

# Environmental analysis of plastic production processes: Comparing petroleum-based polypropylene and polyethylene with biologically-based poly- $\beta$ -hydroxybutyric acid using life cycle analysis

K.G. Harding<sup>a,\*</sup>, J.S. Dennis<sup>b</sup>, H. von Blottnitz<sup>c</sup>, S.T.L. Harrison<sup>a</sup>

<sup>a</sup> *Bioprocess Engineering Research Unit, Department of Chemical Engineering, University of Cape Town, South Africa*

<sup>b</sup> *Department of Chemical Engineering, University of Cambridge, UK*

<sup>c</sup> *Environmental & Process Systems Engineering Research Group, Department of Chemical Engineering, University of Cape Town, South Africa*

Received 10 July 2006; received in revised form 6 February 2007; accepted 19 February 2007

## Abstract

Polymers based on olefins have wide commercial applicability. However, they are made from non-renewable resources and are characterised by difficulty in disposal where recycle and re-use is not feasible. Poly- $\beta$ -hydroxybutyric acid (PHB) provides one example of a polymer made from renewable resources. Before motivating its widespread use, the advantages of a renewable polymer must be weighed against the environmental aspects of its production. Previous studies relating the environmental impacts of petroleum-based and bio-plastics have centred on the impact categories of global warming and fossil fuel depletion. Cradle-to-grave studies report equivalent or reduced global warming impacts, in comparison to equivalent polyolefin processes. This stems from a perceived CO<sub>2</sub> neutral status of the renewable resource. Indeed, no previous work has reported the results of a life cycle assessment (LCA) giving the environmental impacts in all major categories. This study investigates a cradle-to-gate LCA of PHB production taking into account net CO<sub>2</sub> generation and all major impact categories. It compares the findings with similar studies of polypropylene (PP) and polyethylene (PE). It is found that, in all of the life cycle categories, PHB is superior to PP. Energy requirements are slightly lower than previously observed and significantly lower than those for polyolefin production. PE impacts are lower than PHB values in acidification and eutrophication. © 2007 Elsevier B.V. All rights reserved.

**Keywords:** Bioplastics; Life cycle assessment (LCA); Polyhydroxyalkanoate; Polyhydroxybutyrate; Polypropylene; Polyethylene

## 1. Introduction

Biopolymers are renewable, largely biodegradable and can have very similar properties to conventional polyolefin polymers. These are all desirable properties given that the use of conventional plastics is wide spread. Polyolefins are produced from fossil fuels and resource depletion may become a determining factor in future production. Understanding their environmental impact is important when comparing them to biopolymers.

The environmental benefits that could occur in replacing conventional polymers with biopolymers may however come at an economic loss (Zinn et al., 2001; Godbole et al., 2003). Biopolymers currently of interest include thermoplastic starch (TPS),

polylactides (PLA), poly- $\beta$ -hydroxybutyric acid (PHB) and its copolymers (PHAs), and polymer fills. PHBs are considered strong candidates as they have very similar properties to synthetic polymers, as seen in Table 1, but degrade completely to water and carbon dioxide under aerobic conditions (Lee, 1996). However, the full environmental benefits of PHBs are unknown as no full life cycle assessment (LCA) study exists (Patel et al., 2002). This study aims to clarify the environmental advantages of PHB over the petroleum-based plastics (polyolefins), specifically polypropylene and polyethylene.

Studies of PHBs in comparison to the conventional plastics polypropylene (Akiyama et al., 2003), polyethylene (Luck, 1996; Heyde, 1998; Kurdikar et al., 2001; Akiyama et al., 2003), polystyrene (Luck, 1996; Heyde, 1998; Gerngross, 1999; Akiyama et al., 2003) and poly(ethylene terephthalate) (Gerngross and Slater, 2000; Akiyama et al., 2003) have focused on carbon dioxide emissions and energy requirements

\* Corresponding author. Fax: +27 21 650 5501.

E-mail address: [sue.harrison@uct.ac.za](mailto:sue.harrison@uct.ac.za) (S.T.L. Harrison).

Table 1  
Properties of polypropylene and poly- $\beta$ -hydroxybutyric acid (PHB)

	Units	Polypropylene	PHB
Density	kg/m <sup>3</sup>	900–910 <sup>a</sup>	1250 <sup>b</sup>
Melting point	°C	176 <sup>c</sup>	45–180 <sup>c</sup> P(3HB) = 180 <sup>c</sup>
Tensile strength	MPa	38 <sup>d</sup>	13–40 <sup>b</sup>
Shrinkage	%		1–3 <sup>b</sup>
Elongation	%	400 <sup>d</sup>	5–680 <sup>d</sup>
Young's modulus	MPa	17000 <sup>d</sup>	350–1000 <sup>b</sup>
Glass-transition temperature	°C	–10 <sup>c</sup>	15 <sup>a</sup> P(3HB) = 4 <sup>c</sup>
Service temperature	°C		–30 to 120 <sup>b</sup>
Specific heat (20–80 °C) <sup>d</sup>	kJ/kgK	1.9	
Thermal conductivity (20–150 °C) <sup>d</sup>	kW/mK	0.42–0.61	

<sup>a</sup> Ogorkiewicz (1970).

<sup>b</sup> Delft (2004).

<sup>c</sup> Doi (1990).

<sup>d</sup> Sudesh et al. (2000).

and arrive at conflicting conclusions. PHB production results showed reductions in greenhouse gas emissions (Gerngross, 1999; Gerngross and Slater, 2000; Akiyama et al., 2003), but greater energy requirements (Gerngross, 1999; Gerngross and Slater, 2000; Kurdikar et al., 2001). However, Akiyama et al. (2003) recorded a decrease in energy requirements of PHB production. Luck (1996), Heyde (1998) and Kurdikar et al. (2001) reported a range of results based on different process technologies and methods of biopolymer production. Certain outcomes were dependent on specific process conditions. These literature studies, as well as the current study, consider polymer production only.

Based on results from the laboratory production of PHB by microbial growth developed to mimic the ICI-Zeneca Biopol process operated at pilot scale (10 m<sup>3</sup>), this study models the scaled up production of this polymer. A full mass and energy balance for a potential process was undertaken for 1000 kg of polymer. The results were used in a cradle-to-gate life cycle assessment (LCA) of the polymer to give impacts in all the LCA impact categories: abiotic depletion, global warming, ozone layer depletion, human toxicity, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification and eutrophication. The LCA results are for production only (cradle-to-gate) and exclude the impacts of use, recycle or disposal (cradle-to-grave). The results were compared with those from Boustead (2000) for polypropylene (PP) and polyethylene (PE).

