ECONOMIC ANALYSIS ON PRODUCTION OF BACTERIAL POLYHYDROXYALKANOATES FROM PALM OIL MILL EFFLUENT

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Introduction

Biodegradable bacterial biopolymers or polyhydroxyalkanoates (PHA) produced under nutrient-limiting conditions such as a high carbon/nitrogen ratio (C/N ratio) possess thermoplastic properties and have been widely reported to be potential replacements for petrochemical-based plastics which are essentially non-biodegradable (Anderson and Dawes, 1990, Brandl *et al.*, 1990, and Byrom, 1987). How-

ever, the PHA thus produced currently sells for more than US\$6.00 per kg (Chang, 1994), compared with conventional plastics which are currently sold below US\$2.00 per kg.

We have reported the anaerobic treatment of palm oil mill effluent (POME) coupled with PHA production using photosynthetic bacteria to reduce PHA production cost. (Hassan *et al.*, 1996 and 1997). As the leading producer of palm oil, annually nearly 10 million tons of POME with no less than 20000 ppm BOD is generated and wasted in Malaysia (Ma and Ong, 1986; Ibrahim, 1992). Photosynthetic bacteria could be successfully cultured under non-sterile

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conditions for treating food wastewaters (Kitamura *et al.*, 1984). In Malaysia, with abundant sunlight throughout the year, it would be comparatively easier to culture these bacteria continuously in an open system. POME is suitable for producing PHA because of its high C/N ratio (Ma and Ong, 1986). Treating POME anaerobically eliminates the need for aeration which is costly. Anaerobically treated POME yields volatile organic acids such as acetic and propionic acids which served as carbon sources for producing PHA (Hassan *et al.*, 1996).

This paper assesses the economic feasibility of producing PHA industrially in Malaysia by identifying the main factors which contribute to the overall PHA production cost in the coupled system with the treatment of POME. We also evaluate the effect of increasing the cell PHA content and increased concentration of dissolved PHA in chloroform on the price of PHA to find a better process for the PHA production.

1. Methods

1.1 Proposed system

The effluent is first treated anaerobically to convert the BOD into organic acids (Hassan *et al.*, 1996). After the sludge is separated by alkaline sedimentation (Hulse, 1978), hydrochloric acid is used to neutralise the clarified mixture and photosynthetic bacterium inoculum is added for the PHA production stage, which is conducted in open, shallow ponds with gentle mixing and exposure to sunlight. The treated effluent which is low in BOD can then be discharged after the PHA-laden cells are separated. PHA is separated from the cells or sludge using solvent extraction by chloroform. In order to reduce costs, we suggest a central or shared facility which will process the cells from a few mills within a specified area in the state of Johor where the density of palm oil mills is high. This indicates that transportation cost is required in addition.

1.2 Assumptions

1.2.1 Wastewater treatment cost The treatment cost of POME to accommodate the PHA production by bacteria is assumed to be unchanged from that for a traditional POME treatment system, since both systems use ponds. The traditional system utilises many such ponds for the overall treatment of POME; whereas in the coupled system, fewer ponds are required for the partial treatment of POME. Thus the remaining ponds could be modified for the PHA production step. The costs for sodium hydroxide and hydrochloric acid required for sludge separation and subsequent neutralisation of the effluent are added in the production cost of PHA.

1.2.2 Sludge cost Cells, or sludge with 25% moisture content are assumed to be obtained from the

palm oil mills at no extra charge, apart from the costs for sodium hydroxide and hydrochloric acid mentioned above and the transport cost.

1.2.3 Other related costs Labor costs and interest are not included in our cost estimation. The pay-back period is taken to be 5 years.

1.2.4 Basis of analysis The basis used is to select an area with many palm oil mills situated within a specified distance, and to calculate the optimum cost of obtaining PHA from the cells cultivated in all the factories concerned. The area chosen is inside an 80 km area, somewhere in northern or central Johor; with 24 large mills each of capacity 60 tons of fresh fruit bunches (FFB) h^{-1} and operating for 20 hours a day (600 tons palm oil d^{-1}). The mills are positioned on each intersection point of a 20 km by 20 km grid (apart from the central grid point) inside that square. This is deemed to be a valid basis since Johor has the highest density of palm oil mills in Malaysia.

Theoretically, we could consider two extremes. On the one hand, all the mills could extract the PHA from the cells in a facility located within the factory premises. This would mean 24 such small PHA recovery installations. There are no transport costs involved, but the economies of scale would not favor such a system. On the other hand, all the PHA-laden cells could be transported to be processed in one large central PHA recovery factory. This would benefit from the economy of scale; however, high transport costs would be required. Hence, an optimum cost for the whole system should be obtained, involving several mills pooling their sludge for recovery of PHA. The PHA recovery factory operates annually for 250 days. Each cost is estimated as mentioned below to obtain the total costs involved in each case from which the unit cost of PHA is determined.

