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Case study for a palm biomass biorefinery utilizing renewable non-food sugars from oil palm frond for the production of poly(3-hydroxybutyrate) bioplastic

Mior Ahmad Khushairi Mohd Zahari [a, b], Hidayah Ariffin [c, d], Mohd Noriznan Mokhtar [a], Jailani Salihon [e], Yoshihito Shirai [f], Mohd Ali Hassan [a, c, *]

[a] Department of Process and Food Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia
[b] Faculty of Chemical and Natural Resources Engineering, Universiti Malaysia Pahang, Lebuhraya Tun Razak, 26300 Kuantan, Pahang, Malaysia
[c] Department of Bioprocess Technology, Faculty of Biotechnology and Biomolecular Sciences, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia
[d] Laboratory of Biopolymer and Derivatives, Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia
[e] Faculty of Chemical Engineering, Universiti Teknologi Mara, 40450 Shah Alam, Selangor, Malaysia
[f] Department of Biological Functions and Engineering, Graduate School of Life Science and Systems Engineering, Kyushu Institute of Technology, 2-4 Hibikino, Wakamatsu-ku, Kitakyushu, Fukuoka 808-0196, Japan

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A B S T R A C T

In this paper, we assess the economic viability of renewable non-food sugars from oil palm frond (OPF) as fermentation feedstock for the production of the bioplastic, poly(3-hydroxybutyrate), P(3HB) within an integrated palm biomass biorefinery. The production cost of P(3HB) is estimated based on 9900 t/y of the potential amount of renewable sugars that can be produced from OPF in a typical palm oil mill in Malaysia. Based on the case study, approximately 99,780 t/y of renewable sugars could be produced from 10 neighbouring palm oil mills, each with the capacity to process an average of 200,000 t/y of fresh fruit bunch (FFB). With 20,000 t/y of P(3HB) production, the specific production cost of P(3HB) using renewable sugars from OPF is estimated at $ 3.44/kg P(3HB), which is 41% lower compared with that produced from commercial glucose.

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1. Introduction

Biodegradable polyhydroxyalkanoates (PHA) have been reported as potential replacements for non-biodegradable petrochemical-based plastics due to its thermoplastic properties (Anderson and Dawes, 1990). In addition to having thermal and mechanical properties similar to conventional plastics, biodegradation of polymeric materials under certain environments and biocompatibility with living organisms makes PHA a more attractive option than conventional ones in the near future. Moreover, as over 99% of plastics are of fossil fuel origin, their rapid increase will put further pressure on the already limited non-renewable resources on earth (Ren, 2003). However, the high cost of bacterial fermentation is a major hurdle for commercial production and application of PHA in consumer products. The most significant factor contributing to the high production cost of PHA by bacterial fermentation is the cost of substrate, mainly the carbon source.

Instead of using commercially available pure substrates as a carbon source, many researchers are now diverting their focus towards the utilization of renewable biomass as raw materials for the production of P(3HB). This is because the utilization of waste materials as starting materials for PHA biosynthesis constitutes a more viable strategy for cost-effective biopolymer production, while simultaneously helping the industry to overcome disposal problems. In addition, renewable biomass can be considered as a relatively cheap and non-petroleum-based carbon source for PHA production (Hassan et al., 2013). The sources of renewable biomass can be the industry, agriculture or household waste materials.

In Malaysia, the government has proposed the National Biomass Strategy 2020 for the use of biomass, especially from the

* Corresponding author. Department of Bioprocess Technology, Faculty of Biotechnology and Biomolecular Sciences, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia. Tel.: +60 3 8947 1047; fax: +60 3 8946 7590.
E-mail address: alihas@upm.edu.my (M.A. Hassan).

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palm oil industry, to be converted into higher value downstream uses (MIA, 2011; Hassan et al., 2013). As of 2009, Malaysia has 4.7×10^6 ha of oil palm plantations and 416 palm mills operating across the country. Based on this figure, Malaysian oil palm industry is estimated to generate over 115×10^6 t of oil palm biomass (wet mass), including oil palm empty fruit bunch (OPEFB), oil palm frond (OPF) and oil palm trunk (OPT), in addition to 60×10^6 t of palm oil mill effluent (POME) (MPOC, 2010; Ng et al., 2011). To reduce the environmental problems due to the production of huge quantities of waste materials from oil palm industry, there have been many reports on the bioconversion of waste to wealth. For instance, Yoshizaki et al. (2012) proposed an economic analysis of biogas and biocompost production at palm oil mill, with clean development mechanism (CDM) in Malaysia. The report indicated that CDM would have a significant impact and ensure economic viability for both projects with a 25% internal rate of return (IRR), RM 12.39×10^6 of net present value (NPV) and 3.5 years of payback period (PBP) for the biogas project, compared with 31% of IRR, RM 10.87×10^6 of NPV and 2.9 years of PBP for the compost project (Yoshizaki et al., 2012) (In this paper, the currency rate of Malaysian Ringgit (RM) to US Dollar ($) is fixed at 0.333). The economic viability of the project was further improved with the integrated technology of biogas energy and compost production for a palm oil mill (Yoshizaki et al., 2013). Apart from that, Hassan et al. (1997) reported the economic analysis of PHA production from POME in Malaysia. Based on the report, with a content of 50% PHA in the dried cells and 2% dissolved in the chloroform, the calculated minimum cost for obtaining PHA from POME was estimated to be below $ 2/kg. By increasing the PHA content in the cell from 50 to 80 %, the unit cost of PHA could be reduced marginally whereas an increase in the amount of PHA dissolved in chloroform from 2 to 5 % would result in a remarkable reduction of the PHA cost to less than $ 1/kg (Hassan et al., 1997; Mumtaz et al., 2010). At this price, PHA would be expected to compete with other biopolymers and plastics in the market. In addition, it is encouraging to see that the production cost of P(3HB) by bacterial fermentation can be as low as $ 2–3/kg, which is close to the price of major competing biodegradable polymers, such as poly(lactide) (Lee, 1996; Lee and Choi, 1998; Van Wegen et al., 1998; Reddy et al., 2003).

