



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

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## ABSTRACT

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

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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  $4.7 \times 10^6$  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  $115 \times 10^6$  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  $60 \times 10^6$  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  $12.39 \times 10^6$  of net present value (NPV) and 3.5 years of payback period (PBP) for the biogas project, compared with 31% of IRR, RM  $10.87 \times 10^6$  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 biorenewable. 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

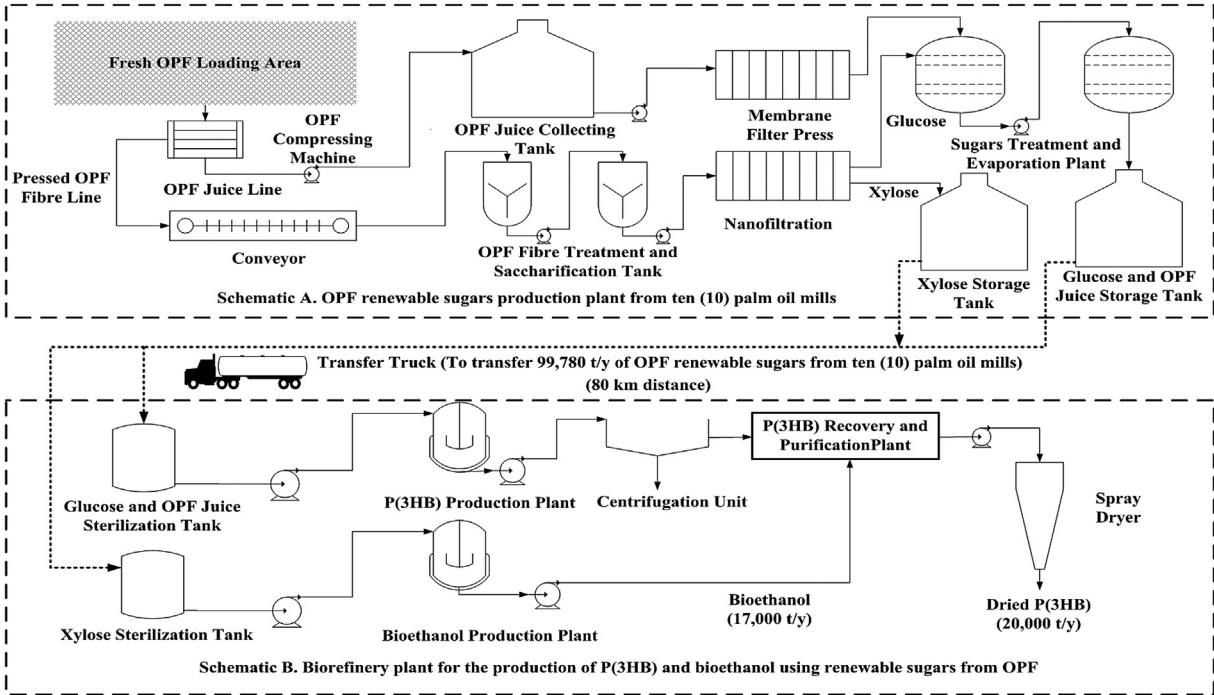


Fig. 1. Proposed diagram of integrated OPF renewable sugars and biorefinery plant for the production of P(3HB) and bioethanol.

converted into mixed sugars (Zahari et al., 2014). The mixture of sugars comprising glucose and xylose is separated by nano-filtration method as reported by Sjöman et al. (2007). Finally, the separated product, which is glucose mixed with OPF juice is used as fermentation feedstock for P(3HB) production, while xylose is used as feedstock for bioethanol production. The overall mass balance for the production of renewable sugars from OPF is presented in Fig. 2.

2.2.2. Transportation cost

Current cost estimates, based on the density of the product and the distance of transportation, range from about \$ 0.067 to 3.33/(t km) (MIA, 2011). The average transport cost in Malaysia is taken to be \$ 10/t for a 100 km distance as quoted by The Malaysian Transport Association. As a basis for calculation, the transportation cost was estimated at \$ 10/t OPF processed for less than 100 km distance.

