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Integrated pulping and biorefining of palm residues based on semichemical cooking and fiber fractionation

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HIGHLIGHTS

- Development of a new strategy for complete utilization of palm residues.
- Cellulose enzymatic digestibility of separated parenchyma cells were significantly improved.
- Obtained vascular bundles were efficiently converted to pulp.
- Properties of RPS pulp were all improved without loss of physical strength.

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ABSTRACT

This work validates a new strategy for complete utilization of palm residues by separating fibers and parenchyma for the respective purposes of pulping and biorefining. The parenchyma cells were fractionated from royal palm sheath (RPS) after neutral sulfite semichemical (NSSC) cooking for producing fermentable sugars, leaving vascular bundles for manufacturing pulp and paper. Parenchyma cells could be readily and completely screened out prior to defibration. They were more digestible by cellulase than vascular bundles or the pulp derived from them. Cellulose enzymatic digestibility (CED) of parenchyma cells rapidly reached 82% in 12-h hydrolysis and finally up to 92%. The CEDs of parenchyma were maintained around 90% at a medium solid consistency, 12% (w/w). The average length, retention and drainability of RPS pulp were all improved without loss of physical strength after removing parenchyma. This work may help establish a new platform for maximizing the utilization efficiency of parenchyma-rich biomass.

1. Introduction

Palm residues, including fronds, trunks and empty fruit bunches, are one of the most available lignocellulosic biomass sources in tropical areas around the world (Singh et al., 2012). Manufacturing pulp and paper is the most popular way to convert palm residues into value-added products (Daud and Law, 2011; Singh et al., 2012). Various processes such as organic solvent, soda/anthraquinone, alkaline sulfite-anthraquinone, alkaline peroxide mechanical and neutral sulfite semichemical (NSSC) processes have been developed for pulping of palm residues (Rodríguez et al., 2008; Jiménez et al., 2009; Khristova et al., 2005; Arniza et al., 2006; Wanrosli et al., 2007). However, the parenchyma cells (pith) were a major barrier that hampered the progress for efficient utilization of palm residues. (Daud and Law, 2011). Like sugarcane bagasse, reed stalk and many other non-wood pulping feedstocks, palm residues have a high content of parenchyma, *e.g.* in oil palm fronds and trunks, parenchyma cells account for 30% and 60% of the biomass, respectively (Singh, 1995; Daud and Law, 2011). Presence of parenchyma cells increases chemical consumption, decreases pulp yield and fiber length, and causes operational difficulties especially in washing and papermaking stages (Sanjuán et al., 2001). Therefore, a depithing procedure is required prior to pulping (Daud and Law, 2011). The separated parenchyma pith can be further combusted to generate heat power. However, direct combustion decreases the utilization efficiency of biomass, increases the investment costs and causes environmental contamination (Küçük and Demirbaş, 1997).

A more promising approach for utilizing parenchyma cells is to convert their polysaccharide components, mainly cellulose and hemicelluloses, into simple sugars that can be fermented to biofuels and value-added products. Parenchyma biorefining, a method of complete utilization of non-wood biomass, also relieved supply

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competition of raw materials in the pulp and paper industry. Recently, the potencies of parenchyma biorefining have been investigated; *e.g.* enzymes and single cell proteins were efficiently produced from coir and sugarcane bagasse pith (Jabasingh, 2011; Rodríguez-Vázquez and Díaz-Cervantes, 1994). Furthermore, Zhao et al. studied the bioconversion of bagasse parenchyma into ethanol and lignin products, leaving fibers for papermaking (Zhao et al., 2011). However, there are still some practical difficulties for the use of parenchyma due to the absence of a thermochemical treatment prior to depithing, especially the incomplete depithing (Sharma et al., 2000) and their low enzyme digestibility (Molina et al., 1984).

In this study we developed and validated a new strategy for the integrated pulping and biorefining of parenchyma-rich biomass mainly based on semichemical cooking and fiber fractionation (Fig. 1). Palm residues are chemically cooked and divided into two distinct size fractions: vascular bundles and parenchyma pith. The bundle fractions are then mechanically defibrated with an optional subsequent bleaching to produce pulp and paper. Meanwhile, the pith fractions are subjected to enzymatic hydrolysis and yeast fermentation to produce biofuels and biochemicals.

2. Methods

2.1. Materials

Royal palm sheath (RPS) was collected from freshly fallen leaves in South China Botanical Garden (Guangzhou, China). Prior to use, the sheath was air-dried, cut into chips (30 × 20 mm) and stored at 4 °C. Cellulase (Celluclast 1.5L) and β-glucosidase (Novozym 188) were purchased from Sigma–Aldrich (St. Louis, US). All chemicals used in this study were of analytical grade.

