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ECONOMICAL STUDY OF BIO-BASED POLYBUTYLENE SUCCINATE PRODUCTION FROM OIL PALM BIOMASS

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ABSTRACT

This work demonstrates the economic feasibility of the production of bio-polybutylene succinate (bio-PBS) with 99.69% purity. Based on an extensive literature review, bio-succinic acid (bio-SA) was produced via fermentation from oil palm fronds (OPF), which was then purified via vacuum filtration, evaporated, crystallised and dried to attain 99.27% purity. The purified bio-SA was then hydrogenated to produce 1,4-butanediol (BDO), prior to polymerisation with bio-SA to produce bio-PBS via esterification. The mass balance analysis performed with SuperPro Designer® showed a negligible error. The proposed design gained profit in a short period of time based on 24.14% internal rate of return (IRR), 6.33 years dynamic payback period (DPP) and RM3366.31 million net present value (NPV). Direct comparison between simulation data and manual calculations showed <25.00% difference, which proved the dependability of the simulation results. Sensitivity analysis predicted that an increment in either bio-PBS's production rate or bio-PBS and by-products pricing can increase the value of NPV and IRR. However, the increment in raw material price and fixed capital investment (C_{FCI}) can lower their values. Collectively, the results highlighted the feasibility of this process on a large scale as it has the potential to generate revenues, ultimately resulting in a sustainable bioplastic industry for packaging applications.

Keywords: bio-polybutylene succinate, economic analysis, oil palm fronds, SuperPro Designer®.

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INTRODUCTION

For more than half a century, plastics have been widely used in practically all commercial products, most notably in packaging via petrochemical processes (Ncube *et al.*, 2021). Among the advantages of plastic packaging are its lightweight, strength, flexibility and low cost (Gerassimidou *et al.*, 2021). Accordingly, the world produced an estimated 6.3 billion tonnes of plastic waste, with only 9% being recycled and more than 80% being deposited in landfills or natural environments (Liang *et al.,* 2021). Such conventional plastic contains potentially harmful components such as phthalates, polyfluorinated compounds, bisphenol-A (BPA), brominated flame retardants, and antimony trioxide. The strong chemical bonds on the plastics make them nearly impossible to be completely decomposed in the natural environment (Rafiqah *et al.*, 2021).

As a country that is heading towards championing the sustainable development goals (SDGs), especially SDGs 13 (climate action), 14 (life below water) and 15 (life on land), Malaysia has been lauded for making good progress in minimising plastic waste in the country. Bioplastics

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were introduced in place of traditional plastics to reduce dependency on limited petroleum resources and associated environmental impacts (Siracusa *et al.*, 2020). Bioplastics are a type of polymer that is derived from biological material, wherein microorganisms such as bacteria, fungi, actinomycetes, and others can degrade them in a short period of time. Bio-polybutylene succinate (bio-PBS) is one of the biodegradable bioplastics that can be produced from agro-industrial biomass, such as oil palm biomass, to minimise environmental pollution (Ioannidou *et al.*, 2022).

Currently, the oil palm (*Elaeis guineensis* Jacq.) generates one of the most abundant biomass sources in Malaysia, particularly the oil palm fronds (OPF) (Onoja *et al.*, 2019). *Figure 1* illustrates the OPF biomass comprising the juice (*i.e.*, liquid fraction) and bagasse (*i.e.*, solid fraction obtains after mechanical pressing). OPF is a major component of the oil palm waste generated by fresh fruit bunch (FFB) pruning, which amounted to ca. 1.5 million tonnes in 2010 and ca. 21.0 million tonnes in 2014 (Mohamad *et al.*, 2020). OPF is the main carbohydrate used in the production of bio-succinic acid (bio-SA) and its application focused more on zero waste technology (Luthfi *et al.*, 2017; Tan *et al.*, 2016).

Given the richness in carbohydrate content, OPF is recommended to be used as raw material for bio-SA production, which serves as a monomer unit in bio-PBS. The first step of bio-SA production is mechanical pre-treatment, such as grinding and crushing, which would reduce the size and moisture content of the OPF (Luthfi *et al.*, 2017; Tu *et al.*, 2019). Pre-treatment is a critical step in the biochemical conversion pathway, which can account for up to ca. 20% of the total cost of the overall process (Amin *et al.*, 2017; Luthfi *et al.*, 2017). Acid hydrolysis is commonly used as pre-treatment to recover pentose from biomass hemicellulose while preserving cellulose and lignin (Bukhari *et al.*, 2021). Thereafter, the recovered sugars can be used in the fermentations to produce bio-SA using *Actinobacillus succinogenes* 130Z as succinate-producing microorganisms (Luthfi *et al.*, 2017; Tu *et al.*, 2019). This bio-SA alongside other carboxylate byproducts were in the form of liquid broth during the fermentation stage.

Purification of fermentation broth is required to achieve bio-SA with 99.00% purity for efficient bio-PBS synthesis (Dai *et al.*, 2020). Evidence in literature suggested that carboxylic acids such as formic and acetic acids could be eliminated by evaporation and distillation, depending on the boiling point of the compound (Law *et al.*, 2019; Omwene *et al.*, 2021). While vacuum distillation for 12 hr at 60°C could eliminate both formic acid and acetic acid, bio-SA with 99.18% purity could be achieved by evaporation before undergoing crystallisation (Li *et al.*, 2010; Thuy *et al.*, 2017). Following that, hydrochloric acid (HCl) or sulphuric acid (H_2SO_4) was used to adjust the pH of the fermentation broth from 6.0-7.0 to 2.0. This is because SA has only 3.00% solubility, whereas formic acid and acetic acid are still soluble in water at 4°C and pH 2.0 (Law *et al., 2019*; Li *et al.*, 2010). Then, hydrogenation of bio-SA with γ-butyrolactone (GBL), an intermediate product, could result in the production of 1,4-Butanediol (BDO) and tetrahydrofuran (THF) using ruthenium (Ru) and rhenium (Re) as catalysts. THF is a high-performance solvent while GBL is an essential intermediate chemical in pyrrolidone derivatives manufacturing (Baidya *et al.*, 2019; Di *et al.*, 2015). PBS, on the other hand, is a versatile semi-crystalline polymer, which makes it popular in a variety of industries (Rafiqah *et al.*, 2021).