## 2. Poly- $\beta$ -butyric acid production

The biopolymer, polyhydroxyalkanoate (PHA) can be synthesised in a number of ways: (i) wild type or recombinant microorganisms (e.g. Akiyama et al., 2003), (ii) *in vitro* production via PHA-polymerase catalysed polymerisation, (iii) using genetically engineered plants (e.g. Gerngross, 1999; Gerngross and Slater, 2000; Kurdikar et al., 2001) or (iv) by the anaerobic digestion of biological wastes (Zinn et al., 2001; Reddy et al., 2003). This study is confined to microbial production of poly- $\beta$ -butyric acid, a grouping of the PHA biopolymers, which requires ambient growth temperatures but long residence times

(Lee, 1996; Reddy et al., 2003). Carbon sources include glucose strains or waste effluents, such as beet or cane molasses, plant oils, plant-derived fatty acids and alkanes (Sudesh et al., 2000). For many systems, the cheapest and most appropriate carbon source for production is cane sugar (Nonato et al., 2001), although starch and whey can also be used to produce PHB (Kim, 2000).

Commercial data are not readily available for a full LCA study, although Chen et al. (2001) have presented some results for poly(3-hydroxybutyrate-co-3-hydroxyhexanoate) production in a 20 m<sup>3</sup> reactor and Akiyama et al. (2003) on computer simulated PHB production using bioreactor volumes between 300 and 700 m<sup>3</sup>. Lee and Choi (1998) estimated the economics of production of 100,000 te/y of biopolymer but do not give sufficient detail for this study. Results from studies at the laboratory scale, including process conditions and media preparation, have also been presented (Harrison, 1990; Wang and Lee, 1997; Grothe et al., 1999; Kim, 2000; Chen et al., 2001; Yu et al., 2005). This includes PHB production using *Cupriavidus nectar*, *Azohydromonas lata*, *Escherichia coli*, *Azotobacter chroococcum* and *Aeromonas hydrophila* on carbon sources such as glucose, sucrose and starch in batch, fed batch and continuous processes with details given in Table 2. Partial details of microbial growth, PHB accumulation and process conditions are also described by Lee (1996), Steinbüchel and Fuchtenbusch (1998), Nonato et al. (2001), Zinn et al. (2001) and Khanna and Srivastava (2005).

PHB yields and growth rates are quoted by several authors, including Ackerman and Babel (1998), Grothe et al. (1999), Nonato et al. (2001) and Khanna and Srivastava (2005). The amount of polymer, as a percentage of total biomass, ranges from 20 to above 85%. Maximum PHB concentrations, productivities and yields are shown to be 106 kg PHB/m<sup>3</sup>, 4.94 kg PHB/m<sup>3</sup>/h and 0.8 kg PHB/kg substrate, respectively, as seen in Table 3.

Harrison (1990), Lee and Choi (1998), Chen et al. (2001), Zinn et al. (2001) and Akiyama et al. (2003) describe downstream processing for polymer recovery and purification units possibly including cell disruption, surfactant pretreatment, solvent extraction, precipitation, flocculation, filter pressing, rotary vacuum drying, centrifugation and spray drying. Downstream processing can yield up to 95% recovery of polymer (Lee and

Table 2  
Literature review of process conditions

	Organism	Process conditions	Carbon substrate	Fermentation media	Reactor type
Harrison (1990)	<i>Cupriavidus necator</i> (“ <i>Wautersia eutrophus</i> ”, “ <i>Ralstonia eutrophus</i> ”, “ <i>Alcaligenes eutrophus</i> ”)	6.5 dm <sup>3</sup> 30 °C 1500 rpm max., 2 6-blade impellers	Glucose	H <sub>3</sub> PO <sub>4</sub> (1 dm <sup>3</sup> /m <sup>3</sup> ), (NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> (1.4 kg/m <sup>3</sup> ), K <sub>2</sub> SO <sub>4</sub> (1.7 kg/m <sup>3</sup> ), MgSO <sub>4</sub> .7H <sub>2</sub> O (1.9 kg/m <sup>3</sup> ), trace elements (9 dm <sup>3</sup> /m <sup>3</sup> )	Fed batch
Wang and Lee (1997)	<i>Azohydromonas lata</i> (“ <i>Alcaligenes latus</i> ”)	6.6 dm <sup>3</sup> 30 °C 700 rpm max. 40% DO	Sucrose	KH <sub>2</sub> PO <sub>4</sub> (0.6 kg/m <sup>3</sup> ), Na <sub>2</sub> HPO <sub>4</sub> .12H <sub>2</sub> O (3.6 kg/m <sup>3</sup> ), MgSO <sub>4</sub> .7H <sub>2</sub> O (1 kg/m <sup>3</sup> ), CaCl <sub>2</sub> .2H <sub>2</sub> O (0.1 kg/m <sup>3</sup> ), citric acid (0.1 kg/m <sup>3</sup> ), trace elements (3 dm <sup>3</sup> /m <sup>3</sup> ) (NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> , KH <sub>2</sub> PO <sub>4</sub> , Na <sub>2</sub> HPO <sub>4</sub> ,	Fed batch
Grothe et al. (1999)	<i>Azohydromonas lata</i> (“ <i>Alcaligenes latus</i> ”)	0.2 dm <sup>3</sup> 25–37 °C 200 rpm (shake flask) 96 h	Sucrose	MgSO <sub>4</sub> .7H <sub>2</sub> O, trace elements	Batch
Kim (2000)	<i>Azotobacter chroococcum</i> , <i>Escherichia coli</i>	2.5 dm <sup>3</sup> 30 °C	Starch	Whey powder (11.5% proteins, 74% lactose) (30 kg/m <sup>3</sup> ), (NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> (4 kg/m <sup>3</sup> ), KH <sub>2</sub> PO <sub>4</sub> (13.3 kg/m <sup>3</sup> ), MgSO <sub>4</sub> .7H <sub>2</sub> O (1.2 kg/m <sup>3</sup> ) citric acid (1.7 kg/m <sup>3</sup> ), trace element solution (10 dm <sup>3</sup> /m <sup>3</sup> )	Fed batch
Chen et al. (2001)	<i>Aeromonas hydrophila</i>	20 m <sup>3</sup> 46 h	Glucose	Yeast extract, lauric acid, (NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> (1–2 kg/m <sup>3</sup> ), Na <sub>2</sub> HPO <sub>4</sub> (3.5–5.8 kg/m <sup>3</sup> ), MgSO <sub>4</sub> .7H <sub>2</sub> O (0.2–0.5 kg/m <sup>3</sup> ), CaCl <sub>2</sub> .2H <sub>2</sub> O (0.05–0.1 kg/m <sup>3</sup> ), Trace elements (1–2 kg/m <sup>3</sup> )	Fed batch
Yu et al. (2005)	<i>Cupriavidus necator</i> (“ <i>Wautersia eutrophus</i> ”, “ <i>Ralstonia eutrophus</i> ”, “ <i>Alcaligenes eutrophus</i> ”)	2 dm <sup>3</sup> 26 °C  48 h Aeration: 20% of saturation	Glucose, Sodium propionate	Na <sub>2</sub> HPO <sub>4</sub> .7H <sub>2</sub> O (6.7 kg/m <sup>3</sup> ), KH <sub>2</sub> PO <sub>4</sub> (1.5 kg/m <sup>3</sup> ), (NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> (2.5 kg/m <sup>3</sup> ), MgSO <sub>4</sub> .7H <sub>2</sub> O (0.2 kg/m <sup>3</sup> ), FeS (60 g/m <sup>3</sup> ), CaCl <sub>2</sub> (10 g/m <sup>3</sup> ), trace mineral solution (10 dm <sup>3</sup> /m <sup>3</sup> ) 2% (w/v) glucose, 0.2% (w/v) yeast extract	Continuous