Previously, we demonstrated that OPF juice can be used as an alternative fermentation substrate for the production of value-added products, including P(3HB) and bioethanol (Zahari et al., 2012a, 2012b, 2014). OPF juice contains a substantial amount of sugars, which makes it a favourable fermentation feedstock. Furthermore, its daily availability due to harvesting activity at the plantation adds value to this bioresource. To determine its viability as fermentation feedstock, cost analysis and the economic potential of the OPF juice needs to be studied. Thus, this case study was performed to evaluate the economic potential of fermentable renewable sugars from OPF by taking P(3HB) fermentation as an example.

2. Materials and methods

In this study, it is assumed that renewable sugars produced from OPF will be transported to the centralized biorefinery plant for P(3HB) production from at least 10 palm oil mills within a 80 km radius that have similar capacity to process oil palm fresh fruit bunch (FFB) at 200,000 t/y as previously reported by Zahari et al. (2014). Additionally, it is assumed that the biorefinery plant will be located at one of the 10 mills to utilize the surplus energy from the palm oil mill. Fig. 1 shows the proposed diagram of integrated OPF renewable sugars and biorefinery plant for the production of P(3HB).

2.1. Basis of the proposal

As a basis for economic analysis, the production cost of P(3HB) was estimated based on the potential amount of renewable sugars that can be produced from OPF in a year from 10 palm oil mills. The fresh OPF will be pressed in the mill, whereby OPF fibre will be saccharified to obtain additional renewable sugars (mainly glucose). The renewable sugars produced are partially concentrated by evaporation and transported to a centralized biorefinery plant to be used as a fermentation feedstock for P(3HB) and bioethanol production.

Due to constraints in the transportation cost, and to benefit from the economy scale, we propose only one biorefinery plant processing renewable sugars from OPF to produce P(3HB) from among the 10 palm oil mills. Fresh fronds (petiole section only) are collected in the plantations during harvesting of the FFB, transported to the mill and subsequently pressed in the mill to obtain the renewable sugars. The pressed OPF fibre will be saccharified to obtain more renewable sugars. Therefore, several costs are involved in the renewable sugars production from OPF, including transportation, harvesting and collection of OPF from the oil palm plantation to the mill. Additionally, the cost of enzymes used for the saccharification of OPF fibre is also included.

Renewable sugars produced from each mill will be concentrated and transported to a centralized biorefinery plant for P(3HB) production. We propose the distance between the centralized biorefinery plant and each of the palm oil mills to be not more than 80 km, as shown in Fig. 1.

2.2. Renewable sugars production cost

In this study, the major costs contributing heavily to the total production cost of renewable sugars from OPF are transportation, harvesting and collection cost of OPF from the oil palm plantation to the mill, pre-processing cost and the cost of enzymes used for the saccharification of OPF fibre. All prices used in this study were determined based on the current situation in Malaysia and valued in US Dollar ($).

2.2.1. Description of the process

We have previously reported that 50% (wt/wt) of OPF juice could be obtained from fresh OPF by using a simple sugarcane pressing machine (Zahari et al., 2012a). To obtain the OPF juice at an industrial scale, we proposed the use of a compressing sap system that was developed by Murata et al. (2013). In their report, they use a compressing sap system to obtain the saps containing sugars from the oil palm trunk (OPT). As OPT can be pressed due to its high sugar content, it was postulated that the same process can be performed on OPF. Apart from OPF juice, pressed OPF fibre was also produced as a by-product of the OPF pressing process. Pressed OPF fibre contains a substantial amount of carbohydrate, which is also useful as fermentation feedstock (Zahari et al., 2014). As shown in Fig. 2, there are two avenues for producing sugars from OPF. Firstly, sugars in the OPF juice could be obtained by pressing the fresh OPF using a compressing sap system. The OPF juice is filtered to remove solid particles, evaporated to reduce the content of water and finally stored in a storage tank prior to use as fermentation substrate for P(3HB) production. Secondly, the OPF pressed fibre undergoes a physical-mechanical pre-treatment before being hydrolysed to glucose and xylose by saccharification using 20 FPU of cellulase (Meiji Seika), as previously explained in Zahari et al. (2014). Based on the report, maximum glucose and xylose concentrations of 0.469 g and 0.298 g, respectively per g of OPF petiole could be obtained from the saccharification method with 95% of holocellulose being

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