Generally, the synthesis of PBS involving bio-SA is divided into two steps: esterification and polycondensation (Rafiqah *et al.*, 2021). The esterification of bio-SA with BDO involved the use of excess diol and diacid to produce PBS oligomer while removing water. The PBS

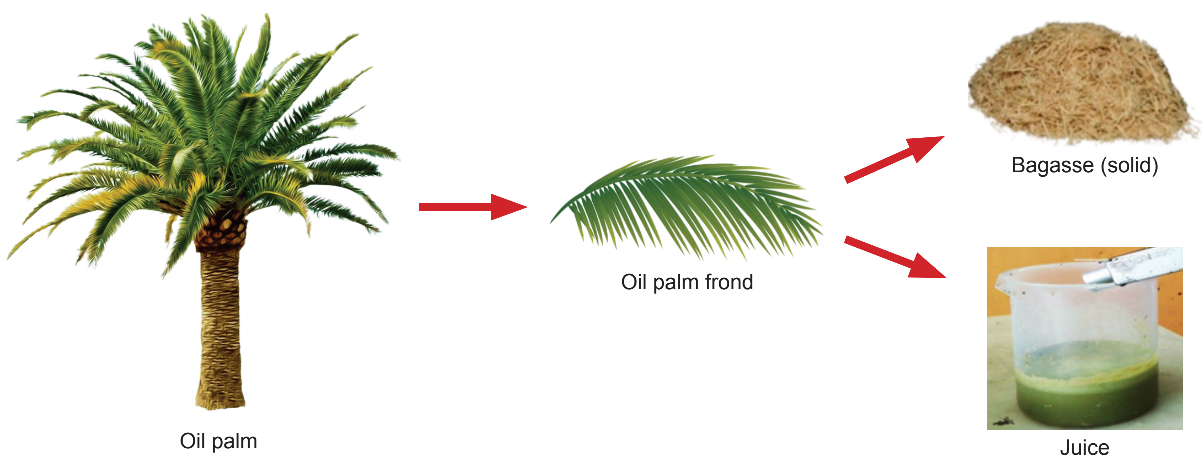

Figure 1. Illustration of oil palm fronds biomass.

oligomers will then be transesterified under vacuum using various catalysts, such as stannous octoate ($SnOct_2$), antimony (III) trioxide (Sb_2O_3), and titanium (IV) butoxide ($Ti(OBu)_4$) to produce high molar mass PBS (Ferreira *et al.*, 2015). The vacuum should be sufficient to remove water and BDO during polycondensation. This method can improve mechanical properties, heat resistance and thermoplastic processes simultaneously (Luthfi *et al.*, 2017; Rafiqah *et al.*, 2021; Tu *et al.*, 2019).

Many studies reported the use of bio-PBS as a composite matrix for multifold applications, including agriculture, packaging, medicine and textiles, given its excellent mechanical properties, high flexibility, melting processing efficiency and biodegradable permeability (Luthfi *et al.*, 2017; Rafiqah *et al.*, 2020; 2021). Thus, bio-PBS is suitable to be used for packaging and provides interesting features such as rigid, robust and exhibits excellent adhesiveness. Processing of bio-PBS is quite simple and can be carried out either by extrusion, thermal formation, or injection moulding (Thurber *et al.*, 2020).

Currently, there is lack of studies dealing with OPF and its possible valorisation into bio-PBS, mostly pointing to OPF as a potential source for biofuels, eco-products, succinic acid production, or livestock feed (Luthfi *et al.*, 2017). There is yet a study on large-scale production of bio-PBS, particularly, using biomass as raw material. Various simulation software, such as DWSIM, SuperPro Designer®, Aspen Plus®, and HYSIS, have been used to demonstrate the chemical operating units used in each processes (SimulateLive.com 2017). SuperPro Designer® software was used in this study to demonstrate the operation of chemical units used in bio-PBS production as it has an extensive database, covering special units of chemical operations. It has also been used in various industries, including pharmaceuticals and biotechnology. Besides that, SuperPro Designer® software can be used for process optimisation, project economic analysis, pollution reduction and control, as well as utility and manpower management (Mabrouki *et al.*, 2015).

Lastly, the data collated from the simulation can be used for economic assessment. The economic analysis can be used to determine the economic efficiency of the bio-PBS manufacturing process, including the profit and whether the whole process is feasible (Turton *et al.*, 2018). Profitability analysis can also be used to determine the rate of return on investment (ROI), dynamic payback period (DPP), internal rate of return (IRR) and net present value (NPV). Besides that, sensitivity analysis was performed to determine parameters that had the most significant influence on the project's performance (Mahmod *et al.*, 2021).