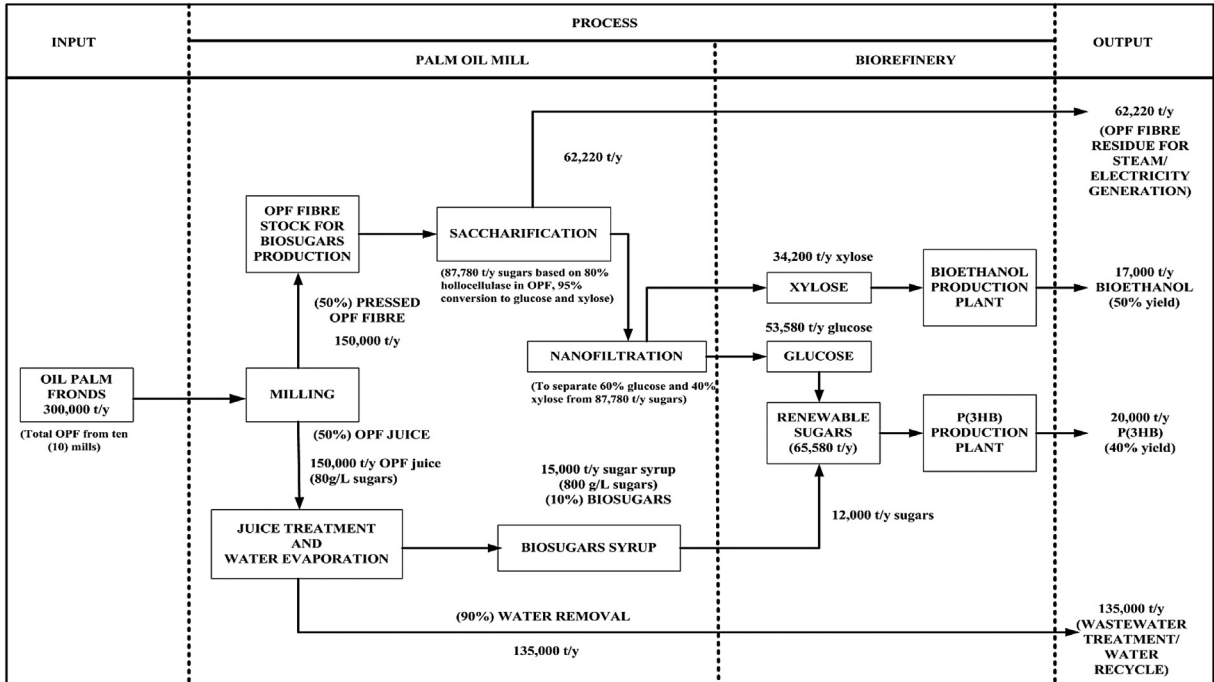


Fig. 2. Overall mass balance for the production of renewable sugars from oil palm frond (OPF) from 10 palm oil mills.

### 2.2.3. Harvesting and collection cost of oil palm frond

The OPF is obtained during harvesting of FFB. Currently, cut fronds are left as topsoil replacement and natural fertilizer (MIA, 2011). Different methods could be adopted to collect the fronds, ranging from simple manual collection with a wheelbarrow, collection with a buffalo cart or a motorized cart, to advanced mechanization. The choice of collection method for a specific plantation depends on the terrain (e.g., elevation, spacing of trees), labour constraints and economy of scale. Depending on the collection method, cost estimates range from \$ 5.33–22.33/t (dry mass basis) (MIA, 2011). As a basis for calculation, the cost for harvesting and collection of OPF was estimated at \$ 10/t OPF.

