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Techno-economic analysis of a food waste valorization process via microalgae cultivation and co-production of plasticizer, lactic acid and animal feed from algal biomass and food waste

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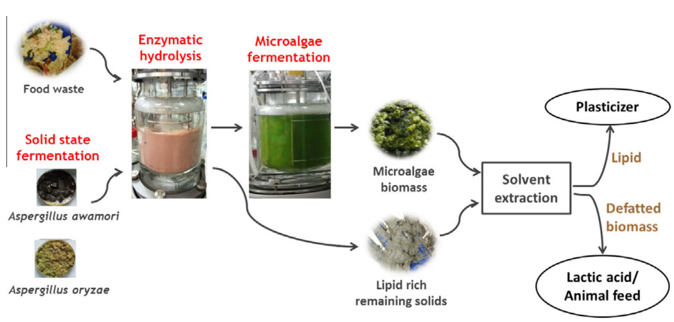
HIGHLIGHTS

- A techno-economic study of food waste valorization was done with Super-Pro Designer®.
- The process included fungal hydrolysis, microalgae cultivation and biomass processing.
- Production of lactic acid and plasticizer from food waste was economically feasible.
- The NPV and IRR were US$ 3,028,000 and 18.98%, respectively.
- Price of lactic acid was the largest determinant of the profitability.

GRAPHICAL ABSTRACT



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ABSTRACT

A techno-economic study of food waste valorization via fungal hydrolysis, microalgae cultivation and production of plasticizer, lactic acid and animal feed was simulated and evaluated by Super-Pro Designer®. A pilot-scale plant was designed with a capacity of 1 metric ton day^{-1} of food waste with 20 years lifetime. Two scenarios were proposed with different products: Scenario (I) plasticizer & lactic acid, Scenario (II) plasticizer & animal feed. It was found that only Scenario I was economically feasible. The annual net profits, net present value, payback period and internal rate of return were US$ 422,699, US $ 3,028,000, 7.56 years and 18.98%, respectively. Scenario II was not economic viable due to a deficit of US $ 42,632 per year. Sensitivity analysis showed that the price of lactic acid was the largest determinant of the profitability in Scenario I, while the impact of the variables was very close in Scenario II.

1. Introduction

According to a study commissioned by the United Nations Food and Agriculture Organization in 2011, roughly one-third of food produced for human consumption is lost or wasted globally, which results in the generation of 1.3 billion metric tons (MT) of food waste per year (FAO, 2011). In Hong Kong, food waste is also one of the most imminent waste problems due to the closure of the three existing strategic landfills in 2020 and a continuing rise in food waste generation in the future. In 2012, 3337 MT day^{-1} of food waste was generated, which was nearly twice of the amount produced in 2002 (EPD, 2012). In fact, food waste as one of the largest portion of municipal solid waste in different countries has drawn a great research effort in developing advanced valorization strategies to recover energy and nutrients from it (Lin et al., 2014).

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Food waste, which is defined as 'any waste and by-products produced during the food production, processing, wholesale, retail and consumption (FAO, 2011), consists of 30–60% starch, 5–10% proteins and 10–40% lipids (w/w, Pleissner et al., 2013; Zhang et al., 2013). Due to the nutrient-rich composition of food waste, its utilization as feedstock in biorefineries for chemicals, materials and fuels production has been proposed and demonstrated in the recent years in order to reduce the amount of organic waste that needs to be treated and to help alleviating the over-dependence on petroleum (Lin et al., 2013). For example, we previously demonstrated the utilization of waste bread as feedstock for fermentative succinic acid production by *Actinobacillus succinogenes* (Leung et al., 2012; Zhang et al., 2013). Kim et al. reported the production of ethanol using food waste collected from cafeteria via enzymatic hydrolysis and ethanol fermentation with *Saccharomyces cerevisiae* (Kim et al., 2011). Pleissner et al. (2014b) reported the production of natural polymer polyhydroxybutyrate (PHB) using bread waste hydrolysate as substrate in *Halomonas boliviensis* fermentation.

In fact, most of the studies on food waste based processes highlight the cost-efficiency of food waste as raw material as one of the major advantages and thus emphasize on the potential to develop economically feasible processes. In order to examine the feasibility of a process in commercialization, extensive techno-economic studies have been carried out based on the reported experimental results by using process simulation software such as Super-Pro Designer® and Aspen Plus®. For example, our previous research evaluated the economic feasibility of the fermentative succinic acid production from bakery waste at pilot scale with a capacity of 1 MT day^{-1} and concluded that the process was economic feasible with an annual profit of US$ 143,559, internal rate of return of 15.3%, and an overall net present value of US$ 2,577,000 (Lam et al., 2014). What is more, techno-economic evaluation of PHB production from food industry wastes (i.e. whey and rice bran) also showed the economic feasibility for replacing the petroleum-deprived plastic with PHB (Lopez García et al., 2011).