To our best knowledge, the present paper is the first effort that aims to identify the technical and economic feasibility of the production of bio-PBS from OPF. Identifying the best process for producing bio-PBS from bio-SA through extensive literature review is one of the main requirements in simulating large-scale production of bio-PBS. *Figure 2* illustrates the overall research idea of this work. The process simulation to produce bio-PBS was then performed using SuperPro Designer® software, which includes the input and output structure, mass balance analysis and process flow diagram. Lastly, an economic feasibility study on bio-PBS production was performed, including the cost of manufacturing (COM), profitability analysis, comparison of calculations versus simulation data and sensitivity analysis.

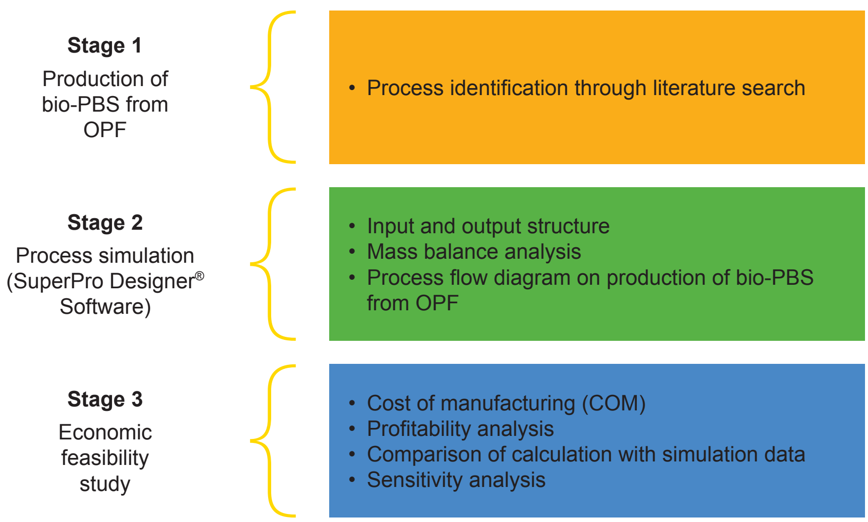

Figure 2. Overall research idea (objective) of this work.

MATERIALS AND METHODS

Raw Materials and Process Description

The information about the process design for the production of bio-SA from OPF was collected from a previous study by Tan *et al.* (2016). OPF (52% glucose, 37% sucrose, 8% fructose, and 3% arabinose) was used as the main carbon source. Size and moisture content of the OPF was reduced through grinding. Then, the ground OPF is acid hydrolysed with 26% H_2SO_4. The sugars in the OPF were then fermented using wild-type *A. succinogenes* 130Z, a succinate-producing microorganism. The conditions for fermentation were 37°C, pH 6.8, 200 rpm and 0.50 vvm carbon dioxide (CO_2). Unreacted CO_2 was recycled into a bioreactor to reduce emissions to the environment.

According to previous studies from Law *et al.* (2019); Li *et al.* (2010); Thuy *et al.* (2017), purification includes several steps of filtration, evaporation, crystallisation and drying of bio-SA. Fermentation broths were purified and evaporated to remove compounds that may affect the purity of the bio-SA. Then, HCl was used to reduce the pH of the fermentation broth before crystallisation to produce bio-SA with at least 99% purity. Lastly, drying was carried out to remove excess volatile compounds and to increase the purity of bio-SA.

Optimal hydrogenation conditions, such as high pressures (45-80 bar) and temperatures (180°C-250°C), were used to produce BDO from bio-SA. Ru-Rutile was chosen as catalyst in hydrogenation due to its high selectivity over BDO (Baidya *et al.*, 2019; Di *et al.*, 2015). Bio-SA and BDO were then esterified to produce bio-PBS and water. $Ti(OBu)_4$ was chosen as catalyst for this process because of its ability to increase the average molecular weight (M_w) of bio-PBS by 33% (Ferreira *et al.*, 2015). The stoichiometric equation for hydrogenation and esterification can be seen in Equation (1) and (2), respectively.

(1) $$C_4H_6O_4\,(s) = 1.31C_4H_{10}O_2\,(l)$$

(2) $$C_4H_6O_4\,(s) + C_4H_{10}O_2\,(l) = (C_8H_{12}O_4)_n\,(s) + 2H_2O\,(l)$$

Process Flow in the Production of Bio-polybutylene Succinate

The process flow diagram for this study, represented in *Figure 3*, was constructed to aid the next step, which was to simulate the mass balance of bio-PBS production from OPF using SuperPro Designer® software (Intelligen, Australia). In this study, OPF was used as raw material and was pre-treated with hydrothermal-assisted acid hydrolysis using H_2SO_4. The sugars in OPF were then fermented with ammonia and CO_2 to produce bio-SA, formic acid, acetic acid, biomass, and water. Next, the fermentation broth was vacuum filtered to remove the biomass. The volatile by-products such as water, acetic acid, and formic acid were then eliminated from fermentation broths through evaporation. The pH of the fermentation broth was then adjusted with HCl prior to the crystallisation process. After that, the fermentation broth was dried to remove extra water and produce bio-SA crystals. Some bio-SA crystals were hydrogenated to produce BDO, while other bio-SA crystals were esterified with BDO to produce the end product (bio-PBS) and water.

