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Techno-economic analysis of a food waste valorisation process for lactic acid, lactide and poly(lactic acid) production

Tsz Him Kwan, Yunzi Hu, Carol Sze Ki Lin*

School of Energy and Environment, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong

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ABSTRACT

A sustainable food waste valorisation process was proposed by designing a plant with a capacity of 10 metric tons (MT) hour^{-1} of food waste powder with a 20-year lifetime. Three scenarios were proposed with different products: Scenario I) lactic acid, Scenario II) lactide, Scenario, and III) poly(lactic acid) (PLA). Mass balance showed conversion yields of 3.1 MT of 80% lactic acid, 1.7 MT of lactide, and 1.3 MT of poly(lactic acid) from 10 MT of food waste powder. All scenarios were economically feasible, but Scenario I had the highest annual net profits (US$ 22,184,169), internal rate of return (31.1%), net present value (US$234,803,060) and the shortest payback period (5.1 years) at a discount rate of 5%. The minimum selling prices of lactic acid, lactide and poly(lactic acid) were US$943 MT^{-1}, US$2073 MT^{-1} and US$3330 MT^{-1}, respectively. Sensitivity analysis showed that the prices of lactic acid, lactide and poly(lactic acid) were the largest determinants of the profitability in the plant while the sale of by-products (animal feed) was also critical to the plant's economics. This work has cast insights on the techno-economic performance of a sustainable food waste treatment under a decentralised approach in urban areas.

1. Introduction

Nowadays, around a third of the food produced for human consumption is lost or wasted globally, resulting in 1.3 billion metric tons (MT) of food waste per year (FAO, 2011). The problem is particularly serious in highly populated cities where large amounts of food waste are generated every day. For example, the domestic sector in Taipei, Hong Kong and Seoul produces 0.07, 0.13 and 0.07 MT of food waste per capita every year, respectively (Environment Bureau, 2014). Apart from prevention and reduction through education and policy, advanced technology also plays an important role to facilitate recycling in food waste management. In recent years, food waste biorefinery has been proposed to convert different kinds of food waste into value-added products, which could facilitate the recovery of nutrients and development of a sustainable bioeconomy (Lin et al., 2014). As a result, different bioconversion processes have been developed to utilise food waste for the production of various commodities and platform chemicals, such as ethanol (Kiran and Liu, 2015), butanol (Huang et al., 2015), polyhydroxybutyrate (Pleissner et al., 2014a), microalgae biomass (Pleissner et al., 2013) and biocolourants (Haque et al., 2016).

Lactic acid (LA) is one of the 12 most promising value-added building blocks that can be derived from sugars and used for the production of various commodity and specialty chemicals (DOE, 2004). One of the most common applications of LA is to synthesise poly(lactic acid) (PLA), which contributes to more than 35% of the bioplastic market due to its eco-friendly properties and great material performance (AMR, 2015). Meanwhile, lactide which is the intermediate during PLA polymerisation also has various applications as polymer additives, adhesives, coatings, printing toners, and surfactants (Vink and Davies, 2015). Nowadays, LA, lactide and PLA are mainly derived from renewable biomass resources such as sugar beet and corn (Castro-Aguirre et al., 2016). In order to avoid food resource competition, waste materials and industrial by-products such as kitchen waste, whey, coffee mucilage, corn cobs, corn stalks, wheat bran and brewer's spent grains have been explored as alternative feedstock for fermentative LA production (Venus, 2006; Venus and Richter, 2006). A few bioconversion strategies including enzymatic hydrolysis and fermentation, simultaneous hydrolysis and fermentation, open fermentation and direct fermentation have been intensively studied with different LA producing microorganisms (Pleissner et al., 2017; Venus, 2006).

* Corresponding author.
E-mail address: carollin@cityu.edu.hk (C.S.K. Lin).

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Nomenclature

CEPCI	Chemical engineering plant cost index
FAN	Free amino nitrogen
FCI	Fixed capital investment cost
HKOWRC	Hong Kong Organic Waste Recycling Centre
IRR	Internal rate of return
LA	Lactic acid
PC	Purchase cost of equipment
PHB	Polyhydroxybutyrate
PLA	Poly(lactic acid)
MT	Metric ton
NPV	Net present value
NREL	National Renewable Energy Laboratory
ROI	Return on investment

Although a few recent studies have addressed the mass balance of the bioprocess (Pleissner et al., 2016a,b; 2017; Neu et al., 2016), most of the studies only focused on process demonstration and optimisation without in-depth technical and economic evaluation, which prevented further process upscaling and commercialisation. Most importantly, the challenges in using waste material as feedstock such as impurity removal, heterogeneity of the biomass and utilisation of remaining residues are seldom addressed, which leaves uncertainties in regard to process upscaling and the feasibility of using the waste-derived LA for PLA synthesis.