### 2.2.4. Pre-processing cost

Different biomass types can undergo different forms of pre-processing in order to reduce the moisture content, reduce the weight or volume to be transported and/or in preparation for a specific end use (MIA, 2011). For instance, trunks and fronds can be chipped, dried and/or pelletised, while OPEFB and mesocarp fibre can be shredded, dried and/or compacted. Palm kernel shells already have very low moisture content and thus can be used or transported without further pre-processing. Depending on the type of biomass and the extent of pre-processing required, cost estimates range from \$ 5–180/t for mesocarp fibres, fronds, trunks and OPEFB (MIA, 2011). With drying accounting for a large proportion of pre-processing cost, it is likely that both plantations and downstream industries will explore scenarios that do not require biomass to be dried. Since fresh OPF was used in this case study, there will be no drying process required. Therefore, the pre-processing cost was estimated at \$ 5/t OPF.

### 2.2.5. Cost of enzymes for saccharification process

The cost of enzymes for saccharifying lignocellulosic biomass has dramatically decreased over the past decade by approximately 20-fold (MacMillan et al., 2011). Currently, the cost of enzymes is estimated at approximately \$ 0.04 to 0.07/kg glucose. As a basis for calculation, the cost of enzymes for saccharification of OPF fibre to obtain renewable sugars (glucose and xylose) is estimated at \$ 20/t OPF fibre processed (Lee and Ofori-Boateng, 2013).

### 2.3. Poly(3-hydroxybutyrate) production cost

As a basis for calculation, the data for cost estimation were taken from the integrated production of biodegradable plastic, sugar and ethanol from sugarcane, which was reported by Nonato et al. (2001). In this case study, *Cupriavidus necator* NCIMB 11599 (mutant strain of H16) was used for the production of P(3HB) using renewable sugars from OPF and the data for the fermentation process were reported earlier in Zahari et al. (2014). For the P(3HB) extraction and purification process, a similar method reported by Muhammadi et al. (2012) was proposed in this case study. The NaOH digestion method, which resulted in a recovery efficiency of more than 95%, was employed for the recovery of P(3HB). Purification steps were accomplished by using ethanol and water. The use of non-organic, non-halogenated solvent is favourable for PHA production and recovery at large scale as it not only minimizes the overall production cost but also eliminates tedious wastewater treatment steps afterwards (Muhammadi et al., 2012).

## 3. Results and discussion

The availability of cheap carbon source at the biorefinery location is one of the important factors influencing the selection of biomass as a carbon source. Attempts have been made to produce low cost and renewable sugars from oil palm biomass to reduce the

dependence on food crops, especially sugarcane as fermentation feedstock for the production of value-added products. Previously, Kosugi et al. (2010) and Yamada et al. (2010) have shown that renewable sugars from OPT can be used as renewable feedstock for bioethanol production. However, OPT is only available for renewable sugars during felling and replanting, which takes place every 20–25 years. Therefore, it is impossible to have the OPT supply all year-round. In contrast, because OPF is available daily, renewable sugars from OPF could be potential feedstock candidates for the production of value-added products.

To determine the viability of renewable sugars from OPF, it is important to estimate the total amount of OPF that could be generated based on the amount of FFB processed in a typical palm oil mill in Malaysia. An average size of palm oil mill in Malaysia has the capacity to process 200,000 t/y of oil palm fresh fruit bunch (FFB). Considering that 2 OPF will be pruned for each FFB harvested, a total of 300,000 t/y OPF will be obtained from 10 mills (Zahari et al., 2014). Detailed calculations for renewable sugars projection from a typical palm oil mill in Malaysia were reported earlier in Zahari et al. (2014) with some modification as shown in Fig. 2.

### 3.1. Renewable sugars production costs

To evaluate the economic viability of OPF as fermentation feedstock for P(3HB) production, it is important to estimate the production cost of renewable sugars from OPF. As previously mentioned in Section 2.1, we propose only one biorefinery plant processing renewable sugars from OPF to produce P(3HB) from 10 palm oil mills. The total OPF processed in the palm oil mills for renewable sugars production is estimated at 300,000 t/y (Zahari et al., 2014).