Table 3  
Literature review of percentage PHB content of biomass, concentration, productivity, yield and biomass growth rates following its aerobic microbial production

	Percentage polymer wt % PHB	Biomass concentration kg biomass/m <sup>3</sup>	Polymer concentration kg PHB/m <sup>3</sup>	Polymer productivity kg PHB/m <sup>3</sup> /h	Polymer yield kg PHB/kg substrate	Biomass growth rate /h
Harrison (1990) <sup>a</sup>	70	150	106	1.18 <sup>b</sup>	0.36	0.11–0.33
Wang and Lee (1997), Lee and Choi (1998)	87–88.3	111	98.7	4.94–5.13	0.42	0.044 <sup>b</sup>
Grothe et al. (1999)	63	1.1–3.9 <sup>b</sup>	0.73–2.48	0.15 (0.38 kg sucrose/m <sup>3</sup> /h)	0.4	0.075
Kim (2000)	20–80	54–87	0.864–61	0.0149–0.9	0.04–0.33	0.017 <sup>b</sup>
Chen et al. (2001)	50	50	25	0.54	0.25 <sup>b</sup>	0.029 <sup>b</sup>
Nonato et al. (2001)	65–70	120–150	78–105 <sup>b</sup>	1.44	0.32	0.014–0.018 <sup>b</sup>
Akiyama et al. (2003)	75–85	100–200	75–170 <sup>b</sup>	4.63	0.3–0.8	0.023–0.046 <sup>b</sup>
Khanna and Srivastava (2005)	76	9.3–159 <sup>b</sup>	7.1–121	1.15–2.42	0.36–0.4	0.265
Yu et al. (2005)	22–90 <sup>b</sup>	3.10–7.96	1.73–2.8	0.045–0.252		0.019–0.136

<sup>a</sup> Reference from which information is taken for modeling PHB production.

<sup>b</sup> Calculated estimate values.

Choi, 1998; Nonato et al., 2001) at purities greater than 98% (Nonato et al., 2001; Zinn et al., 2001).

### 3. PHB simulation model

The inventory data for the life cycle assessment (LCA) of poly-β-hydroxybutyric acid production was based on the lab-

oratory study of Harrison (1990) which was linked to a pilot scale process. This work used a variation of the BIOPOL flow-sheet, developed by ICI for production of bacterial PHB from glucose (Asrar and Grys, 2002). Here it is scaled up from laboratory data to give 1000 kg of PHB. The basic process involves a batch stage allowing bacterial growth of *Cupriavidus necator* (formerly *Wautersia eutrophus*, *Ralstonia eutrophus* and *Alcali-*

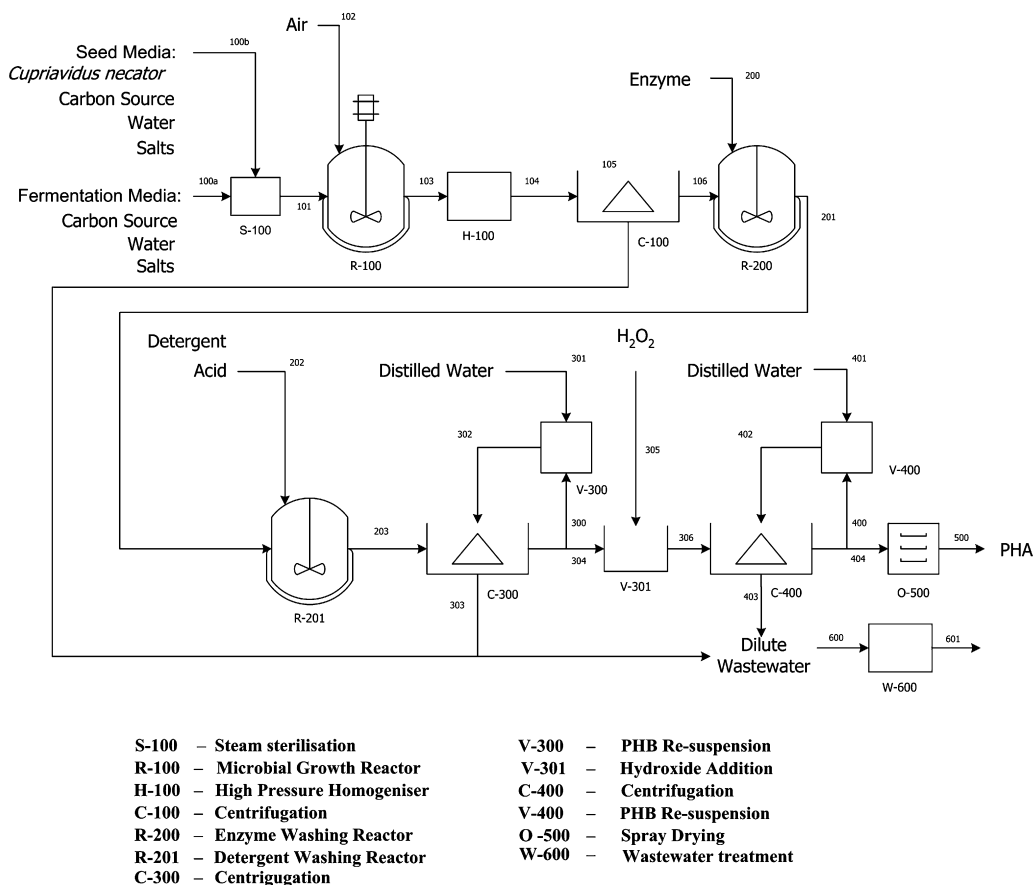


Fig. 1. Process flowsheet for PHB production.