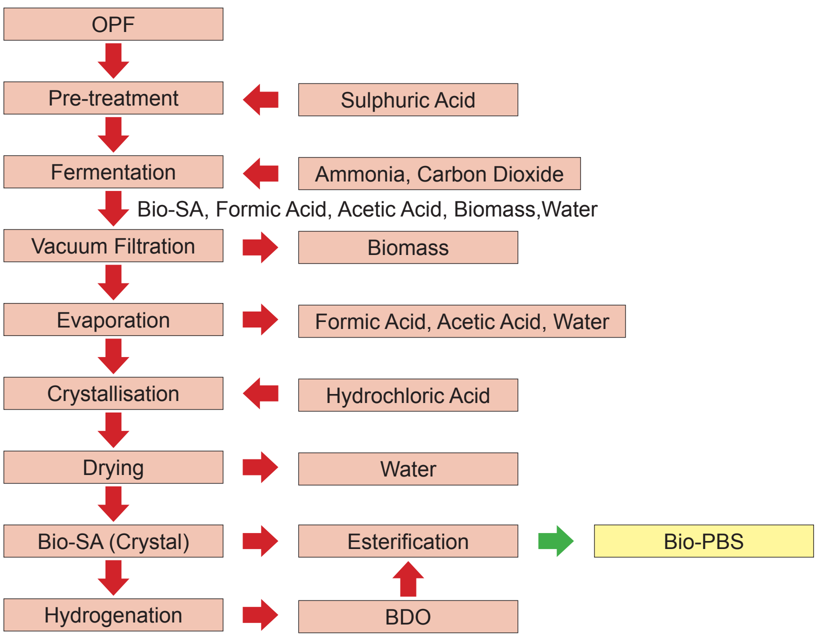

Figure 3. Process flow diagram of bio-PBS production.

Economic Analysis

The use of PBS worldwide registered a CAGR of 38.9% between 2014 to 2020, given its potential in packaging application as well as increasing demand in bioplastics (Tan *et al.*, 2017). Based on Data Bridge Market Research (2020), market for PBS is expected to reach 155.89 ktons by 2027. Thus, the global demand for bio-PBS in 2020 was estimated to be 146 ktons, with only 87 ktons supplied. The market vacancy in Asia-Pasific (APAC) region is around 41 ktons to overcome 59 ktons of shortage. In this research, the bio-PBS production capacity is 5129.46 kg hr^{-1} with the plant operating for 330 days in a year. Some major assumptions were made including a project life of 12 years. Furthermore, the plant start-up and working capital (C_{WC}) were assumed at the end of year 2. Then, 10.0% for start-up cost and 50.0% for investment in year 1 and 2 were assumed from fixed capital investment (C_{FCI}). Besides, the taxation rate is estimated to be 40.0%. Lastly, the depreciation method is based on a 5-year MACR plant life. These assumptions were then used to construct a profitability analysis for the production of bio-PBS from OPF.

C_{TCI} in Equation (3) is the amount of investment required in the construction of a plant where C_{FCI} is the sum of a project's direct and indirect costs. C_{WC}, on the other hand, accounted 20% of C_{FCI} (Bonem, 2018; Turton *et al.*, 2018).

$$C_{TCI} = C_{FCI} + C_{WC} \tag{3}$$

The cost of manufacturing (COM) is the total direct manufacturing cost (DMC), fixed manufacturing cost (FMC) and general expenditure (GE). The simplified expressions to calculate COM and manufacturing costs without depreciation (COM_d) were shown in Equation (4) and (5). Where, C_{RM}, C_{WT}, C_{UL} and C_{OL} are the costs for raw materials, wastewater treatment, utilities and labour, respectively (Turton *et al.*, 2018).

$$COM = 0.28C_{FCI} + 2.73C_{OL} + 1.23(C_{UT} + C_{WT} + C_{RM}) \tag{4}$$

$$COM_d = 0.18C_{FCI} + 2.73C_{OL} + 1.23(C_{UT} + C_{WT} + C_{RM}) \tag{5}$$

Depreciation is classified as four categories: Straight line (SL), double declining balance (DDB), sum of years depreciation (SOYD) and unit of production (UOP). The most recent depreciation method used in the United States is the modified accelerated cost recovery system (MACRS), as shown in Equation (6) and (7) (Investopedia, 2021).

$$d_k^{DDB} = \tfrac{2}{5}\,[100 - \textstyle\sum_{j=0}^{k-1} d_J^{DDB}] \tag{6}$$

$$d_k^{SL} = \frac{(Capital\ without\ deppreciation)}{(Excess\ deppreciation\ time)} \tag{7}$$

Payback period (PBP) and ROI are determined in non-discounted cash flow. PBP is the amount of time required to recover C_{FCI}, with shorter PBP value preferred. ROI, in Equation (8), is the ratio of net income to investment. High ROI value indicates high return on investment from the cost of the process (Bonem, 2018; Mahmod *et al.* 2021; Turton *et al.*, 2018). DPP, NPV and IRR are determined in discounted cash flows. NPV, as shown in Equation (9), is used to evaluate investment profitability, whereas IRR is the value obtained when NPV becomes zero (Bonem, 2018; Turton *et al.*, 2018).

$$ROI = \frac{(Average\ annual\ net\ profit)}{Fixedcapitalinvestment(C_{FCI})} - \frac{1}{n} \tag{8}$$

$$NPV = \frac{\sum_{k=1}^{N} NCF_k}{(1+i)^k} \tag{9}$$

Sensitivity analysis was also performed to predict the uncertainties caused by laboratory-scale parameters and some of the assumptions made during the simulation process (Mahmod *et al.*, 2021). In this study, sensitivity analysis was used to identify the parameters that most influenced the study's performance, with 10% variation in baseline case values.

RESULTS AND DISCUSSION

Production of Bio-polybutylene Succinate

According to Tan *et al.* (2016), the main raw material used in the production of bio-PBS is 19 286.45 kg hr^{-1} of OPF, which composed of 75% solid biomass and 25% juice. The OPF biomass was acid hydrolysed in acid hydrolysis reactor (P-4/R-101) at 82% conversion using H_2SO_4 at 100°C and 1.01 bar (*Figure 4*). At the same time, OPF juice is sterilised in heat steriliser (P-2/ST-101) to prevent contamination of the sugar (Tan *et al.*, 2016). The sugars in the OPF are then fermented in bioreactor (P-6/FR-101) with CO_2, ammonia, and *A. succinogenes* 130Z to produce bio-SA, formic acid, acetic acid, biomass, and water at 95% conversion. This fermentation process takes place at 37°C and 1.01 bar.