From 300,000 t/y of fresh OPF, 150,000 t/y (50%) of OPF juice (containing mixture of sugars: 70% glucose, 26% sucrose and 4% fructose) (Zahari et al., 2012a) and 150,000 t/y of pressed OPF fibre could be produced. Diluted OPF juice will be concentrated for use as renewable sugars for fermentation feedstock in syrup form. Considering that at least 80% of the OPF is holocellulose with a 95% conversion yield to mixture of renewable sugars (60% glucose and 40% xylose) as reported earlier in Zahari et al. (2014), the total glucose and xylose obtainable from OPF fibre would be 53,580 t/y and 34,200 t/y, respectively. The overall mass balance for sugars production from OPF is shown in Fig. 2. The total wet mass of glucose, xylose and OPF juice produced from the OPF process is estimated at approximately 99,780 t/y and will be transported to the biorefinery plant as fermentation feedstock for P(3HB) and bioethanol production. Bioethanol produced from this proposed integrated process can be used as a solvent for P(3HB) purification as well as a source of energy for P(3HB) production (Zahari et al., 2014). Detailed calculation for the cost estimation of renewable sugars production from 300,000 t/y of OPF is presented in Table 1.

Based on the amount of renewable sugars currently obtained from OPF juice, it was estimated that approximately 0.040 kg of renewable sugars per kg OPF could be generated (Zahari et al., 2012a). Additionally, approximately 0.77 kg of renewable sugars could be obtained from 1 kg of OPF fibre by saccharification process based on the maximum theoretical yield of holocellulose to renewable sugars (Zahari et al., 2014). Therefore, it is estimated that 425 kg of dry mass of renewable sugars could be produced from one tonne of fresh OPF processed. The current price of raw sugar from sugarcane is around \$ 0.50/kg (USDA, 2013). Therefore, the value of renewable sugars obtained from OPF is estimated at around \$ 212/t OPF. This shows that the value of renewable sugars from OPF is almost 5 times higher than the production cost of renewable sugars from OPF i.e., \$ 45/t OPF as shown in Table 1.



**Table 1**

Cost estimation for renewable sugars production from 300,000 t/y of oil palm frond (OPF) processed.

Item	Cost (\$)	% of total cost
Transportation costs @ \$ 10/t OPF processed	3,000,000	22.2
Harvesting and collection cost @ \$ 10/t OPF processed	3,000,000	22.2
Pre-processing cost @ \$ 5/t OPF processed	1,500,000	11.2
Enzyme cost (for saccharification process) @ \$ 20/t OPF processed	6,000,000	44.4
Total cost	13,500,000	100
Specific production cost of renewable sugars (\$/t OPF processed)	45	

### 3.2. Poly(3-hydroxybutyrate) production cost

Based on our previous report, approximately 20,000 t/y of P(3HB) could be produced from 300,000 t/y of fresh OPF (Zahari et al., 2014). The cost composition for P(3HB) production is estimated as follows: raw material (29%), P(3HB) extraction and purification cost (20%), equipment depreciation (27%), energy (11%) and others (13%).

Based on the yield of P(3HB) from OPF juice, which is 0.33 g P(3HB)/g sugar consumed (Zahari et al., 2014), the production of P(3HB) requires 3 kg of renewable sugars per kg of final product. Therefore, the total glucose and OPF juice required to produce 20,000 t/y of P(3HB) is 65,580 t/y. On the other hand, another 34,200 t/y of xylose is needed for the production of 17,000 t/y of bioethanol, which will be used as a solvent for P(3HB) purification as well as a source of energy for P(3HB) production. Raw material cost, which is the cost of renewable sugars from OPF, is estimated at \$ 0.20/kg, which is 60% lower than the current price of raw sugar from sugarcane. This estimation was made based on the production cost of renewable sugars from OPF at \$ 0.045/kg OPF processed. The total production cost of P(3HB) from OPF is estimated at \$  $68.8 \times 10^6$ /y and the detailed calculation is shown in Table 2.