2.2. Neutral sulfite semichemical (NSSC) pulping

The cooking stage of the NSSC process was conducted in a 4-L KRK rotary digester. For each cooking, 300 g (on oven-dry basis) RPS chips were treated with 6% (w/w) Na_2SO_3 and 2% (w/w) Na_2CO_3 at a liquid-to-solid ratio of 4 L/kg. The cooking temperature was ramped to 175 °C in 60 min and maintained for 30 min. After cooking, the solids were mechanically disintegrated for 10,000 revolutions at 2% (w/w) consistency in a standard laboratory pulp disintegrator. Finally, the solids were thoroughly washed with deionized water by filtering with a 400-mesh nylon screen.

The defibration stage was executed in a KRK high-consistency disc refiner using a two-stage process. The plate (Φ305 mm) gap was 0.45 mm in the first stage and 0.1 mm in the second. Solids retained on a 14-mesh screen were considered as reject and those passed but retained on a 400-mesh screen were accepted. For comparison, the accepted pulp was further refined in a PFI refiner according to TAPPI T 248 to improve pulp quality and uniformity.

2.3. Fiber fractionation

Fiber fractionation was performed after cooking but prior to defibration. The disintegrated solids were fractionated in a Bauer-McNett fiber classifier (Andritz, US) according to Tappi T233 cm-95, using screen sizes of 14, 30, 50, 100 and 200 mesh. The six fractions were carefully collected by filtering through the 400-mesh nylon screen. The mean and the standard deviation from triplicates were reported.

2.4. Microscopic observation

RPS chips were sequentially treated with boiling water and 30% H_2O_2/acetic acid (1:1, v/v) to release individual cells. The sheath cells, RPS pulps and fractions were stained with Herzberg Stain and examined with a Model BX51 microscope (Olympus, Japan). Cut sections (1 × 1 × 10 mm) and dispersed pulp samples were freeze-dried and sputter-coated with gold for scanning electron microscopy (SEM). SEM micrographs were obtained using a FEI quanta 200 microscope (Hillsboro, US) operating at a high vacuum of $3.72e^{-4}$ Pa.

2.5. Enzymatic hydrolysis

Enzymatic hydrolysis was carried out by suspending the solids in acetate buffer solution (0.05 M, pH 4.8) in 150 ml Erlenmeyer flasks to a consistency of 2, 5, 7.5, 10, 12, 15 or 20% (w/w, weight percentage of solids). The pretreated solids were hydrolyzed with cellulase and β-glucosidase at 50 °C, pH 4.8 and 150 rpm for 72 h. About 0.3 mL of hydrolysate was withdrawn after 2, 6, 12, 24, 48, 72 h, heated at 90 °C for 10 min, cooled and centrifuged at 10,000*g* for 5 min. The glucose concentration in the supernatant was determined by using glucose assay kits (Rongsheng-biotech, China). Cellulose enzymatic digestibility (CED) was defined as the percentage of glucan hydrolyzed to glucose based on the initial glucan content in the pretreated biomass. All CED data reported are average values from two independent hydrolysis experiments.

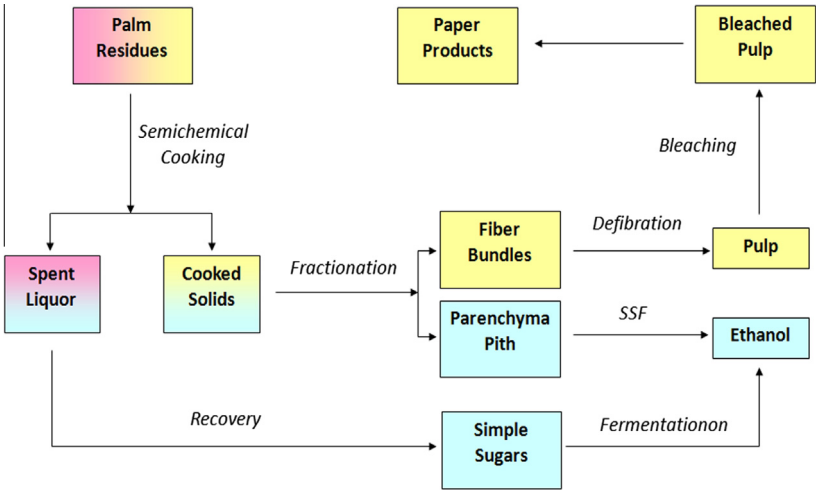

Fig. 1. Schematic diagram of the integrated pulping and biorefining for utilization of palm residues.