*genes eutrophus* (DSMZ, 2006)), followed by a fed batch phase in which the cells accumulate intracellular polymer with significant increase in non-polymer cell mass. Substantial downstream processing is needed to liberate and purify the polymer product. These data are similar to that for other authors as shown in Table 3 and can be taken as representative of PHB production.

In the process shown in Fig. 1, the seed (*Cupriavidus necator*, sucrose,  $(\text{NH}_4)_2\text{SO}_4$ ,  $\text{K}_2\text{HPO}_4$ ,  $\text{NaHPO}_4$ ,  $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ ,  $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$  and trace salts) and fermentation media (sucrose,  $\text{H}_3\text{PO}_4$ ,  $(\text{NH}_4)_2\text{SO}_4$ ,  $\text{K}_2\text{SO}_4$ ,  $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ , trace salts and antifoam) are prepared and sterilized in a continuous system at  $139^\circ\text{C}$  (S-100). Details of quantities used are given in Table 4. The medium is added to an aerated semi-batch reactor with a working volume of  $9.4\text{ m}^3$  and agitated with a stirrer dissipating  $0.5\text{ kW/m}^3$  power. Following batch production of biomass, a sucrose feed is initiated. With the onset of phosphate limitation, PHB accumulates. The total reaction time is 80 h, producing 1417 kg biomass (71% PHB) at a concentration of 12.4% biomass. Sucrose is used in this model as its life cycle parameters are available for LCA analysis; it is similar to the glucose normally used in production for which rigorous life cycle assessment (LCA) data were not available. Production of PHB from sucrose has been reported (Akiyama et al., 2003; Khanna and Srivastava, 2005).

After PHB growth and accumulation, downstream processing is performed in batch. Cells are disrupted in a high-pressure

homogeniser H-100 (70 MPa; 3 passes). Solids are then removed by centrifugation (C-100;  $10,000 \times g$  for 20 min) and sent for further purification. The solid PHB is re-suspended with the alkaline serine protease, Optimase L660, to digest the non-polymeric cell matter. The temperature is maintained at  $70^\circ\text{C}$  and pH controlled at 8.0 with potassium hydroxide in a stirred tank reactor (R-200) for 2 h.

PHB is further processed by treatment with a non-ionic detergent (Synperonic NP8) in a stirred tank reactor ( $70^\circ\text{C}$  and pH of 7.0) (R-210) for 2 h. Additional product purification is achieved in repeated cycles of dilution with water and centrifuge action (C-300/V-300), followed by hydrogen peroxide treatment (V-301) and a final water washing and centrifuge cycles (C-400/V-400). The purified PHB is ultimately spray dried (O-500) from a moisture content of 25 wt% to below 200 ppm, as given in Table 4.

Energy is obtained for PHB production from steam, electricity and natural gas as seen in Table 5. Steam is used for media sterilization, steaming out of the reactor vessel and backing steam. Data for media sterilization (1065 kg) are based on first principles and include heat integration, while data based on values scaled from a similar enzyme production process (Dennis, 2000) are used for steaming out of the vessel (9.6 kg) and backing steam (3819 kg). Space heating is assumed to be zero. It is assumed that the energy needs for heating the downstream processes enzyme washing (R-200) and detergent addition (R-201)

Table 4  
Process conditions for the production of 1000 kg of PHB

	Unit	
Seed media		<i>Cupriavidus necator</i> , sucrose (10 kg/m <sup>3</sup> ), (NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> (1.8 kg/m <sup>3</sup> ), K <sub>2</sub> HPO <sub>4</sub> (1.9 kg/m <sup>3</sup> ), NaHPO <sub>4</sub> (1.56 kg/m <sup>3</sup> ), MgSO <sub>4</sub> ·7H <sub>2</sub> O (0.8 kg/m <sup>3</sup> ), FeSO <sub>4</sub> ·7H <sub>2</sub> O (0.008 kg/m <sup>3</sup> ), trace salts solution (CuSO <sub>4</sub> ·5H <sub>2</sub> O, ZnSO <sub>4</sub> ·7H <sub>2</sub> O, MnSO <sub>4</sub> ·H <sub>2</sub> O, CaCl <sub>2</sub> ·2H <sub>2</sub> O)
Fermentation media		Sucrose (270 kg/m <sup>3</sup> ), H <sub>3</sub> PO <sub>4</sub> (0.8 dm <sup>3</sup> /m <sup>3</sup> ), (NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> (1.1 kg/m <sup>3</sup> ), K <sub>2</sub> SO <sub>4</sub> (1.4 kg/m <sup>3</sup> ), MgSO <sub>4</sub> ·7H <sub>2</sub> O (1.6 kg/m <sup>3</sup> ), trace salts (Na <sub>2</sub> SO <sub>4</sub> , MnSO <sub>4</sub> ·H <sub>2</sub> O, ZnSO <sub>4</sub> ·7H <sub>2</sub> O, CuSO <sub>4</sub> ·5H <sub>2</sub> O), PPG.EEA 142 antifoam (0.375 kg/m <sup>3</sup> )
Sterilisation	S-100	139 °C (continuous sterilisation) – including heat integration
Microbial growth	R-100	Temperature: 30 °C; pH: 7 Reactor volume: 9.4 m <sup>3</sup> (working) Total reaction time: 80 h Aeration: 0.6 vol/vol/min Agitation energy: 0.5 kW/m <sup>3</sup> Biomass (PHB) concentration: 150 (106) g/l Polymer concentration: 71% PHB
Cell disruption	H-100	High pressure homogenisation 3 passes; 70 MPa; 16 °C Energy efficiency of breakage: 1.25 J/mg biomass disrupted
Enzyme addition	R-200	Re-suspensions equivalent to 150 kg/m <sup>3</sup> Optimase L660 (MKC) – alkaline serine protease enzyme Agitation energy: 0.8 kW/m <sup>3</sup> Temperature: 70 °C; pH: 8 Residence time: 2 h
(Non-ionic) detergent addition	R-201	Synperonic NP8 Agitation energy: 0.8 kW/m <sup>3</sup> Temperature: 70 °C; pH: 7 Residence time: 2 h
Water washing (I)	V-300 C-300	Number of washes: 4 Wash volume: 1/3 of reactor volume (3.1 m <sup>3</sup> ) Centrifugation: 20 min; 10,000 g Power required: 2.11 kW/m <sup>3</sup> (per wash)
H <sub>2</sub> O <sub>2</sub> addition	V-301	Concentration: 1.20% v/v
Water washing (II)	V-400 C-400	Number of washes: 2 Wash volume: 1/3 of reactor volume (3.1 m <sup>3</sup> ) Centrifugation: 20 min; 10,000 g Power required: 2.11 kW/m <sup>3</sup> (per wash)
Spray drying	O-500	Initial moisture content: 11% Final moisture content: 0.1% Drying rate: 4.8 GJ/t
Downstream processing recovery: 95%		