Recently, we demonstrated an integrated process for food waste valorization through fungal hydrolysis and microalgae cultivation including the production of bio-based plasticizer and lactic acid. The overall yield was found to be 0.09 g of plasticizer g^{-1} of food waste and 1.67 g of lactic acid g^{-1} of food waste under supply of additional glucose (Pleissner et al., 2015a,b). Meanwhile, as suggested by the local Hong Kong food waste recycling industry, the defatted algal biomass and defatted solid from hydrolyzed food waste are also promising nutrient supplements in animal feed production (HKOWRC, 2014). Therefore, the objective of this work is to evaluate the economic feasibility and profitability of the production of bio-based plasticizer, lactic acid and animal feed from food waste using computer simulation.

2. Methods

2.1. Simulation description

A pilot plant processing 1 MT day^{-1} of food waste was simulated using Super-Pro Designer 8.0®. Mass and energy balance calculation as well as the economic analysis were performed with the aid of the software. The plant was assumed to be built in Hong Kong with 20 years lifetime, including 1 year of construction and start-up phase. The operation mode was set to be batch mode with 312 days $year^{-1}$ operation time (85% of the working capacity). The calculation of the cumulative cash flow of the plant was done using Microsoft Excel 2010. In this study, two scenarios were proposed with different products: Scenario (I) plasticizer & lactic acid and Scenario (II) plasticizer & animal feed.

2.2. Process description

The process simulated in this study has been demonstrated in laboratory-scale and reported in our previous publications (Pleissner et al., 2013, 2014a, 2015a,b). The process flow of the pilot plant was designed accordingly and depicted in Fig. 1 using Super-Pro Designer 8.0®.

As shown in Fig. 1a, food waste was first grinded into pieces smaller than 1 cm^3 and blended with water at a solid-to-liquid ratio of 43.5%. It was then mixed with the fungal solid mashes of *Aspergillus awamori* and *Aspergillus oryzae*, which were grown on bakery waste at 30 °C for 7 days in solid state fermentation, to facilitate the fungal hydrolysis for the recovery of glucose, free amino nitrogen and phosphate (Pleissner et al., 2013). The hydrolysis was carried out in a bioreactor at 55 °C for 36 h. After the hydrolysis, the remaining lipid-rich solids were separated by centrifugation at 10,000*g* for 15 min. The hydrolysate was filter-sterilized and transferred to a fermentor for microalgae, *Chlorella pyrenoidosa*, cultivation. The inoculum of *C. pyrenoidosa* was prepared using food waste hydrolysate, containing 5 g L^{-1} glucose, 0.2 g L^{-1} FAN and 0.1 g L^{-1} phosphate, as culture medium in shake flasks at 28 °C and an initial pH of 6.5 for 5 days, followed by seed fermentation for 2 days. Algae fermentation was carried out aerobically at a pH of 6.5 and 28 °C for 5 days and algal biomass was obtained after centrifugation of the fermentation broth at 10,000*g* for 15 min. After that, algal biomass and lipid-rich solids from food waste were lyophilized, followed by lipid extraction with $CHCl_3$:CH_3OH (1:1, v/v). It was assumed that the solvent used in lipid extraction can be completely recovered and reused in subsequent extractions (Vlysidis et al., 2011a). Lipids were then used in plasticizer production, while the defatted solids and defatted algal biomass were used as nitrogen sources in lactic acid fermentation and raw materials in animal feed production in Scenario I and Scenario II, respectively.

The defatted algal biomass was proteolyzed using Flavourzyme® 1000 L and Neutrase® 0.8 L (Novozymes, DK), while defatted remaining solids were not. Both materials were then used as nitrogen sources in fermentative lactic acid production by *Bacillus coagulans* strain 162 (DSM 2314). Furthermore, the medium was supplemented with 60 g L^{-1} glucose. The inoculum was prepared in shake flasks at 100 rpm at 52 °C and an initial pH of 6.5 for 15 h, followed by seed fermentation for 1 day. The inoculum size was 6% (v/v). The recovery of lactic acid involved solid–liquid separation by centrifugation, impurities adsorption using granulated activated carbon (GAC) and ion-exchange chromatography. The recovery yield was assumed to be 92% (Cao et al., 2002). The fermentative lactic acid production process is depicted in Fig. 1b.

The transesterification of fatty acids in algal and food waste lipids was carried out for 1 h at 90 °C with the mixture of CH_3OH:HCl:$CHCl_3$ (10:1:1, v/v/v) in a reactor. After cooling down the reaction mixture to room temperature, the formed fatty acid methyl esters (FAMEs) were extracted using hexane and undergone epoxidation with 30% H_2O_2, toluene and formic acid at room temperature for 24 h in a stirred reaction vessel. It was assumed that the solvents used in the process can be completely recovered and reused (Vlysidis et al., 2011a). The process flow of plasticizer production is shown in Fig. 1c.

2.3. Economic analysis

The economic performance of the two scenarios was studied by estimating the capital cost, operation cost and revenue generation. Profitability and sensitivity analyses were carried out to evaluate and compare the economic feasibility of the two scenarios.