



# A modified method for calculating practical ethanol yield at high lignocellulosic solids content and high ethanol titer

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## ABSTRACT

A modified method for calculating practical ethanol yield in the simultaneous saccharification and fermentation (SSF) at high lignocellulosic solids content and high ethanol titer is proposed considering the liquid volume change caused by high titer ethanol generation and the water consumed during cellulose degradation. This modified method was applied to determine the practical ethanol yields of several practical SSF operations and the results compared to those using the conventional method. The results show that the liquid volume increase with ethanol formation during SSF was approximately five times greater than the volume decrease due to water consumption during cellulose degradation. Furthermore, the practical ethanol yields calculated using traditional method were underestimated and the underestimated errors increased with the increasing ethanol titer. The present work may provide a convenient and accurate method for calculating practical ethanol yield in a high solids and high ethanol titer SSF systems.

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## 1. Introduction

One of the major technical barriers for commercialization of cellulosic ethanol is the high energy cost of ethanol distillation from the low ethanol titer fermentation broth (Galbe et al., 2007). Therefore, simultaneous saccharification and ethanol fermentation (SSF) at high solids loading of the pretreated lignocellulose feedstock became a common practice to obtain higher ethanol titer (Varga et al., 2004; Jorgensen et al., 2007; Zhang et al., 2010a). At present, most ethanol yield calculation methods for SSF operations at either high or low solids loading were based on Eq. (1) as follows:

$$\text{Ethanol yield (\%)} = \frac{[EtOH]_f - [EtOH]_0}{0.511 \times f \times [Biomass]_0 \times 1.111} \times 100\% \quad (1)$$

where the term  $([EtOH]_f - [EtOH]_0)$  indicates the ethanol produced during the fermentation in grams per liter of the fermentation broth (g/L, w/v) from the beginning of the fermentation  $([EtOH]_0)$  to the end  $([EtOH]_f)$ ,  $[Biomass]_0$  is the dry biomass concentration in grams per liter of the fermentation broth (g/L, w/v) at the beginning of the fermentation,  $f$  is the cellulose fraction of dry biomass (g/g, w/w), 0.511 is the conversion factor for glucose to ethanol based on stoichiometric biochemistry of yeast, 1.111 is the conversion factor for cellulose to equivalent glucose.

In Eq. (1), a hidden assumption is that the liquid volume of the SSF system is constant, thus the term  $([EtOH]_f - [EtOH]_0)$  used for

measuring the produced ethanol is on the same volume basis. However, for a closed SSF system with the recovery of the vaporized water by the condenser of the bioreactor, the total liquid volume does change: it increases with the liquid ethanol generation and decreases with the water consumption in the hydrolysis of cellulose. The volume change caused by glucose released from cellulose could be neglected because almost all the glucose was transformed into ethanol in the final broth (Zhu et al., 2011). The constant volume assumption can only be valid when both the ethanol produced and the water consumed are negligible. When the high ethanol titer from the SSF is required, i.e., 5–7% (w/w) ethanol in the fermentation broth, the high solids loading of lignocellulose feedstock may reach 30–40% by the weight percentage (grams solids in 100 g of the total SSF materials, w/w). The term  $([EtOH]_f - [EtOH]_0)$  in Eq. (1) is no longer accurate to apply because the volume unit of  $[EtOH]_f$  and  $[EtOH]_0$ , the liter “L”, does not mean the same volume: the “L” in  $[EtOH]_f$  indicates the mixture volume of the water (after water loss in enzymatic hydrolysis) and the ethanol produced in the SSF, while the “L” in  $[EtOH]_0$  only indicates the initial water volume with minor initial ethanol. In this situation, the ethanol produced and even the water consumed can not be simply ignored and should be taken into account in the ethanol yield calculation.

Most previous ethanol yield calculating methods were based on the constant liquid volume assumption without considering the ethanol produced and the water loss (Suryawati et al., 2008; Faga et al., 2010; Zhang et al., 2010a, 2010b, 2011). As a result, the reported ethanol yields might be lower than they should be, because

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