References: Perry et al. (1984), Engler (1985), Harrison (1990), Baker and McKenzie (2005).

can be met with heat integration. For 1000 kg of PHB, 4980 kg steam is needed, an equivalent of 12.7 GJ of energy.

Electricity is used in agitation of reactors (R-100, R-200, R-201), cell disruption (H-100), centrifugation (C-100, C-300, C-400) and the electrical requirement to pump air in aeration.

An agitation energy of 0.5 kW/m<sup>3</sup> and 0.8 kW/m<sup>3</sup> is assumed for microbial growth and downstream processes (enzyme and detergent additions), respectively, yielding electrical requirements of 1360 MJ and 36.2 MJ. An energy efficiency of 1.25 MJ required/kg biomass disrupted is assumed for cell breakage in

Table 5  
Breakdown of steam and electricity requirements for production of 1000 kg PHB

Steam (kg)		Electricity (MJ)		Natural gas (MJ)	
Medium sterilization	1065	Agitation:		Spray	2123
Steam out vessel	9.6	Reactor R-100 (0.5 kW/m <sup>3</sup> )	1360	dry-	
Backing steam	3819	Enzyme washing R-200 (0.8 kW/m <sup>3</sup> )	18.1	ing	
		Detergent washing R-201 (0.8 kW/m <sup>3</sup> )	18.1	(Baker	
		Cell disruption, HPH, 1.25 J/mg biomass H-100 (Engler, 1985)	1770	and	
		Centrifuge energy, 8 kW/h/1000 gal (Perry et al., 1984)	263.5	McKenzie,	
Total	4890	Energy for aeration (Aspen model)	512	2005)	
Energy equivalent; 2.6 MJ/kg (MJ)	12700	Electricity total	3942	Natural gas total	2123
Total energy for 1000 kg PHB (GJ)					18.8



Table 6  
Mass and energy values for PHB production used in the LCA study

Products			
PHB (kg)	1000		
Feed			
Electricity (MJ)	3942	Sulphates:	
Steam (2.6 MJ/kg) (kg)	4893	MgSO <sub>4</sub> .7H <sub>2</sub> O (kg)	20.9
Energy equivalent (MJ)	12700	K <sub>2</sub> SO <sub>4</sub> (kg)	18.6
Natural gas (MJ)	2123	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> (kg)	14.8
Air (kg)	290	Na <sub>2</sub> SO <sub>4</sub> (kg)	3.0
Process water (m <sup>3</sup> )	65.2	ZnSO <sub>4</sub> .7H <sub>2</sub> O (kg)	1.16
Cooling water (m <sup>3</sup> )	13.1	MnSO <sub>4</sub> .H <sub>2</sub> O (kg)	0.92
Sucrose (from cane sugar) (kg)	1810	FeSO <sub>4</sub> .7H <sub>2</sub> O (kg)	0.82
Acids:		CuSO <sub>4</sub> .5H <sub>2</sub> O (kg)	0.12
H <sub>2</sub> SO <sub>4</sub> (kg)	3.02	CaCl <sub>2</sub> .2H <sub>2</sub> O (kg)	2.3
H <sub>3</sub> PO <sub>4</sub> (conc.) (kg)	8.12	K <sub>2</sub> HPO <sub>4</sub> (kg)	0.095
H <sub>2</sub> O <sub>2</sub> (kg)	52.9	NaHPO <sub>4</sub> (kg)	0.078
Optimase L660 (MKC) (kg)	2.4	PPG.EEA 142 antifoam (m <sup>3</sup> )	0.005
Synperonic NP8 (ICI Ltd.) (m <sup>3</sup> )	0.033		
Waste			
Dilute wastewater (m <sup>3</sup> )	65.2	Solid waste (biomass) (kg)	420
COD (te O <sub>2</sub> )	0.80		

the homogeniser (Engler, 1985) and a power per unit time per volume of 8 kW/h/1000 gal (2.1 kW/h/m<sup>3</sup>) (Perry et al., 1984) for centrifugation, adding 1770 MJ and 263.5 MJ to the process. The energy needed for aeration is calculated using an Aspen Plus<sup>®</sup> model as 512 MJ.

Natural gas is used to provide energy to the spray drying process; energy which could also originate from other sources for different drying techniques. Using the equation of Baker and McKenzie (2005), 2123 MJ of energy is required. A total energy requirement of 18.8 GJ per 1000 kg PHB produced is calculated as shown in Table 5. The material and energy flows used in the LCA study are given, on the basis of 1000 kg purified PHB, in Tables 5 and 6.

