Resources, Conservation & Recycling 129 (2018) 27–35

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Valorisation of textile waste by fungal solid state fermentation: An example of circular waste-based biorefinery

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ARTICLE INFO

Keywords:
Aspergillus niger
Cellulose hydrolysis
Circular textile
Fungal cellulase
Solid state fermentation
Textile waste recycling

ABSTRACT

This study investigated the feasibility of using textile waste as feedstock for cellulase production through solid state fermentation. *Aspergillus niger* CKB was selected with the highest cellulase activity (0.43 ± 0.01 FPU g^{-1}) after 7 days of cultivation on pure cotton. Material modification techniques including autoclaving, alkali pretreatment and milling were applied on six types of textiles with various cotton/polyester blending ratios. The results indicated that using autoclaved textile blending cotton/polyester of 80/20 led to the highest cellulase activity (1.18 ± 0.05 FPU g^{-1}) with CMCase, β-glucosidase and avicelase activities of 12.19 ± 0.56 U g^{-1}, 1731 ± 4.98 U g^{-1} and 2.58 ± 0.07 U g^{-1}, respectively. The fungal cellulase was then extracted and applied to textile waste hydrolysis, in which a sugar recovery yield of 70.2% was obtained. The present study demonstrates a novel circular textile waste-based biorefinery strategy with recovery of glucose and polyester as value-added products.

1. Introduction

Disposal and management of textile waste have risen increasing global concerns. Textile waste includes the waste generated from streams of fibre, textile and clothing manufacturing process, commercial service and consumption (Pensupa et al., 2017). The worldwide textile consumption increased from 47 million tonnes to 90 million tonnes in the recent decade (Shui and Plastina, 2013), and it is forecasted to keep rising along with the population growth and general increase of household purchasing power (Statista, 2016). The annual generations of textile waste in China, the United Kingdom and the United States are estimated to be 26.0, 1.7 and 15.1 million tonnes, respectively (SMaRT, 2016; WRAP, 2016; Yang and Yuan, 2016). On global average, 32 kg of textile wastes are discarded per capita each year, of which around 85% end up in landfill (EPA, 2015). Since the post-consumer textile waste is not easily decomposed, accumulation of such waste would lead to infectious diseases, attract pests and spread odors in the environment (Gordon and Hsieh, 2006). According to the evaluation by Waste & Resource Action Programme (UK), 95% of landfilled textile waste is recyclable, whereas only 14–15% recycling rate has been achieved at this stage (WRAP, 2016). Nowadays, textile waste recycling mainly relies on second-hand dumping and reprocessing into rags, which actually do not capture values from textiles (Esteve-Turrillas and de la Guardia, 2017; Woolridge et al., 2006).

Biorefinery is the process to convert biomass to fuels, valuable chemicals and materials (Clark et al., 2006). As an alternative to fossil fuels, renewable biomass sources and organic fraction of waste streams would be major contributors in the future supply (Garcia-Nunez et al., 2016; Smith et al., 2015). Cellulose contributes to approximately 35–40% of textile waste, which could become a potential feedstock for production of biological products (*e.g.* ethanol and biogas) (Jeihanipour et al., 2010; Shen et al., 2013). Bioconversion of textile waste has been investigated recently through pretreatment and hydrolyzing cellulose to fermentable glucose. The general idea in various pretreatment technologies is to expose cellulosic fibre to cellulase by increasing surface area and removing inhibitors such as sizing agent coated on textile surface. Gholamzad et al. (2014) reported the conversion of polyester-cotton textile to ethanol via alkaline pretreatment followed by simultaneous saccharification and fermentation. Jeihanipour et al. (2013) examined a high-rate biogas production scheme from post-consumer jeans (100% cotton) through *N*-methylmorpholine-*N*-oxide (NMMO) pretreatment and anaerobic digestion, yielding 400 mL methanol g^{-1} volatile solids day^{-1}.

Degradation of highly crystalline structure of cellulose requires synergy of endoglucanases (EC 3.2.1.4), exoglucanases (EC 3.2.1.91) and β-glucosidases (EC 3.2.1.21) in a complete cellulase system. It was

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http://dx.doi.org/10.1016/j.resconrec.2017.09.024
Received 27 June 2017; Received in revised form 20 September 2017; Accepted 25 September 2017

Table 1
Fungal cellulase production by solid state fermentation.

Strain	Substrate	Moisture (%)	Time (day)	FPase activity (FPU g^{-1})	Reference
Aspergillus terreus	Rice straw	86	7	11.0	Narra et al. (2012)
Aspergillus fumigatus SK1	Oil palm trunk	80	7	3.4	Ang et al. (2013)
Trichoderma reesei RUT-C30	Horticultural waste	80	7–8	15.0	Xin and Geng (2010)
Trichoderma reesei RUT-C30	Wheat bran	37	7	3.8	Singhania et al. (2007)
Aspergillus niger P47C3	Soybean bran	60	5	5.6	Delabona et al. (2013)
Aspergillus niger NS-2	Wheat bran	60	4	17.0	Bansal et al. (2012)
Aspergillus niger	Wheat bran	50	3	2.9	Chandra et al. (2007)
Aspergillus niger USM AI 1	Sugarcane bagasse	70	2	2.3	Lee et al. (2010)
Aspergillus sp. SEMCC-3.248	Rice grass	70	5	1.1	Liang et al. (2012)