1.2.5 Transportation costs As mentioned above, the palm oil mills and PHA factories are placed evenly on the grid inside an 80 km by 80 km area. Thus we have many possible systems: 1 PHA factory for 24 palm oil mills, or the ratio could be 1 : 12 hence 2 PHA factories required, or 1 : 6 hence 4 total PHA factories, and so on. As an estimate of the total distance covered, the trucks are assumed to travel along the grid lines to reach the PHA factory. Based on the mass balance for each palm oil mill (Ma and Ong, 1986), around 600 tons d^{-1} of POME would be generated, from which 8.7 tons d^{-1} of organic acids could be obtained (Hassan *et al.*, 1996). About 2.6 tons PHA d^{-1} can be accumulated by the bacterial cells assuming a 30% yield. With 50% dry cell weight of PHA (Hassan *et al.*, 1996) and assuming 25% moisture of the dried cells, the amount of cells which has to be transported per mill is 7 tons d^{-1} . The average transport cost in Malaysia is taken to be US\$4 per ton for a 40 km distance as quoted by The Malaysian Transport Association.

Fig. 1 Process layout for recovery of PHA from dried cells (Plant capacity: 168 tons sludge d⁻¹)

Table 1 Current costs of materials, transport and utilities in Malaysia and amounts required for 168 tons sludge d⁻¹ PHA factory

Item	Current Cost (US\$)	Amount required yr ⁻¹
Chloroform	1136 ton ⁻¹	5750 tons
Hexane	383 ton ⁻¹	3025 tons
Sodium hydroxide	450 ton ⁻¹	208 tons
Hydrochloric acid	75 ton ⁻¹	20.8 tons
Diesel oil	300 ton ⁻¹	2920 tons
Water	2 ton ⁻¹	21000 tons
Electricity	0.1 kWh ⁻¹	1210000 kWh
Transport	0.1 ton ⁻¹ km ⁻¹	2079000 t.km

1.3 Production costs

The proposed layout of the PHA extraction factory including material balance is shown in **Fig. 1**. The sludge containing PHA is mixed with hot chloroform to dissolve the biopolymers. The cell PHA content is taken to be 50% based on our previous work (Hassan *et al.*, 1997) and the concentration of PHA dissolved in chloroform used is 2%. The filtered solution is then mixed with hexane to precipitate out the PHA and the solvents are recovered by distillation and recycled. Fresh solvents are added to account for losses; with 0.5% make-up. Mass and energy balances are performed based on the production capacities of the PHA factories. Sodium hydroxide used for PHA separation and hydrochloric acid required to neutralise the pH of the treated effluent for disposal in the palm oil mills are also included in the costings. The costs of materials are obtained from industry in Malaysia or based on estimates of their prices in Japan (The Chemical Daily Co. Ltd., 1995) and corrected for the Malaysian situation by multiplying by 0.5 of the prices in Japan as a local factor. Current industrial costs for utilities in Malaysia are used. These costs are summarised in **Table 1**.

1.4 Capital costs

The total capital cost estimates are performed for one, two, four, eight, twelve and 24 PHA recovery factories by using an integrated computer program that we developed. Costs for the individual equipments are obtained from a chemical engineering handbook (Holland *et al.*, 1984). The costs of capital equipment at different scales are obtained by incorporating the suggested exponents as given by the following equation:

$$C_2 = C_1 (q_2/q_1)^n \quad (1)$$

where C and q are cost and size of a piece of equipment, respectively. Subscripts 1 and 2 denote the different sizes. C_1 , q_1 , and n were cited from the reference (Holland *et al.*, 1984). Three times our estimated values for the freight charges and costs for installation and commissioning in Malaysia are added to the total plant cost. The cell PHA content and the ratio of PHA to chloroform are expected to be important factors in determining the overall PHA plant size; since higher cell PHA content would result in larger equipment sizes such as tanks and distillation columns, whereas higher PHA concentration in the solvent would reduce the plant size and cost. Hence, the effect of increased PHA content in the dried cells on the plant equipment size is analysed, as well as the effect of increasing the percentage of PHA dissolved in the chloroform.