As shown in Table 3, the estimated production cost of P(3HB) using renewable sugars from OPF at \$ 3.44/kg P(3HB) was slightly higher compared with the production cost of PHA estimated from POME at \$ 2/kg (Hassan et al., 1997), sucrose at \$ 2.65/kg (Lee and Choi, 1998), crude glycerol at \$ 1.94 to 2.38/kg (Posada et al., 2011), cheese whey at \$ 2.67/kg (Van Wegen et al., 1998) and sugarcane at \$ 2.65/kg (Nonato et al., 2001). Although the production cost of P(3HB) from OPF was slightly higher compared with sucrose and sugarcane, the use of OPF as a renewable carbon source is advantageous because OPF is a biomass generated abundantly in the oil palm plantation. On the other hand, feedstock for microbial fermentation today is currently taken from edible food source, including sugarcane, soy bean, corn starch and glucose that are also

**Table 2**

Detailed calculation for the specific production cost of P(HB) using 99,780 t/y of renewable sugars from OPF (estimated annual cost: \$  $68.8 \times 10^6$ ).

Item	Cost (\$)	% of total cost
Raw material cost (renewable sugars from OPF)	19,956,000	29
P(3HB) extraction and purification cost	13,760,000	20
Equipment depreciation	18,576,000	27
Energy	7,568,000	11
Others	8,940,000	13
Total	68,800,000	100
Specific production cost (\$/kg P(3HB))	3.44	

**Table 3**

Comparison of P(3HB) specific production cost from renewable carbon sources.

Renewable carbon sources	Specific production cost (\$/kg P(3HB))	Production strain	References
Palm oil mill effluent (POME)	2.00	<i>Rhodobacter sphaeroides</i>	Hassan et al. (1997)
Corn starch hydrolysates	3.72	Recombinant <i>Escherichia coli</i>	Choi and Lee (1999)
Cheese whey	2.67	Recombinant <i>Escherichia coli</i>	Van Wegen et al. (1998)
Cheese whey	3.84	<i>Haloferax mediterranei</i>	Koller et al. (2007)
Sucrose	2.65	<i>Alcaligenes latus</i>	Lee and Choi (1998)
Sugar cane	2.65	<i>Alcaligenes latus</i>	Nonato et al. (2001)
Crude glycerol	1.94–2.38	<i>Cupriavidus necator</i> JMP 134	Posada et al. (2011)
Glucose	5.85	<i>Ralstonia eutropha</i>	Nonato et al. (2001)
Oil palm frond (OPF)	3.44	<i>Cupriavidus necator</i> NCIM11599	This study

consumed by humans and animals. Competition for food consumption between the needs for the growth of human and animals and microbes may affect food chain survival. Therefore, the use of OPF as a source of fermentable sugars may reduce the dependence on food crops and help avoid the food versus fuel issue.

Furthermore, bioethanol produced from this proposed integrated process can be used as a source of energy for P(3HB) production as well as a natural solvent for P(3HB) purification. It will be appropriate to use bioethanol produced from this process as a source of energy for P(3HB) production, which in turn reduces the total production cost. Moreover, the most interesting aspect from this proposed integrated process is the availability of bioethanol for P(3HB) purification, which is a critical step in its production process. Similar to the integrated concept proposed by Nonato et al. (2001), the use of naturally produced and biodegradable solvents in this proposal would allow the production of a very pure P(3HB), while protecting the environmental aspect of the project.

Moreover, Nonato et al. (2001) reported that the production cost for 30,000 t/y of P(3HB) using commercial glucose as a substrate was \$ 5.85/kg P(3HB). Our proposal shows that by using renewable sugars from OPF for P(3HB) production, the production cost can be reduced by approximately 41% compared with commercial glucose. This shows that renewable sugars from OPF are more economically attractive as fermentation feedstock for the production of P(3HB) and other value-added products. Furthermore, by considering  $83 \times 10^6$  t (wet mass) of OPF being generated from  $4.7 \times 10^6$  ha of total oil palm planting area (MPOC, 2010), it is estimated that  $4.65 \times 10^6$  t of renewable sugars can be produced from the Malaysian palm oil industry. Approximately 0.5 t/ha (dry mass basis) of total renewable sugars could be produced from fresh OPF generated in Malaysia, which can serve as renewable and sustainable sugars fermentation feedstock in a biorefinery for value-added products.

