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Valorisation of food and beverage waste via saccharification for sugars recovery

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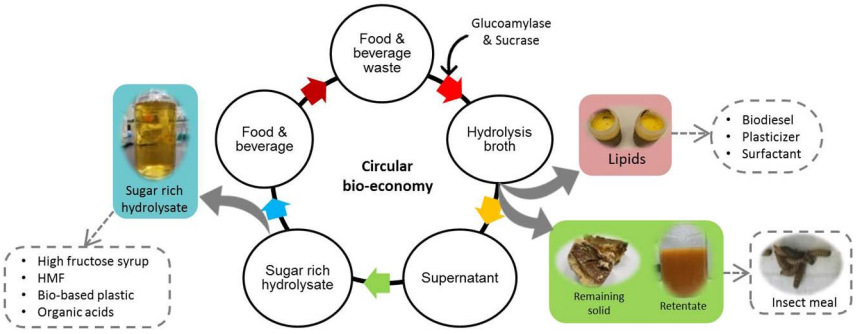
GRAPHICAL ABSTRACT



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ABSTRACT

Valorisation of mixed food and beverage (F&B) waste was studied for the recovery of sugars via saccharification. Glucoamylase and sucrase were employed to hydrolyse the starch and sucrose present in the mixed F&B waste because of the high cost-effectiveness for such recovery. The Michaelis-Menten kinetics model suggests that preservatives and additives in beverages did not inhibit glucoamylase and sucrase during saccharification. High levels of glucose (228.1 g L^{-1}) and fructose (55.7 g L^{-1}) were efficiently produced within 12 h at a solid-to-liquid ratio of 37.5% (*w/v*) in 2.5 L bioreactors. An overall conversion yield of 0.17 g sugars per g of mixed F&B waste was obtained in mass balance analysis. Lastly, possible industrial applications of the sugar-rich hydrolysate and by-products are discussed. This study is believed to cast insights into F&B waste recycling via biotechnology to produce high-value added products to promote the establishment of a circular bio-economy.

1. Introduction

Food waste is defined as any waste and by-products generated in the food supply chain which comprises production, processing, wholesale, retail and consumption (FAO, 2011). There is high demand for recycling food waste due to massive amounts of its generation and the valuable organic content that can be recycled for various applications (Lin et al., 2014). Food waste biorefinery has been proposed and demonstrated in recent years as an advanced approach to utilise food waste as raw material for the production of bio-based chemicals, materials and fuels via bioprocesses (Lin et al., 2014). For example, Leung et al. (2012) used bread waste for succinic acid production via fungal hydrolysis and fermentation with *Actinobacillus succinogenes*. Pleissner et al. (2013) adopted a similar approach to produce microalgae biomass

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using restaurant leftovers. Recent studies have begun to explore some practical issues and difficulties in application, such as a decentralised approach to apply food waste biorefinery in urban areas (Pleissner, 2016) and the techno-economic feasibility of commercialisation (Kwan et al., 2015). One of the most critical factors about commercialisation of the bioprocesses is the impact of food waste composition since it varies significantly by sources over time and determines the production efficiency in the bioprocesses. Therefore, utilisation of industrial food waste is an attractive option due to its stable composition, intensive generation manner and ease of collection (Kwan et al., 2014).

A significant amount of food and beverage (F&B) waste is generated by the F&B manufacturing industry across the globe. In the United Kingdom, beverage waste accounts for 18.6% of household food waste, and among this, 60% of the beverage waste is avoidable (Quested et al., 2013). A typical oatmeal manufacturing plant was reported to dispose of 766 metric tons of waste to landfill, and among this, 76% is edible (Hyman, 2009). In fact, most of the F&B waste is rich in carbohydrates. For instance, potato chips, oatmeal and bakery products consist of 30–60% starch while juices, energy drinks, and soft drinks generally contain about 100 g L^{-1} of fructose, glucose and sucrose (Haque et al., 2017; Leung et al., 2012; Ventura et al., 2011). It is hypothesised that abundant sugars (principally glucose and fructose) could be easily produced by a simple enzymatic saccharification step at appropriate conditions. Compared with traditional waste treatment methods such as composting, incineration, and landfill reported in literatures, biorefinery of F&B waste for sugars recovery is an environmental-friendly technology in which the processes are proceeded under mild conditions and do not generate pollutants (Haque et al., 2017). Furthermore, it produces sugars which can be used as renewable feedstock for various purposes such as the production of organic acids by fermentation and high fructose syrup by sugar refining (Haque et al., 2017). It does not only promote the development of a circular bio-economy, but also facilitates an efficient resource recycling in the industry. So, this study will investigate a bioprocess to produce sugar-rich hydrolysate via saccharification of mixed F&B waste.