#### 4. Life cycle assessment

A cradle-to gate life cycle inventory of granular polypropylene (PP) and polyethylene (PE) production, developed by Boustead (2000), and presented in the SimaPro model of ETH-ESU (Frischknecht and Suter, 1996), is summarized in Table 7 for comparison to the results obtained above for the production of 1000 kg of PHB shown in Table 6. The LCA of the different polymer production methods is carried out using the LCA software package SimaPro v7 (PRé Consultants B.V.) and the CML 2 Baseline 2000 v2.03 assessment method. The system was defined as cradle-to-factory gate production of plastic granules, including all raw material and agricultural inputs, detergent and enzyme use and wastewater treatment. It takes CO<sub>2</sub> uptake into account during the sugar cane growth for glucose requirements. It excluded the impacts of construction of the process plant and equipment maintenance, according to the common, but disputed, practice (Heijungs et al., 1992). A functional unit of 1000 kg of polymer is used. The mass of polymer needed per item manufactured is similar for PHB, PP and PE (Crank et al., 2004).

In PHB production, the LCA results for sucrose, based on results for production in South Africa (Theka, 2002; Botha, 2006), were used as representative of glucose data. The bagasse from the sugar cane, co-produced in the processing of sucrose, was used for electricity generation, thereby releasing a portion

Table 7  
Values for polyolefin production as used in the LCA of Frischknecht and Suter (1996)

	Polypropylene	High density polyethylene	Low density polyethylene
Products			
Polyolefin (kg)	1000	1000	1000
Feed			
Electricity (GJ)	4.0	1.5	3.0
Propylene (kg)	1050	–	–
Ethylene (kg)	–	1020	1050
Oil (kg)	75	13	50
Refinery gas (kg)	61	10	40
Emissions			
To air:			
NMVOC (kg)	37	–	0.007
NOx (kg)	37	–	–
Particulates (kg)	2.5	–	–
Ethane (kg)	–	16	2.2
To water:			
Ethylbenzene (g)	5.8	–	–
1,1,1-Trichloro-ethane (g)	5.8	–	–
Benzene (g)	1.5	0.00065	7.6
Toluene (g)	4.6	0.009	7
p-dimethyl-phthalate (g)	–	–	5.1
Phenols (g)	–	0.002	0.9
Dichloro-ethane (g)	–	–	0.22
Chloroform (g)	0.15	–	–
Mercury (g)	–	–	0.018

Table 8  
LCIA of polymer production for 1000 kg of polymer product—CML 2 Baseline 2000 V2.03

Impact category	Unit	This study		Boustead (2000)	
		PHB	PP	HDPE	LDPE
Abiotic depletion	kg Sb <sub>eq</sub>	<b><u>21.8</u></b>	41.4	35.3	39.4
Global warming (GWP100)	kg CO <sub>2</sub> eq.	<b><u>1960</u></b>	3530	2510	3040
Ozone layer depletion (ODP)	kg CFC-11 <sub>eq</sub>	<b><u>0.00017</u></b>	0.000862	0.000766	0.0018
Human toxicity	kg 1,4-DB <sub>eq</sub>	<b><u>857</u></b>	1870	2590	2890
Fresh water aquatic ecotoxicity	kg 1,4-DB <sub>eq</sub>	<b><u>106</u></b>	234	176	210
Marine aquatic ecotoxicity	kg 1,4-DB <sub>eq</sub>	<b><u>1,290,000</u></b>	1,850,000	<b><u>1,230,000</u></b>	<b><u>1,610,000</u></b>
Terrestrial ecotoxicity	kg 1,4-DB <sub>eq</sub>	<b><u>8.98</u></b>	44	33.7	40.3
Photochemical oxidation	kg C <sub>2</sub> H <sub>2</sub>	<b><u>0.78</u></b>	1.7	17.5	3.92
Acidification	kg SO <sub>2</sub> eq.	<b><u>24.9</u></b>	48.8	<b><u>22.5</u></b>	<b><u>27.4</u></b>
Eutrophication	kg PO <sub>4</sub> <sup>3-</sup> eq.	5.19	5.84	<b><u>0.811</u></b>	<b><u>0.951</u></b>

Key: underlined bold values are the lowest values in each category.  
Values in bold print are within 50% of the lowest value in each category.

of CO<sub>2</sub> that was taken up during cultivation. Carbon dioxide released in other areas of production (e.g. fossil electricity production) was also taken into account.

## 5. Results

### 5.1. Poly-β-hydroxybutyric acid

Using the CML 2 Baseline 2000v2.03 method of assessment, for 1000 kg of PHB produced, 1960 kg of CO<sub>2</sub> equivalent is released into the atmosphere, while acidification and eutrophication are characterised by emissions of 21.8 kg SO<sub>2</sub><sup>-</sup> eq. and 5.19 kg PO<sub>4</sub><sup>3-</sup> eq., respectively, as seen in Table 8.

The major processes contributing to the LCA impacts in the production of PHB are steam raising and electricity generation. Steam is used in the sterilisation of the feeds to the fermenter and for sterile protection. These findings are supported by analyzing the impacts in individual impact categories (CML 2 Baseline 2000 v2.03 assessment method) as shown in Fig. 2.

The steam production or electricity requirement contributes the most to each overall impact with the exception of eutrophication. In particular steam raising dominates abiotic depletion, global warming, photochemical oxidation and acidification. Electricity needed dominates impacts of ozone layer depletion, human toxicity, fresh water ecotoxicity, marine ecotoxicity and terrestrial ecotoxicity. Sugar production and the use of fertilisers show a high contribution to eutrophication, acidification and photochemical oxidation. Other process contributions are relatively small, except for natural gas and crude oil usage (in ozone layer depletion) as seen in Fig. 2.

### 5.2. PHB versus polypropylene

Poly-β-hydroxybutyric acid is more favourable than polypropylene (PP) production in all LCA categories as indicated in Fig. 3. Production of 1000 kg of PP releases 3530 kg CO<sub>2</sub> eq. (over 80% more than PHB production) as seen in Table 8. Ozone layer depletion (0.00862 kg CFC-11<sub>eq.</sub>) is over 50 times

