BIOMASS AND BIOENERGY 74 (2015) 224–232

Available online at www.sciencedirect.com

ScienceDirect

http://www.elsevier.com/locate/biombioe

The effects of screw elements on enzymatic digestibility of corncobs after pretreatment in a twin-screw extruder

Jun Zheng [a], *Kim Choo* [a,b], *Lars Rehmann* [a,*]

[a] *Department of Chemical and Biochemical Engineering, University of Western Ontario, 1151 Richmond Street, London, Ontario N6A 3K7, Canada*

[b] *Lambton College, 1457 London Road, Sarnia, Ontario N7S 6K4, Canada*

ARTICLE INFO

Article history:
Received 21 November 2014
Received in revised form
20 January 2015
Accepted 25 January 2015
Available online

Keywords:
Cellulosic ethanol
Zea mays
Lignin
Biorefinery
Alkali

ABSTRACT

Extrusion of lignocellulosic biomasses can be an effective physical continuous pretreatment method towards bioethanol production. Extrusion processes would typically precede enzymatic cellulose saccharification in a given pretreatment. The screw configuration determines the functionality of the extruder and different screw elements (conveying, kneading and reverse) can have different effects on enzymatic digestibility. This study investigates the effects of individual functional screw elements on enzymatic digestibility after extrusion. It was found that extrusion enhanced enzymatic digestibility under all tested condition. Reverse and kneading screw elements however resulted in lignin redistribution over the cellulose fibres, blocked pores (shown via SEM) and resulted in less digestible biomass, compared to conveying screw elements. Lignin removal via NaOH reversed this effect and the highest digestibility was found for biomass extruded in the presence of reverse screw elements (the most severe conditions tested in this study), indicating that lignin redistribution can counteract otherwise positive effects of extrusion pretreatment.

1. Introduction

Long-term economic, environmental and geopolitical concerns associated with the use of and access to fossil fuels, have resulted in increased research on alternative, nonpetroleum-based sources of liquid fuels in the past decades [1] and lignocellulosic-based biofuels are considered a logical evolution of current starch-based ethanol processes [2–4].

Conversion of lignocellulosic biomass into fermentable sugars for further biofuel production is hindered by the close association of cellulose, hemicelluloses and lignin [5]. Typically pretreatment steps are required to separate the three main fractions and to increase enzymatic accessibility to the cellulose during the subsequent hydrolysis step [6,7]. A wide range of pretreatment methods have been studied generally on different lignocellulosic biomass sources for improving their hydrolysis, such as steam explosion, organosolvent and

* *Corresponding author*. Tel.: +1 519 661 2111x89008; fax: +1 519 661 3498.
E-mail address: lrehmann@uwo.ca (L. Rehmann).
http://dx.doi.org/10.1016/j.biombioe.2015.01.022

lime treatment. However, most of these technologies have high processing cost and can produce sugar degradation products due to the use of severe reaction conditions [8,9]. Recently, the extrusion process, commonly used in the polymer industry, has been expanded as a continuous physical pretreatment method towards ethanol production by means of heat, compression and shear forces, which can disrupt and modify biomass structures during its passage through an extruder. Several studies have shown that significant improvements on sugar recovery at low cost, and good adaptability to different process modifications were obtained from the extrusion pretreatment [10–13].