estimated that the cost of cellulase accounts for 10–40% of the total production cost in current biorefinery process (Deswal et al., 2011; Johnson, 2016). Therefore, exploring low-cost cellulase producing techniques and substrates is currently under intensive study. Microbial cellulase production using cellulosic residues via submerged fermentation or solid state fermentation have been investigated (Murthy and Naidu, 2012), and the later has greater advantages as relatively low energy consumption and simple downstream processing (Hölker et al., 2004; Soccol et al., 2017). Fungal cellulase secreted by microorganisms such as *Aspergillus niger* or *Trichoderma reesei* on horticulture waste, agriculture and kitchen waste have been studied, as summarised in Table 1. Whereas cotton-based textile waste has not been utilized as substrate and carbon source in SSF or in cellulase production.

The present study aims to develop an integrated biorefinery strategy in textile waste valorisation. Cotton-based textile waste was utilized as substrate for fungal cellulase production by solid state fermentation. The cellulase obtained was subsequently applied in textile waste hydrolysis to recover sugar and polyester (PET) for material recycling and reuse. The proposed strategy enable the capture of the embodied value of the PET fibre, which contributes to the transition of a circular textiles industry.

2. Materials and methods

2.1. Textile waste

Different types of textile waste blending of cotton and polyester provided by H & M (Hennes & Mauritz, Far East) were used as raw feedstock in this study. Pure cotton, pure PET and jeans (99% cotton and 1% elastane) were also employed. Each type was classified by component and dyestuff as listed in Table 2. Dyestuff is a category of substances for staining or coloring on fabrics.

2.2. Microorganisms

Different cellulase producing fungal strains were used in solid state fermentation. *Trichoderma reesei* ATCC 24449 was collected from American Type Culture Collection. *Aspergillus niger* N402 was obtained from Prof. David Archer in the University of Nottingham in the United Kingdom. *Aspergillus niger* CKB and *Rhizomucor variabilis* were obtained from Dr. Diannan Lu at Tsinghua University in China. *Aspergillus oryzae* was isolated from a soy sauce starter by the Amoy Food Ltd., Hong Kong (Leung et al., 2012). *Trichoderma longibrachiatum* was collected from Prof. Colin Webb from The University of Manchester in the United Kingdom. All strains were cultivated on potato dextrose agar (PDA) medium in petri dishes at 28 °C for 7 days. The spores were collected in 30% glycerol solution and stored in −80 °C freezer until use.

Table 2
Textile waste used in this study.

Component (w/w%)	Dyestuff
Pure cotton	Reactive dyestuff
Cotton/PET (80/20)	Reactive dyestuff
Cotton/PET (60/40)	Reactive dyestuff
Cotton/PET (40/60)	Reactive dyestuff
Pure PET	Disperse dyestuff
Jeans (cotton 99% and elastane 1%)	Indigo dyestuff

2.3. Textile waste modification

The textile waste used in this study were grinded into small pieces (around 0.8 × 0.8 cm^2), and pretreated by three different modification methods, *i.e.* autoclaved modification, freezing alkali/urea soaking and milling. For autoclaving pretreatment, mineral solution was added to the textile waste fabrics to adjust the desired initial moisture content and the textile waste samples were autoclaved at 121 °C for 15 min. For freezing alkali/urea soaking, textile waste fabrics were mixed with 7 w/v% sodium hydroxide and 12 w/v% urea at −20 °C for 6 h and then washed by deionized water (DI water) flushing to remove chemical residues. Collected textile samples were dried in an oven at 40 °C to constant weight. Lastly for milling modification, textile waste fabrics were milled to fine powder form (< 1 mm) by a laboratory-scale hammer crusher.

2.4. Solid state fermentation (SSF)

Fungal cellulase was produced on textile waste via solid state fermentation (SSF). For each SSF, 2 g (dry weight) of crude or modified textile waste sample was inoculated with 0.3 mL spore suspension (2×10^8 spores mL^{-1}) in a petri dish. The mineral solution consisted of following compositions (g L^{-1}): urea, 0.3; KH_2PO_4, 2; $(NH_4)_2SO_4$, 1.4; $MgSO_4$, 0.3; $CaCl_2$, 0.4; $FeSO_4$, 0.005; $MnSO_4$, 0.0016; $ZnSO_4$; 0.0014; $CoCl_2$, 0.002 (Mandels and Weber, 1969). Additionally, yeast extract (Angel, China) was supplemented by 2.5 w/w% as nitrogen source. DI water was added to the substrate to adjust the initial moisture content at 65%–85%. The weight of each petri dish (with substrate, medium and inoculum) was measured at the beginning of SSF and DI water was added every day to maintain the weight constant. The pH of the prepared medium was 6.3–6.5. SSF was conducted in an incubator at 28 °C for 7–9 days under static condition. Each condition was repeated in duplication.

2.5. Enzyme extraction

At the end of incubation, fungal enzyme was extracted. For each SSF sample, 2 g of fermented substrate was mixed with 60 mL sodium citrate buffer (50 mM, pH 4.8) in a blender (Ling Yang Frozen Machine Co., Hong Kong) for 10 s. The mixture was centrifuged at 4 °C, 10,000*g* for 3 min to collect the clear supernatant as crude enzyme solution (Pensupa et al., 2013).