2. Results

2.1 PHA production capacity

Based on the mass balances, the estimated cell or sludge weight with 25% moisture content produced per mill is 7 tons d⁻¹. Depending on the ratio of the number of PHA factories to palm oil mills, the production capacities of the PHA factories can be obtained; ranging from 7 tons cells d⁻¹ when the cells are processed on site within the same premise, to 168 tons cells d⁻¹ when the cells from all the participating mills are transported to a single central PHA factory. The PHA production capacities in each PHA factory ranged from 2.6 to 63 tons PHA d⁻¹, respectively.

2.2 Transport, production and capital costs

A comparison of the transport cost, production cost and capital cost for the PHA production system for the 168 tons sludge d⁻¹ PHA factory is shown in **Table 2**. It is evident that the transport cost estimates are quite low in comparison to the other production costs and the capital cost. More than 70% of the total cost is due to the capital cost.

2.3 Optimum cost

The optimum cost for producing PHA in the proposed set-up is shown in **Fig. 2**. The lowest PHA price is found at the 168 tons sludge d⁻¹ PHA factory,

Table 2 Breakdown of costs for PHA production factory processing 168 tons dried sludge d^{-1} (estimated annual cost: US\$30.3 Million)

Item	% of Total Cost
Equipments	71.1
Solvents	25.4
Diesel oil	2.2
Water	0.1
Reagent	0.2
Electricity	0.4
Transport	0.6

Fig. 2 Optimum cost estimation for unit cost of PHA (Plant capacity: from 7 to 168 tons sludge d^{-1})

indicating that it is best to operate with only one PHA factory for all the 24 palm oil mills concerned. This is due to the rather low transportation costs in Malaysia. With 50% PHA content in the dried cells and with 2% PHA dissolved in the chloroform, the calculated minimum PHA cost from POME is below US\$2 kg^{-1} . **Figures 3** and **4** show the effects of PHA content in cell and PHA concentration in chloroform on the PHA price, respectively. If the cell content can be increased, the PHA cost could be slightly reduced as shown in Fig. 3. However, if the percentage of PHA dissolved in the chloroform increases, there is a marked reduction in the unit price of PHA as can be seen from Fig. 4.

3. Discussion

In our suggested set-up, it is most economical to produce PHA at a single large PHA recovery factory for all the participating palm oil mills in Johor. The economy of scale far outweighs the transportation costs. The overall plant cost is generally proportional to the production capacity to the six-tenths exponent. Although the transportation cost is directly proportional to the distance covered, the increase is much smaller in comparison to the reduction of the plant cost per kg PHA processed. The basic unit cost

Fig. 3 PHA unit cost at different PHA content in cells (Plant capacity: 168 tons sludge d^{-1})

Fig. 4 PHA unit cost at different PHA concentration in chloroform (Plant capacity: 168 tons sludge d^{-1})

of PHA produced from POME in this set-up is less than US\$2 kg^{-1} .

Assuming a pay-back period of 5 years, the total annual plant and production cost for the large PHA factory (without transportation cost) is estimated to be about US\$30.3 million; with capital cost accounting for more than 70% of the PHA cost. Here no labor cost was included. However, not more than 2% of the total cost is confirmed to be accounted for by labor costs, judging from the Malaysian economy. Much of the capital plant cost is due to the large sizes of equipment and distillation columns required to handle the solvents, especially chloroform. In this study, the amount of PHA in the dried cells is taken to be 50% and the dissolved PHA in the chloroform is 2% based on our previous work (Hassan *et al.*, 1996, and 1997). It is expected that both these parameters would be important determinants of the plant capital cost. Here we establish that by increasing the cell PHA content from 50% to 80%, the unit cost of PHA could be slightly reduced; but by increasing the amount of PHA dissolved in chloroform from 2% to 5% would result in a marked reduction of the price of PHA to less than US\$1 kg^{-1} , indicating that a smaller PHA separation facility is more economically advantageous.

Methylene chloride has higher solubility of PHA than chloroform though its price is higher than that of chloroform (The Chemical Daily Co. Ltd., 1995), indicating that methylene chloride would be more suitable for extracting PHA from sludge and that it might realize a PHA production cost less than US\$1 kg⁻¹.

Conclusion

In conclusion, as illustrated in this case study, the production of PHA by the coupled system with treatment of palm oil mill effluent in Malaysia is economic, with several palm oil mills pooling the PHA-laden sludge to be processed in a central PHA extraction facility. The plant cost contributes most to the overall cost, due to the need to use large amounts of solvents for PHA recovery. Higher PHA to solvent ratios could significantly lower the unit cost of PHA. It is suggested that any PHA recovery using small PHA separation facilities including those without extraction could also be pursued for the economic production of PHA.

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Nomenclature

C = cost of equipment
 q = capacity of plant
 n = exponent

[—]

<Subscript>

1 and 2 = refer to the small and large sizes respectively

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