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Optimizing the enzyme loading and incubation time in enzymatic hydrolysis of lignocellulosic substrates

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HIGHLIGHTS

- ▶ A simple model gives estimated costs of lignocellulosic sugars.
- ▶ Variables include enzyme loading and incubation time.
- ▶ Those variables can be optimized for lowest sugar cost.
- ▶ Optimized values can be expressed in terms of three unit costs.
- ▶ Steam-exploded pine feedstock provided data for a worked example.

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ABSTRACT

A mathematical model for costing enzymatic hydrolysis of lignocellulosics is presented. This model is based on three variable parameters describing substrate characteristics and three unit costs for substrate, enzymes and incubation. The model is used to minimize the cost of fermentable sugars, as intermediate products on the route to ethanol or other biorefinery products, by calculating optimized values of enzyme loading and incubation time. This approach allows comparisons between substrates, with processing conditions optimized independently for each substrate. Steam-exploded pine wood was hydrolyzed in order to test the theoretical relationship between sugar yield and processing conditions.

1. Introduction

Global production of ethanol almost doubled over a period of six years, from 12.1 billion gallons in 2005 to 22.9 billion gallons in 2011 (Renewable Fuels Association, 2006, 2012). Most of this ethanol was produced by fermentation of sugars sourced from grains in North America or sugarcane in South America, and most of it was used for transport fuels. Large annual increases will become increasingly difficult to repeat in the future, at least while ethanol production is based on feedstocks that are also used for food production. Lignocellulosic feedstocks have greater potential for expansion of the bio-based ethanol industry (Van Dyk and Pletschke, 2012). Several recent techno-economic studies have discussed the obstacles involved in the development of lignocellulosic ethanol (Aden and Foust, 2009; Piccolo and Bezzo, 2009; Huang et al., 2009; Gnansounou and Dauriat, 2010; Humbird et al., 2010; Stephenson et al., 2010; Gonzalez et al., 2011; Ljunggren et al., 2011). Two of the outstanding obstacles identified in those studies are the slow rate of enzymatic hydrolysis of cellulose and the cost of the enzymes. Those two obstacles are, to some extent, interdependent. This paper explores the interdependence and identifies the general principles involved in optimizing the balance to minimize production costs.

While enzyme consumption contributes just US$0.05 to the cost of producing a gallon of corn ethanol, it might add as much as US$0.34 to the cost of producing a gallon of lignocellulosic ethanol (Humbird et al., 2011). A common approach to reducing enzyme costs per unit of ethanol has been to increase the incubation time so as to increase the yield of sugar per unit of enzyme. This approach has limitations as increasing the incubation time leads to increased capital expenditure to cover the additional storage capacity. For example, Humbird et al. (2011) designed a plant to process corn stover for annual production of 80 million gallons of ethanol. In their design, incubation of the suspended solids over a period of 84 h, through enzymatic hydrolysis and fermentation,

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