The most significant factor influencing the product transportation, extent of mixing, residence time distribution, product properties and mechanical energy consumption during extrusion processing is the screw configuration. Screw-configurations are highly flexible and have to be specifically developed for each process. Screw elements can vary in pitch, stagger angle and length, and are typically categorized based on their functionality as conveying, kneading and reverse elements. Conveying screw elements largely function to transport and compress the bulk material. The number of flights per unit length, as well as pitches or helix angles can be varied, influencing the residence time and the degree of fill. Kneading elements have a significant mixing and shearing effect combined with weak forward feeding characteristics; while reverse screw elements push the material backward with a reverse flight, producing high local pressures. Reverse screw elements exert extensive mixing and shearing effects on the biomass and also exert a strong axial compression along with upstream conveying screw elements [14–19]. The reverse screw has the highest severity and the conveying screw element has the lowest severity based on its effect on the biomass. With different screw configurations, a variety of functions and processes, such as material conveying, crushing, mixing, melting, shearing, chemical reactions, drying and liquid–solid separation can be conducted in a single unit [20]. Several studies employed twin-screw extruders with complex screw configurations to maximize pretreatment efficiency. Subsequently, the sugar yields were shown to be much higher than untreated materials. However, none of these studies investigated the effects of individual functional screw elements on enzymatic digestibility, rendering rational screw design and generally applicable conclusions challenging. Biomass is exposed to heat, compression and shear forces, leading to physical disruption and chemical changes during the extrusion process. Lignin in particularly can melt and re-condense on the surface of the biomass, thus reducing enzymatic digestibility. It can be removed via sodium hydroxide (NaOH), often used as a pretreatment process from lignocellulosic feedstocks [21,22]. The same technique can be used to evaluate the contribution of possibly re-located lignin on biomass digestibility. The objective of this research was therefore to investigate the effect of individual functional screw elements on the subsequent digestibility of extruded biomass. An extruder was therefore configured with conveying screw elements only, and subsequent a single element was replaced with functional screws in order to isolate the effect of a single screw.

2. Materials and methods

2.1. Materials

Sweet corn (*Zea mays*) was harvested from the Thoma farm near Chatham, Ontario, Canada (42.453367, −82.241060) during the fall harvest in 2013. Kernels were removed at the R&D facilities of GreenField Specialty Alcohols (December 2013, Chatham, Ontario). Corncobs were cleaned and grinded to particle sizes of 0.6–0.76 cm and drying to the mass fraction of 0.08 water in the material. The biomass was stored at 4 °C and processed via extrusion within less than 4 weeks. The composition of structural carbohydrates and lignin of untreated and treated corncobs were determined according to NREL methods outlined by Sluiter et al. [23]. All composition values in this study were based on dry matter. Before extrusion pretreatment, ground corncobs were adjusted by adding water to retain a moisture content of 40%.

All other chemicals (e.g., citric acid, sodium hydroxide anhydrous, sodium citrate, xylose and glucose) were of analytical grade and purchased from Sigma–Aldrich (USA). Cellic® CTec2 cellulose enzyme was obtained from Novozyme (Denmark).

2.2. Twin screw extruder

Experiments were carried out with a pilot-scale Leistritz co-rotating twin-screw extruder (American Leistritz Extruder Corp, USA), which is driven by a 37 kw (50 HP) DC motor. The extruder has twelve modular barrels, each 200 mm in length. Different twin-screws have segmental screw elements each between 15 mm and 90 mm in length. Thermal induction heating from electricity and cooling water circulation are used for barrel heating and cooling, respectively. Feed flow rate, screw speed and barrel temperature were monitored. The ground corncobs were fed into the extruder by a gravimetric feeder (Brabender Technology Company, Canada) and fixed at a mass flow rate of 4 kg h^{-1} for all experiments. The operating conditions of the extrusion process were maintained at a screw speed of 1.67 Hz and a barrel temperature of 75 °C. Fig. 1 shows the schematic modular barrel of the twin-screw extruder. Three screw configuration profiles were tested in this study as shown in Fig. 2. All conveying screw elements were configured to have a constantly decreasing pitch to enhance the degree of fill in Profile 1. A conveying screw element with a pitch of 30 was replaced by two forward kneading screw elements and a combination of a kneading and reverse screw element in zone 10 for Profiles 2 and 3, respectively. A circular die of 1.98 cm diameter was employed for all extrusion experiments.

2.3. Enzymatic hydrolysis

Batch enzymatic hydrolysis was carried out in 20 cm^{-3} screw capped glass vials with Cellic® CTec2 enzyme (Novozyme, Denmark). The enzyme activity was measured to be 168.2 FPU cm^{-3} (Filter Paper Unit) according to NREL standard procedures [24]. Applied enzyme loadings were varied from 2.85 to 3.59 FPU g^{-1} of the extruded corncobs determined