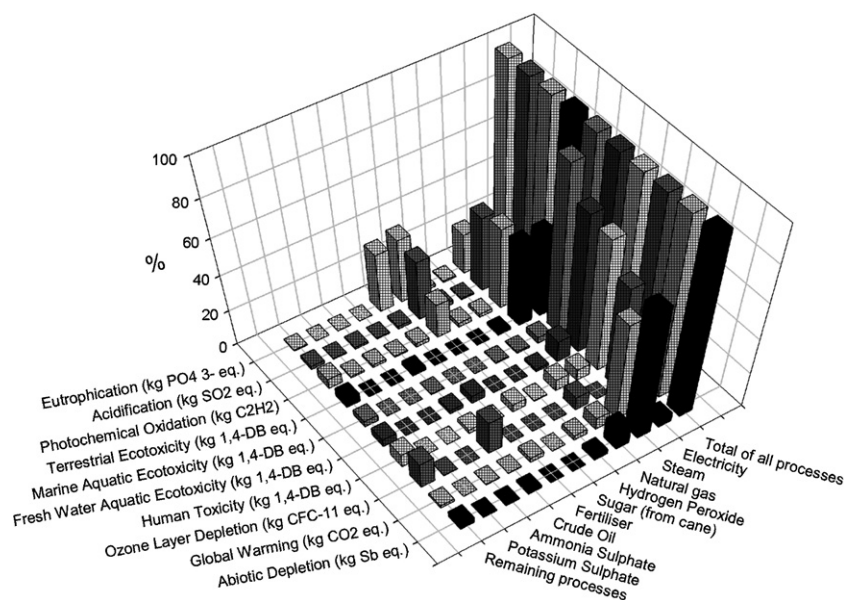


Fig. 2. Percentage contributions of PHB production across all LCA impact categories (CML 2 Baseline 2000 v2.03).

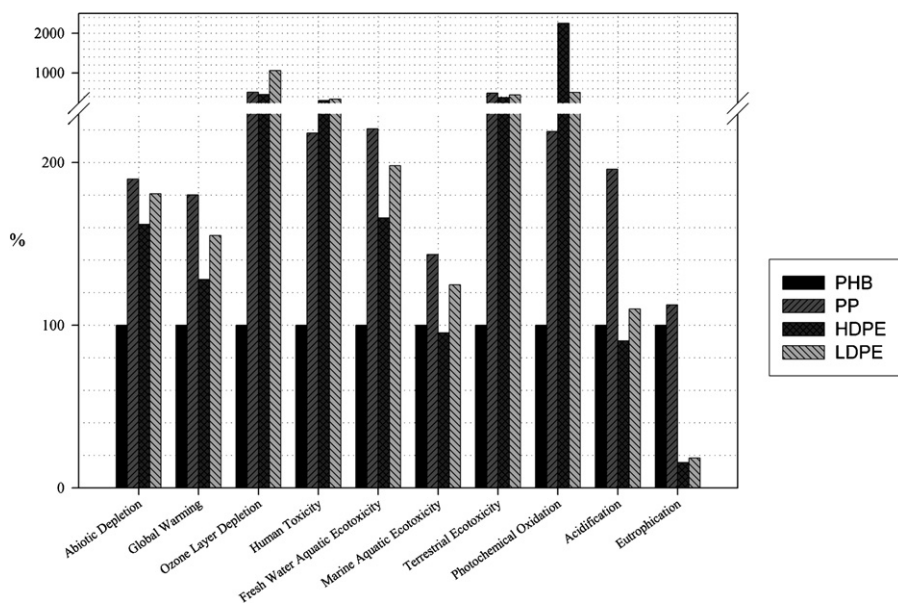


Fig. 3. LCA results—PHB vs. PP and PE (CML Baseline 2000v2.03).

lower in PHB production, representing the greatest reduction of all categories. Terrestrial ecotoxicity (44 kg 1,4-DB<sub>eq.</sub>) is almost 10 times higher in PP production. The decrease in these impacts in PHB production is mainly due to the greatly reduced crude oil requirement, which in PP production is required for both energy and propylene monomer unit production.

The marine aquatic toxicity levels (18,500,000 kg 1,4-DB<sub>eq.</sub>) are 50% higher in PP while photochemical oxidation (1.7 kg C<sub>2</sub>H<sub>2</sub> eq.) human toxicity (1870 kg 1,4-DB<sub>eq.</sub>), fresh water aquatic ecotoxicity (234 kg 1,4-DB<sub>eq.</sub>) and abiotic depletion (41.44 kg Sb<sub>eq.</sub>) give LCA scores approximately double those of PHA. Acidification (48.8 kg SO<sub>2</sub> eq.) and eutrophication (5.84 kg PO<sub>4</sub><sup>3-</sup> eq.) levels are 100 and 12% higher in PP.

### 5.3. PHB versus polyethylene

The environmental impacts of high density polyethylene (HDPE) and low density polyethylene (LDPE) are of the same order of magnitude in all impact categories except photochemical oxidation. All categories except photochemical oxidation, have higher impacts for LDPE than HDPE. These differences in impacts are under 25%. From Fig. 3, for photochemical oxidation, HDPE is significantly (17.5 kg versus 3.92 kg C<sub>2</sub>H<sub>2</sub> per 1000 kg polymer) less favourable owing to the ethene emitted in this process. The impacts of both HDPE and LDPE production are lower than PP production in all categories, except in human toxicity and photochemical oxidation.

Using the CML assessment method, eutrophication (0.811–0.951 kg PO<sub>4</sub><sup>3-</sup> eq. per 1000 kg polymer) impacts of PE production are 500% lower than PHB impacts. This is due to lower NO<sub>x</sub> emissions; partially attributed to the agricultural component of PHB production. Global warming (2510–3040 kg CO<sub>2</sub> eq.), is just less than 50% higher for PE than PHB.

Acidification and marine aquatic toxicity levels are essentially equal as seen in Table 8. PHB production shows a reduced

environmental impact in six categories. In PE production, the impact of abiotic depletion, fresh water toxicity, terrestrial toxicity, human toxicity, photochemical oxidation (HDPE) and ozone layer depletion are 1.7, 1.6–1.9, 3–4, 3, 22 and 4–10 fold those for PHB production depending on the type of PE produced.

## 6. Discussion

The main inputs by mass of PHB production are steam and sucrose. A large amount of water is required (65.2 l/kg PHB), broken down as water for feed (14.6 l/kg PHB), additional make-up water in downstream processing (22.0 l/kg PHB) and wash water used between batches (28.6 l/kg PHB; approximately three times reactor volume; Dennis, 2000). This results in a large amount of wastewater and an associated chemical oxygen demand (COD) of 0.80 t O<sub>2</sub> per 1000 kg PHB. On an energy basis, the proportional contribution of steam, electricity and natural gas is 67.7, 21.0 and 11.3%, respectively. This is a high steam requirement, predominantly originating from backing steam (78%). Opportunity for process optimisation through both water and energy integration studies thus still exist.

