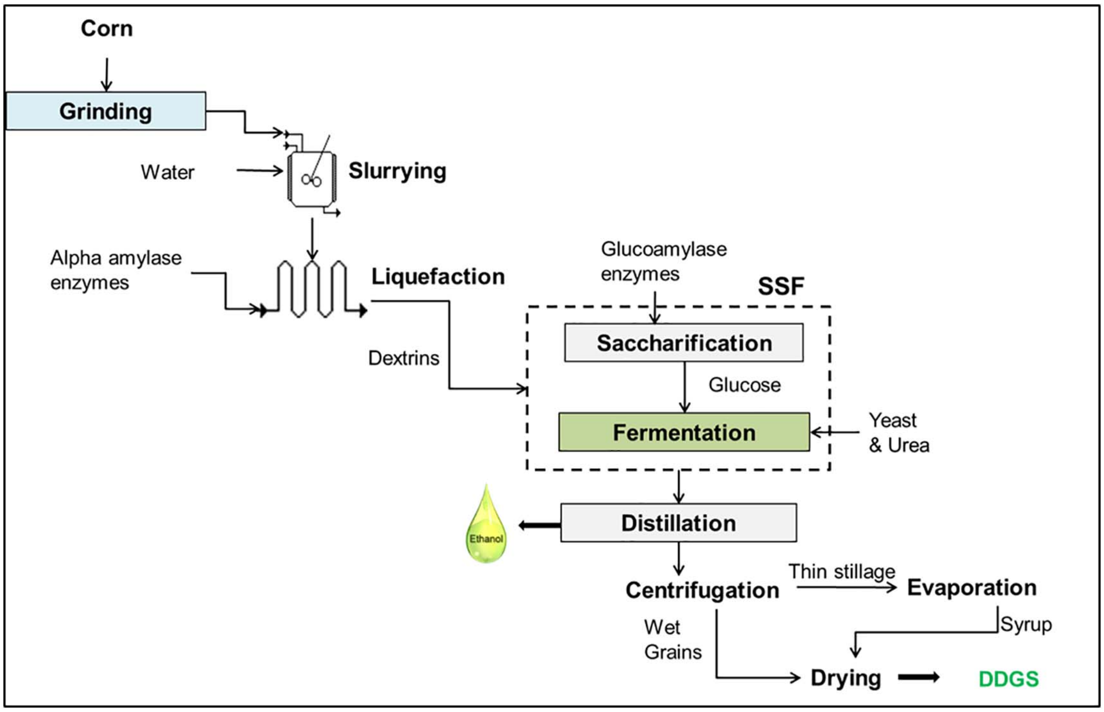

Fig. 1. Schematic of dry grind process for ethanol production from corn.

is corn solid loadings (percentage of corn solids during slurry formation before liquefaction), which directly affects the final ethanol concentrations. Ethanol recovery and downstream processing, which account for about 40–45% of total thermal energy use in ethanol process, is directly dependent on final ethanol concentrations. High solids use can potentially reduce energy use in the process (less fluid to heat and cool in the overall process, less energy to recover ethanol and coproducts, less heat demand for drying of DDGS) and lower the capital cost due to smaller size equipment. Another major advantage of high solids use is a reduction in water consumed to produce ethanol. During dry grind process, each gallon of ethanol produced requires 16 lL (4.2 gal) of water [9]. Considering the current ethanol production volumes (15.25 billion gal), even a small reduction of 0.5 L water per gallon of ethanol produced can save more than 7.5 billion L of water throughout ethanol industry in the United States [10]. Use of high solids during fermentation could also reduce thin stillage production, which would potentially lower the buildup of non-metabolized components (e.g., acetic acid, lactic acid, and glycerol), and reduce fouling in the evaporators [11].

However, the solids loadings during the ethanol process are restricted to 30–32% *w*/w due to challenges of high viscosities of slurries, and yeast stress by high glucose and ethanol concentrations. High solids yield results in high glucose concentrations which causes osmotic stress on yeast and reduce its performance [12]. Glucose inhibition has been reported to occur for concentrations above 15% (*w/v*), with almost complete inhibition of yeast growth at 40% (w/v) glucose concentration [12, 13]. In addition, high sugar concentrations lead to higher than optimal ethanol titers that inhibit yeast growth, partly due to disruption of the cell membrane, and thereby limit ethanol yields [14–17]. The SSF process addresses glucose inhibition issue to some extent. The issue of glucose inhibition can also be addressed by other approaches like the use of granular starch hydrolyzing enzymes (GSHE enzymes) or amylase corn (corn endosperm contain α-amylase) [5]. In situ removal of ethanol during the fermentation, is one potential approach that can allow to maintain the ethanol concentration below inhibitory levels and retain yeast viability and performance [11, 17–20]. Ethanol can be removed from fermentation broth under reduced pressure (vacuum), which allows ethanol evaporation at the normal fermentation temperatures (32–34 °C), without affecting the yeast health. Some earlier studies on ethanol production have concluded that fermentation can be improved by applying vacuum throughout the fermentation or in cycles. However, all of those studies were conducted using continuous fermentation or glucose as a feedstock [17, 19, 20]. Almost all commercial dry grind ethanol plants use corn as a feedstock and run batch fermentations. Shihadeh et al. [18, 21] combined the use of GSHE enzymes and vacuum-assisted fermentation in a batch process and achieved higher ethanol yields at 40% solids. However, higher ethanol yields were obtained only at a 3× dosage of GSHE enzymes, which would significantly increase the process costs. No improvements were noticed at enzyme manufacturer recommended enzyme dosage [18]. It is also important to note that most of the commercial corn ethanol plants work with conventional dry grind process (α-amylase and glucoamylase enzymes) and use of GSHE technology is limited.

The objective of this work was to evaluate the process conditions (vacuum application) to achieve efficient fermentation at high solids (40% or more) during conventional dry grind process at regular (recommended by manufacturer) enzyme dosages. Other than the successful use of high solids, this work also investigates the use of ethanol removal technology to improve yeast productivity at 32% corn solid loadings and shorten the fermentation time. The shorter fermentation time can improve the ethanol plant output, as well as reduce the capital costs.

2. Materials and methods

2.1. Materials

Conventional yellow dent corn harvested in October 2015, was obtained from a commercial seed company. Corn was hand-cleaned and sieved over a 4.76 mm (12/64 in.) round-hole screen to remove damaged kernels and foreign materials. The cleaned corn was stored in a refrigerator at 4 °C until analysis. Ground corn moisture content was determined by drying samples in a hot air oven at 135 °C for 2 h (Approved Method 44–19.01, AACC International, 2010). Starch