The fermentation broth was then vacuum filtered in rotary vacuum filtration (P-7/RVF-102) to remove 98.00% of the biomass, solids suspended in the OPF juice, and excess foreign matter from the acid hydrolysis. Thereafter, the fermentation broth was evaporated in evaporator (P-8/EV-101) to remove 80.00% of the formic acid, acetic acid and water. The pH of the fermentation broth was then adjusted from 6.8 to 2.0 with HCl before going through crystallisation in crystalliser

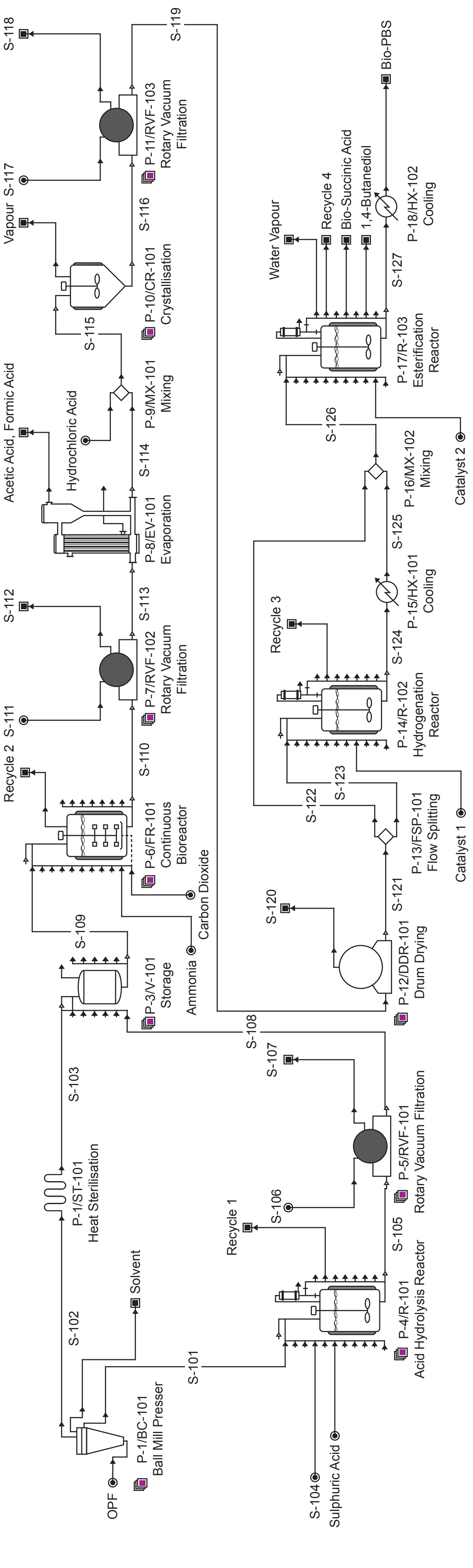

Figure 4. Process flow diagram on production of bio-PBS from OPF using SuperPro Designer® software.

(P-10/CR-101) to increase the purity of bio-SA. Lastly, drying in drum dryer (P-12/DDR-101) was performed to remove any remaining volatile compounds, resulting in bio-SA with 99.27% purity (Law *et al.*, 2019; Li *et al.*, 2010; Thuy *et al.*, 2017).

The bio-SA crystals were then separated into two streams, where one was to be hydrogenated in hydrogenation reactor (P-14/R-102) with Ru-Rutile catalyst to produce BDO with 56% selectivity. The hydrogenation process was carried out at 235.70°C and 60.93 bar (Brzezinska *et al.*, 2020). Lastly, bio-SA crystals and BDO in 1.00:0.74 ratio were esterified in esterification reactor (P-17/R-103) with $Ti(OBu)_4$ catalyst to produce bio-PBS and water with 90% conversion. This esterification process takes place at 170°C and 1.01 bar (Ferreira *et al.*, 2015; Rafiqah *et al.*, 2021).

The annual production of bio-PBS is 40 624.32 tonnes with 99.69% purity. The ratio of OPF to bio-PBS in this study was 1.00:0.27. Low selectivity of bio-SA hydrogenation to BDO led to low yield of bio-PBS from OPF. *Table 1* shows the most common types of catalysts used in SA hydrogenation process. A more in-depth study on the bio-SA hydrogenation can be carried out with the selection of catalysts capable of producing bio-SA with high conversion. According to Luthfi *et al.* (2016), autohydrolysis with sodium hydroxide (NaOH-AH) as pre-treatment prior to enzymatic hydrolysis can yield 33.1 g SA (without formate) and 35.7 g SA (with formate) from 100 g OPF dry biomass. Thus, the yield of bio-PBS production from OPF could be increased by using enzymatic hydrolysis instead of acid hydrolysis.

TABLE 1. CATALYST IN HYDROGENATION OF BIO-SA

Catalyst	Selectivity (%)		
	BDO	GBL	THF
Ruthenium- Rutile (Ru-Rutile)[a]	58.0	40.0	2.0
Ruthenium-P25[a]	5.0	93.0	2.0
Ruthenium-P90[a]	38.0	51.0	11.0
Ruthenium-Anatase-P[a]	29.0	58.0	13.0
Rhenium/Carbon-5%[b]	8.4	41.8	44.5

Source: Brzezinska *et al.*, 2020[a]; Di *et al.*, 2015[b].