However, it should be noted that the production cost of P(3HB) from OPF is heavily dependent on the price of renewable sugars, which accounts for 29% of the final cost. Thus, higher renewable sugars price would increase the total production cost, making the production of P(3HB) from OPF not economically attractive. Additionally, the other major consideration that needs to be accounted for is the productivity of P(3HB) produced from OPF juice, i.e., 0.5 g P(3HB)/(Lh) (Zahari et al., 2014), which is too low compared with those reported by Lee and Choi (1998), i.e., 4.94 g P(3HB)/(Lh). Lower P(3HB) productivity will increase the equipment related cost, which directly increased the total P(3HB) production costs.

This is because, for the same amount of P(3HB) production per year, a process with lower productivity requires larger equipment for fermentation and recovery (Lee and Choi, 1998). Therefore, it is important to increase the P(3HB) productivity from OPF juice, and this will be the focus of a future study.

### 3.3. Impact of the findings of this research

The impact of the findings of this case study can be discussed from several perspectives. Firstly, the utilization of OPF as a fermentation feedstock for the production of value-added products can create new business and profit as well as job opportunities. Considering that more than 400 mills are currently operating across the country, and assuming 10 workers needed for each mill, more than four thousand new job opportunities (1600 skill workers and 2400 operators at a ratio of 2–3) could be created through this new business. Additionally, the utilization of OPF as a fermentation feedstock can create extra income for the oil palm farmers or settlers and generate additional income to the country.

Secondly, the utilization of OPF as fermentation feedstock could also contribute to the proper management of waste disposal from the oil palm industry. A similar concept of waste management proposed by Nonato et al. (2001) in the sugarcane industry could be applied in this study. For instance, the effluents remaining after P(3HB) processing, primarily wasted culture media after biomass removal and effluent waters from the processing can be sprayed on palm oil plantation in the same way as distillery effluents. The biomass remaining after P(3HB) recovery, which is rich in phosphate, calcium, nitrogen and micronutrients, can be composted and applied to the palm oil crops.

Thirdly, OPF is an oil palm biomass that is produced as a by-product of the palm oil industry. Utilization of OPF as an alternative and renewable source of raw material for the production of P(3HB) can reduce the dependence on food crops such as sugarcane, tapioca starch, corn starch and soybean. Additionally, the production of biodegradable plastics from renewable resources also helps preserve the non-renewable resources and contributes to sustainable development (Ren, 2003).

Finally, palm oil mills have a large energy surplus. For instance, the extra steam produced from the FFB sterilizer can be used for sterilization of the fermentation, and the extra electricity produced from the gas turbine driven by methane produced in anaerobic fermentation of POME under the CDM can be used to drive the fermenters (Yoshizaki et al., 2013). Additionally, the problem of higher energy demands for shredding and compressing sap system to obtain the OPF juice could be solved by integration of the renewable sugars extraction process in the oil palm industry, as the mills produce enough energy for their own use. It is believed that the synergy between the new renewable sugars-based industries with the existing palm oil mill has the potential to create a new biomass industry for the bio-economy in Malaysia. In other words, we can conclude that all of the benefits discussed in this case study directly support the three P's sustainability concept (profit, people and planet) as well as the Malaysian National Biomass Strategy 2020, National Biotechnology Policy and the Bio-economy initiatives.

## 4. Conclusion

As shown in this case study, the production cost of P(3HB) from OPF is practical and appropriate. The specific production cost of P(3HB) produced from OPF is estimated at \$ 3.44/kg, which is 41% lower compared with commercial glucose and slightly higher than the estimated cost for PHA production from POME. Utilization of renewable sugars from OPF as fermentation feedstock has many

advantages because it may reduce the dependence on food crops and reduce the fuel versus food issue. This case study shows that renewable sugars from OPF are economically attractive as fermentation feedstock for the production of P(3HB). Overall, renewable sugars from OPF have potential as a sustainable and cheap non-food fermentation feedstock for a sustainable bio-refinery to support the biotechnology industry.

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