Recently, we have developed a bioconversion process of food waste into LA via solid state fermentation, fungal hydrolysis and LA fermentation (Kwan et al., 2016). Lactic acid was recovered with a high purity (>98%) via a newly developed continuous ultrasonic-mediated solvent extraction method (Hu et al., 2017a). Mass balance analysis showed overall conversion yields of 0.23–0.27 g g^{-1} for different kinds of food waste due to their varied composition (Kwan et al., 2016). The LA was successfully used to synthesise lactide and PLA by ring-opening polymerisation using zinc oxide nanoparticle dispersion. It was highlighted as a novel and efficient catalytic method due to moderate synthesis conditions and high production yields (90–92%), compared to tin-based industrial methods (Hu et al., 2017b). On the other hand, in order to cope with the challenges of food waste collection in urban areas with high population density, a decentralised approach was proposed with the incorporation of food waste processing machines into the bioconversion process (Kwan et al., 2016). Food waste currently processed by these machines (so-called food waste powder) has experienced a significant reduction by volume and weight, which facilitates source separation and prevents hygiene problems caused by food waste collection. As the Hong Kong Government has allocated more than HK$50 million in subsidies to encourage the installation since 2011, on-site food waste pre-treatment has commonly been adopted in residential buildings (HKPC, 2016). However, the high operation and maintenance costs have led to a heavy financial burden on residents and the application of food waste powder for composting cannot generate much revenue (HKOWRC, 2016). Therefore, a bioconversion process from food waste powder to high-value PLA was developed and demonstrated in the laboratory (see the block diagram in Fig. 1) (Kwan et al., 2016; Hu et al., 2017a, 2017b). The process also features a few advantages including low-cost raw material, highly efficient and non-polluting technology, and low impurity level in the end products. However, the economics of production of lactic acid and its derivatives are situation-specific and dependent on many factors, such as the costs of raw material, utilities, labour, and capital (Datta et al., 1995). A sustainable bioconversion process should not only focus on resource efficiency, but also the economics of the process. A comprehensive techno-economic evaluation needs to be conducted to estimate the profitability and identify the key process factors which help formulate technology improvement strategies. It could increase the process conversion yields along with associated reductions in modelled production costs (Klein-Marcuschamer et al., 2013) so that investment risk can be substantially decreased by the technological improvement prior to commercialisation.

In this study, techno-economic assessment was carried out to investigate the technical feasibility, profitability and extent of investment risk between LA, lactide and PLA production using food waste powder as the raw material in a plant. Three scenarios were proposed with different products: Scenario I) lactic acid; Scenario II) lactide; and Scenario III) poly(lactic acid). Process flowsheets were developed for each scenario together with mass and utility balance calculations. Sensitivity analysis was conducted to evaluate the effect of crucial parameters on the minimum selling price. To the best of our knowledge, this is the first study that focuses on the

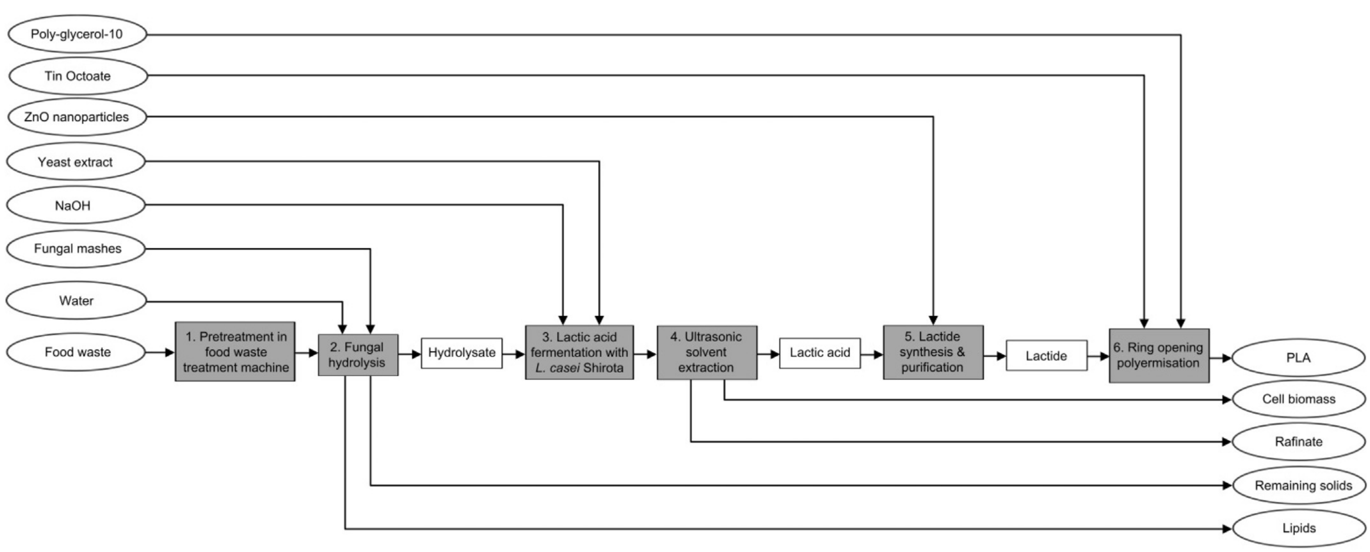

Fig. 1. Production process scheme from food waste to lactic acid, lactide or poly(lactic acid).