Process Simulation on Production of Bio-polybutylene Succinate

Figure 5 illustrates the input and output structure constructed to determine the materials used in the production of bio-PBS from OPF. The mass balance was manually calculated in this study.

According to the input-output mass balance for continuous process in steady state (Turton *et al.*, 2018), the differences between total input and output were 0.17 kg hr^{-1}. The percentage of error for the overall process is 3.35×10^{-5} %.

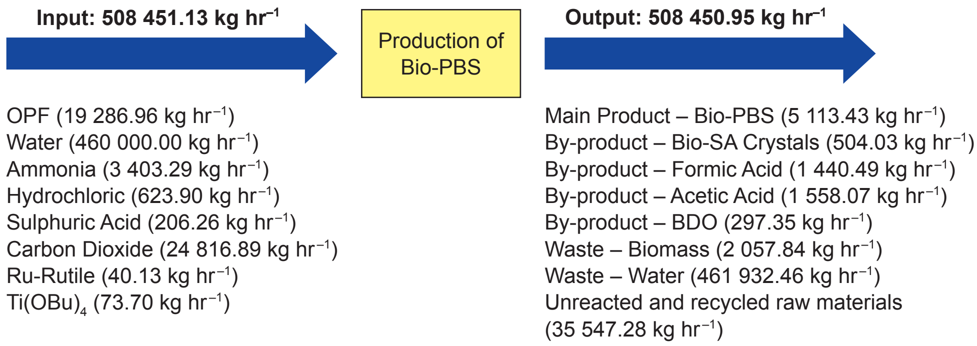

Figure 5. Input and output structure.

Economic Analysis

C_{TCI} was determined by calculating the total cost of equipment (C_{PE}), which is RM189.98 million, as shown in *Table 2*.

The equipment sizing in this study was determined by the SuperPro Designer® software. Thereafter, the direct and indirect costs were calculated, as illustrated in *Table 3*.

The values of C_{FCI} and C_{WC} calculated were RM736.93 million and RM147.39 million, respectively. Using the values obtained, the C_{TCI} value was then calculated to be RM884.32 million. The equation for profit margin calculation is shown in Equation (10), whereby the profit margin obtained was RM1163.51 million (Turton *et al.*, 2018). The value of R in this study was RM2538 million (India Mart, 2021; Molbase, 2021; Tan *et al.*, 2017). COM and COM_d values were calculated to be RM2134.21 million and RM2060.52 million, respectively.

$$\text{Profit Margin} = \sum \text{Revenues} - \sum \text{Cost of Raw Materials} \quad (10)$$

The discounted cash flows for discount rates of 0.00%, 7.00%, 10.00%, 20.00% and 25.00% are shown in *Figure 6*. The IRR value was obtained when NPV equals zero, which was 24.14% in this study. The minimum acceptable rate of return (MARR) is a value that depends on the process and risk level. The MARR in this study was determined to be 16.00% (Tan *et al.*, 2016). This is because integrated process technologies with developed market such as purification, hydrogenation, and esterification were included in this study. Equation (11) was used to determine the reference value of PBP_{ref} at 3.68 years.

$$PBP_{ref} = \frac{0.85}{(MARR + \frac{0.85}{n})} \quad (11)$$

Table 4 summarises the profitability analysis conducted in this study, with DPP value of 6.33 years. To summarise, this study is profitable and worthwhile as the net profit is greater than total capital investment and requires less time to achieve revenue and profits. Manual calculations were compared to the SuperPro simulation considering eight aspects: C_{PE}, equipment installation, C_{TCI}, R, ROI, PBP, NPV at 7% discount rate, and IRR (*Table 5*). Significant differences were observed in C_{PE} and equipment installation since local manufacturing costs are significantly lower than SuperPro software's default settings. The differences also influenced the C_{TCI}, contributing to 53% difference. However, other profitability matrices, such as R, ROI, PBP, NPV and IRR, showed a difference of less than 25%.

Sensitivity Analysis

The sensitivity analysis was conducted with 10% variation in baseline values to identify the parameters (rate of bio-PBS production, price of by-products, bio-PBS, and raw materials, and C_{FCI}) that had the greatest influence on the study's performance. The values and variations of NPV and IRR were analysed in this study as shown in *Figures 7* and *8*.

A positive NPV value indicated that the project is profitable. The value of NPV increased with the increase in bio-PBS production rate, by-product price, and bio-PBS price. In contrast, the value of NPV decreased with the increase in raw material's price and C_{FCI}. Variation in the price of by-products had less impact on NPV due to its lower price, RM22.30 kg^{-1}, compared to RM60.00 kg^{-1} bio-PBS. The minimum value of NPV was obtained with -10% variation in the price of bio-PBS, resulting in RM965.43 million NPV. The +10% variation in the production rate of bio-PBS had greatest impact on the maximum NPV value of RM4266.05 million (*Figure 7*).