However, there are some potential disadvantages of using F&B waste for sugars production that have to be evaluated and overcome. First, the preservatives and additives in F&B waste might exert an inhibitory effect on the enzymes during saccharification and reduce the sugars production yield. A number of enzymes such as apple polyphenol oxidase, tyrosinase and excinuclease were reported to be inhibited by benzoic acid, sorbic acid and caffeine (Janovitz-Klapp et al., 1990; Menon et al., 1990; Selby and Sancar, 1990). However, the enzymes used in sugar production such as amylase, glucoamylase and sucrase are never studied. Furthermore, mixed F&B waste contains a consortium of disaccharides (e.g. sucrose) and polysaccharides (e.g. starch and cellulose) which require the addition of a mixture of enzymes to recover the maximal amount of sugars but it will significantly increase the enzyme cost which reduces the economic competitiveness of the process. Therefore, investigation of the enzyme combination, enzyme cost and inhibitory effect is definitely needed in this study during the development of a bioprocess to recycle F&B waste via saccharification.

On the other hand, the annual production of sugar around the globe exceeds 170 million metric tons, extracted from sugar cane and sugar beet (The Statistics Portal, 2016). Research interest has been focused on lignocellulosic materials as an alternative source of fermentable sugar production in order to reduce the land use and prevent exhaustion of soil fertility during crop cultivation (Kumar et al., 2013; Mäki-Arvela et al., 2011). A number of studies have successfully demonstrated sugar production using various lignocellulosic materials such as sugarcane bagasse (Yu et al., 2013), softwood (Olsen et al., 2015), Jatropha waste (Kumar et al, 2013) and forest harvest residues (Leu et al., 2013). However, the processes were criticised for having poor environmental and economic performance by the use of acid or alkali, energy intensive pre-treatment and formation of inhibitors, which cause negative effects on the microorganisms involved in fermentation (Kumar et al., 2013; Yang and Wyman, 2008). Meanwhile, mass balance of the process is rarely presented to indicate the generation of by-products such as wastewater and remaining residues. This prevented further techno-economic study of the feasibility of upscaling and the subsequent industrial development of sugars recovery from lignocellulosic materials. In view of that, mixed F&B waste could be an ideal feedstock for sugar production because it contains abundant source of carbohydrates which can be recovered as a form of sugars via saccharification under mild conditions (50–60 °C) without any pre-treatment (Haque et al., 2017; Yu et al., 2018). So, evaluation of sugars production using mixed F&B waste via enzymatic saccharification will be conducted in this study accompanied by a mass balance analysis in order to quantify the by-products streams.

This study aimed to utilise mixed F&B waste as a novel feedstock for sugars recovery via enzymatic saccharification. First, saccharification of mixed F&B waste was explored in small reactors by the selection of a suitable enzyme combination based on the amount of sugars recovered and the relevant enzyme cost, followed by the investigation on inhibitory effect by the preservatives and additives in beverages. Then, it was upscaled into 2.5 L benchtop bioreactor to evaluate the sugar production profile and feasibility of increasing solids loading. A mass balance analysis was subsequently conducted to calculate the sugars recovery yield and quantify the by-product streams. Lastly, industrial applications of the sugar-rich hydrolysate and by-products were discussed in order to evaluate the market demand for the products and facilitate complete nutrient recycling under a zero-waste approach.

2. Materials and methods

2.1. Handling of food and beverage waste

Three waste streams, namely mixed beverages, bakery, and carbohydrate-rich food waste were used in this study. The beverages (fruit juices, energy drinks, and soft drinks) and carbohydrate-rich food wastes (oatmeal and potato chips) were collected from local supermarkets and distributors. Bakery waste consisting of cakes, breads and pastries was collected from a Starbucks outlet located in Sha Tin in Hong Kong. The selection of these waste materials was based on the recommendation by a food and beverage company. Mixed waste streams were prepared by blending an equal amount by weight for bakery and carbohydrate-rich food waste, and by volume for beverage waste. Table 1 summarises the compositions of different waste streams (Haque et al., 2017).

2.2. Enzyme combination for saccharification

Enzyme combination for saccharification was investigated in 500 mL Duran bottles at 50 °C for 24 h. Mixed bakery waste (10 g, dry weight), mixed carbohydrate-rich food waste (30 g, dry weight) and 200 mL of mixed beverage waste were homogenised and heated to 50 °C in a 500 mL Duran bottle using a water bath (FL4CA, Clifton, UK) and magnetic stirrer (F13-3X2, MRC Lab, Israel). The pH was adjusted to 5 using 1 M NaOH. Experiments were carried out in duplicate with nine different enzyme combinations: (i) glucoamylase, (ii) sucrase, (iii) pectinase, (iv) glucoamylase & sucrase, (v) pectinase & sucrase, (vi) glucoamylase & pectinase, (vii) glucoamylase, sucrase & pectinase, (viii) amylase, glucoamylase & sucrase, and (ix) glucoamylase, sucrase, amylase & pectinase. The dosage of glucoamylase, sucrase, pectinase, and amylase were 331 U g^{-1}, 123 U g^{-1}, 10 U g^{-1}, and 13 U g^{-1}, respectively (Haque et al., 2017; Lam et al., 2015). All of the enzymes were provided by Novozymes in Denmark. One unit (U) of glucoamylase activity is defined as the amount of enzyme that releases 1 μmol glucose per minute at pH 5.5 and 55°C. One unit (U) of sucrase hydrolyses 1 μmol sucrose per minute at pH 4.5 and 55°C. One unit (U) of pectinase liberates 1 mg galacturonic acid from polygalacturonic acid at 50 °C and pH 3.5 per hour. One unit (U) of amylase releases 1 μmol p-