High value IRR over MARR, which is 16%, indicated that the project is profitable. According to the findings, the IRR value increased with the increase in the value of bio-PBS production rate, as well as the price of by-products and bio-PBS. The increase in raw material price and C_{FCI}, on the

TABLE 2. TOTAL COST OF EQUIPMENT

Equipment	Capacity	Price at 2021 (RM in million)
Ball mill presser	1 696.84 L hr^{-1}	12.67
Heat sterilisation	5 020.98 L hr^{-1}	0.48
Storage	48 165.43 L	3.64
Acid hydrolysis reactor	36 721.77 L	39.08
Rotary vacuum filtration	76.97 m^2	9.06
Continuous bioreactor	237 156.14 L	18.40
Rotary vacuum filtration	75.30 m^2	11.60
Evaporator	418.23 m^2	4.15
Crystalliser	29 569.04 L	6.00
Rotary vacuum filtration	72.04 m^2	4.80
Drum drying	19.87 m^2	44.09
Hydrogenation reactor	4 350.68 L	2.77
Cooler	10.00 m^2	0.11
Esterification reactor	6 591.36 L	3.04
Cooler	10.00 m^2	0.11
Others	-	30.00

TABLE 3. DIRECT AND INDIRECT COST

Details	% of C_{PE}	% of C_{DPE}
	Direct cost (RM)	
Total purchased equipment, C_{PE}	100.00	
Delivered purchased equipment, C_{DPE}	10.00	
Equipment installation	60.00	
Piping system installation	20.00	
Instrumentation and control system		26.00
Electrical system		15.00
Building	50.00	
Yard improvements	10.00	
Land[a]	RM30.00 million (Land Pajam Industrial Land)	
Service facilities (Installed)	55.00	
	Indirect cost (RM)	
Design and engineering	20.00	
Contractor' fee	6.00	
Legal expenses	5.00	
Construction expenses	17.00	
Contingencies Allowance	15.00	

Source: [a] - Propertyguru (2021).

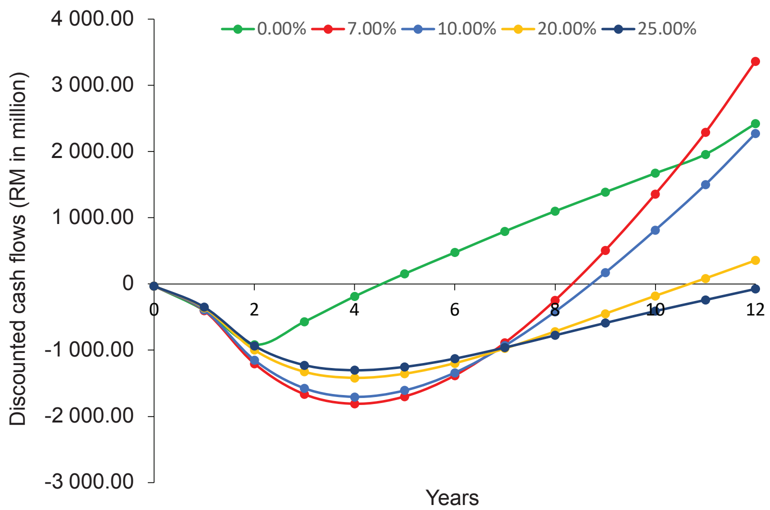

Figure 6. Summary on discounted cash flows.

TABLE 4. SUMMARY ON PROFITABILITY ANALYSIS

In this study		Summary
ROI (32.88%)	MARR (16%)	ROI>MARR
PBP (2.55 yr)	PBP_{ref} (3.68 yr)	$PBP<PBP_{ref}$
NPV (RM3366.31 million)	Positive value	Positive value
IRR (24.14%)	MARR (16%)	IRR>MARR
R (RM2538.11 million)	Positive value	Positive value

TABLE 5. COMPARISON MANUAL CALCULATION WITH SUPERPRO

Details	Manual	SuperPro Software	Differences (%)
C_{PE} (RM in million)	189.98	288.27	34
Equipment installation (RM in million)	113.99	127.78	10
C_{TCI} (RM in million)	884.32	1 918.10	53
R (RM in million)	2 538.11	2 160.28	17
ROI (%)	32.88	42.59	22
PBP (yr)	2.55	2.35	8
NPV (RM in million) at discounted rate 7%	3 366.31	3 971.96	15
IRR (%)	24.14	32.58	25

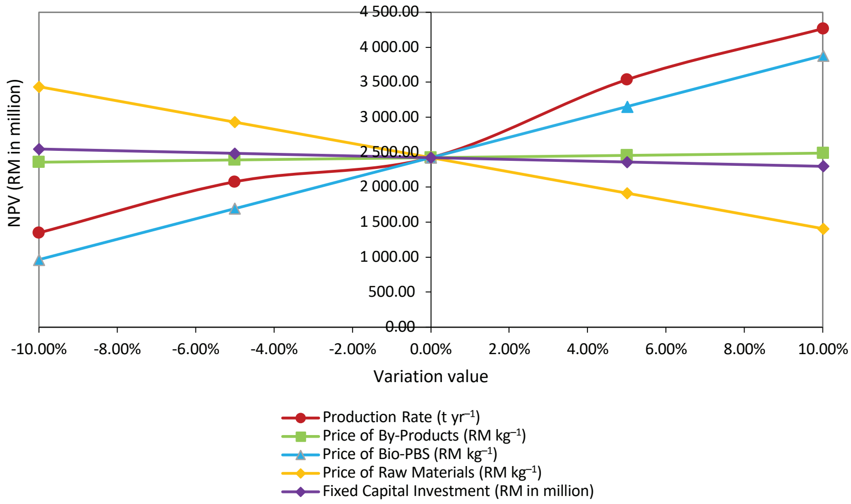

Figure 7. Sensitivity analysis on NPV.

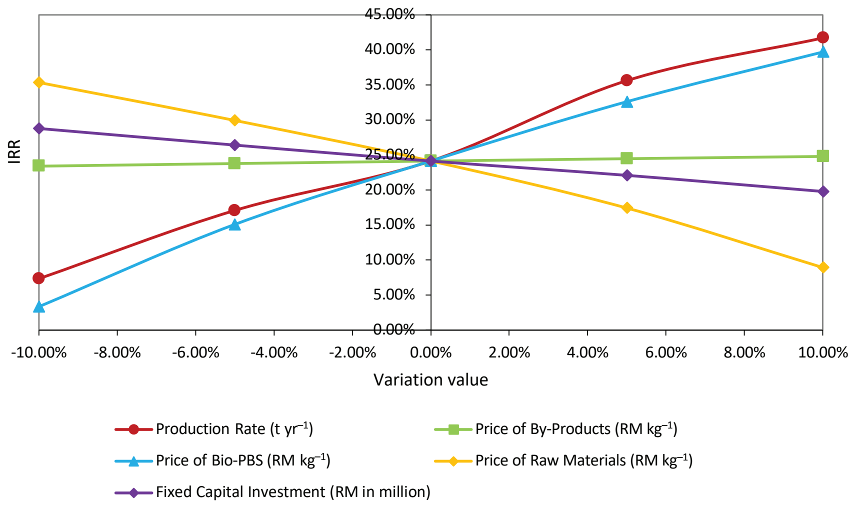

Figure 8. Sensitivity analysis on IRR.

TABLE 6. COMPARISON WITH PREVIOUS STUDIES

Raw materials	Production rate (ktons yr^{-1})	Selling price (RM kg^{-1})	DPP (yr)	References
Glucose	58.63	12.62	7.00	Ioannidou *et al.*, 2022
Corn stover	58.63	13.51	9.00	Ioannidou *et al.*, 2022
Sugar beet pulp	58.63	5.78	6.00	Ioannidou *et al.*, 2022
Sugarcane	24.32	30.12	n.a	Ratshoshi *et al.*, 2021
OPF	40.62	60.00	6.33	This study

other hand, resulted in a decrease in IRR value. These findings are comparable to the sensitivity analysis of NPV. The price parameter of bio-PBS has a minimum IRR of 3.34% with -10% variation. The production rate parameter of bio-PBS, on the other hand, had maximum IRR value of 41.70% with +10% variation (*Figure 8*).

Comparison of economic analysis with previous studies in terms of raw materials, production rate (ktons yr^{-1}), selling price (RM kg^{-1}), and DPP (yr) are shown in *Table 6*. Ioannidou *et al.* (2022) and Ratshoshi *et al.* (2021) produced 58.63 ktons yr^{-1} and 24.32 ktons yr^{-1} of bio-PBS, respectively, while only 40.62 ktons yr^{-1} bio-PBS was produced in this study. The selling price of bio-PBS also showed significant differences, as the value of the selling price is the minimum price from the research conducted by Ioannidou *et al.* (2022) and Ratshoshi *et al.* (2021). This is due to the differences in the process used to produce bio-PBS which led to different effect on the yields of bio-SA and BDO.

According to Ioannidou *et al.* (2022), the fermentation process for producing bio-SA from various raw materials such as glucose, corn stover, and sugar beet pulp involved different process conditions with different succinate-producing microorganism. Purification includes centrifugation adsorption with activated carbon, cation-exchange resin, evaporation, crystallisation and drying to achieve bio-SA with 99.5% purity. Ratshoshi *et al.* (2021), on the other hand, used dilute acid pre-treatment and enzymatic hydrolysis before fermentation of sugarcane to produce bio-SA. The purification of bio-SA, in this case, includes extraction, evaporation, crystallisation and drying to achieve 99.9% purity. Both researchers produced BDO from sugars via fermentation by using an *E. coli* strain. The selling prices of bio-PBS produced from glucose, corn stover, sugar beet pulp and sugarcane were therefore RM12.62 kg^{-1}, RM13.51 kg^{-1}, RM5.78 kg^{-1} and RM30.12 kg^{-1} respectively. This study, on the other hand, focused on hydrogenation process to produce BDO from bio-SA. Low selectivity of BDO (56.00%) resulted in low yield of bio-PBS (Baidya *et al.*, 2019; Brzezinska *et al.*, 2020). Therefore, further study should be conducted on the use of catalysts to achieve high BDO yield.

A similarity between previous reports and this study is that the same catalyst ($Ti(OBu)_4$) was used to produce bio-PBS. Thus, to compensate for the low yield of bio-PBS as a result of low yield from BDO processing, the selling price for bio-PBS should be at least RM60.00 kg^{-1} to generate profit. With bio-PBS as main product in this process, the value of DPP is 6.33 years as OPF as raw material compared to glucose (7 years), corn stover (9 years) and sugar beet pulp (6 years). It can be concluded that this process has reasonable economic feasibility for scaling up by using OPF as raw materials for bio-PBS production.

CONCLUSION

This study provided evidence to the potential of OPF as one of the most promising raw materials in the production of bio-PBS. Based on an extensive literature review, acid hydrolysis of OPF was followed by fermentation with CO_2, ammonia, and *A. succinogenes* 130Z to produce bio-SA, formic acid, acetic acid, biomass, and water. Vacuum filtration, evaporation, crystallisation, and drying were then used to purify the bio-SA to 99.27% purity. Hydrogenation of bio-SA with Ru-Rutile catalyst yielded BDO with 56.00% selectivity. Lastly, bio-SA crystals and BDO are esterified with $Ti(OBu)_4$ catalyst at 1.00:0.74 ratio to yield 90.00% conversion of bio-PBS and water. In terms of profitability, values of ROI and IRR values were higher than MARR (16.00%) while PBP value was lower than the PBP_{ref} (3.68 years) which showed that this project can be profitable in a short period of time. The positive NPV and R values further strengthened the process's economic feasibility, demonstrated that it can be done on a large scale and generating profits in less than 10 years.

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