Gerngross (1999) and Akiyama et al. (2003) compared the production of PHB polymers and polyolefins through LCA, where the results presented were limited to CO<sub>2</sub> emissions and energy demand only. Their results, given in Table 9, differ from each other and from this study. The CO<sub>2</sub> emissions reported by Akiyama et al. (2003), taking the carbon neutral status of the agricultural processes into account, were between 0.26 and 0.45 kg/kg-polymer. Gerngross (1999) reported net CO<sub>2</sub> emissions of 2.4 kg/kg-polymer mainly as a result of the combustion of fossil fuels used to generate energy for the process, similar to the 2.0 kg/kg-polymer reported by Kurdikar et al. (2001). These values compare with 2.6 kg/kg-polymer in this study, resulting from the production of steam (55.4%), electricity (30.8%), combustion of natural gas (6.7%), production of hydrogen peroxide



Table 9  
Carbon dioxide emissions and total energy requirements for polymer production (cradle-to-gate)

Polymer		CO <sub>2</sub> emissions	Energy requirements
		kg CO <sub>2</sub> /kg-polymer	MJ/kg-polymer
PHA/PHB	PHA (Gerngross, 1999)	2.4	50.4
	PHA (Kurdikar et al., 2001)	2.0	–
	PHA (Akiyama et al., 2003)	0.26–0.45	50–59
	PHB (Nonato et al., 2001)	–	113.7
	PHB (This study)	2.6	44.7
Polyolefins	Polypropylene (PP) <sup>a</sup>	3.4	85.9
	High density polyethylene (HDPE) <sup>a</sup>	2.5	73.7
	Low density polyethylene (LDPE) <sup>a</sup>	3.0	81.8

<sup>a</sup> Reference: Frischknecht and Suter (1996).

(2.7%), fertiliser production (2.5%) and other processes (1.9%). Carbon dioxide emissions in polyolefins are reported as 3.4 and 2.5–3.0 kg/kg-polymer for PP and PE, respectively (Boustead, 2000).

Comparing the energy requirements, the study of Gerngross (1999) showed that 50.4 MJ/kg-polymer (2.39 kg fossil fuel equivalent/kg-polymer) are needed, while Akiyama et al. (2003) found that between 50 and 59 MJ/kg-polymer is needed. Nonato et al. (2001) report an electrical energy requirement of 3.24 kWh/kg-polymer and 39.5 kg of steam/kg-polymer, giving a total energy requirement of 113.7 MJ/kg-polymer. These studies include electricity credit from biomass used for energy needs as each author deems relevant. The total cradle-to-gate energy needed for the production of PHB in this study was 42.9 MJ/kg-polymer. This is made up of 41.4 MJ of non-renewable energy and 1.5 MJ renewable energy as seen in Table 10. This can be broken down as 18.8 MJ for PHB production and 24.1 MJ for raw material production. This is lower than in previous studies and lower than the 73–85 MJ/kg-polymer for PP and PE production reported by Boustead (2000).

Although Gerngross (1999) and Nonato et al. (2001) claim that a cradle-to-grave analysis should be done in studying polymers, they, like all other authors, give cradle-to-gate values for energy needs and CO<sub>2</sub> emissions. This study is also a cradle-to-gate study. It does not take re-use or recycling into account. In all cases, recycle will minimise carbon dioxide release and resource depletion. Where recycle is not practical, PHB will degrade

releasing CO<sub>2</sub> (aerobic conditions) or methane (anaerobic conditions) into the atmosphere, while carbon remains locked in PP and PE. If incinerated, PP and PE release CO<sub>2</sub> as well as other chemicals (e.g. sulfur oxides, hydrogen chloride, cadmium, lead, zinc and arsenic etc.) to the environment (Frischknecht and Suter, 1996), increasing environmental burdens.

Toxicity scores should not be over-interpreted since the uncertainty in these categories is large. There are also many compounds that are not taken into account during measurement and diverse methods of quantifying toxicity exist. Productivity levels in the modeled PHB production are slightly lower than from other literature values as shown in Table 3. Improvements in the productivity will have a positive effect on the LCA scores.

## 7. Conclusions

The dominant contributions to the environmental burden in the production of PHB are the large requirement for energy, in particular steam, as well as the high water requirement (65 dm<sup>3</sup> per kg polymer). The use of fertiliser (from agricultural processes), acids and a significant number of salts, adds to the toxicity levels of wastewater and the eutrophication potential.

Despite this, the production of polyhydroxy-β-butyrate is more beneficial in a full cradle-to-gate life cycle assessment study than polypropylene (PP) production. Ozone layer depletion is almost completely removed, with toxicity levels also greatly reduced. Abiotic depletion and acidification are reduced significantly, while global warming and eutrophication levels are reduced to a lesser extent. The production of polyethylene (PE) is equally or more favourable than PP production in all LCA impact categories. PE production has lower environmental burdens than PHB production in acidification and eutrophication. Impacts in all other categories are lower for PHB than PE production.

Energy requirements and carbon dioxide emissions were compared by Gerngross (1999), Kurdikar et al. (2001), Nonato et al. (2001) and Akiyama et al. (2003), indicating environmental benefits of PHB production over polyolefins. This is the first report to give a full set of LCA results for PHB production. Its findings strengthen the support of PHB over PP and PE production beyond global warming and energy requirements, removing any doubts raised on the merits of PHB production.

This study does not include the effects of polymer disposal (i.e. cradle-to-grave). It is expected that incineration of polyolefins add additional negative environmental

Table 10  
Breakdown of total energy for cradle-to-gate production of 1 kg PHB

Energy used in PHB production only	Energy (MJ)	Total energy used in cradle-to-gate production of PHB	Energy (MJ)
Electricity	3.9	Non-renewable, fossil	38.8
Steam	12.7	Non-renewable, nuclear	2.6
Natural gas	2.1	Renewable, biomass	1.03
		Renewable, wind, solar, geothermal	0.03
		Renewable, water	0.41
Total	18.8	Total	42.9
Energy used in processes prior to PHB production			24.1

impacts to their life cycles, giving PHB further environmental advantages.

## References

- Ackerman, J.-U., Babel, W., 1998. Approaches to increase the economy of the PHB production. *Polym. Degrad. Stabil.* 59, 183–186.
- Akiyama, M., Tsuge, T., Doi, Y., 2003. Environmental life cycle comparison of polyhydroxyalkanoates produced from renewable carbon resources by bacterial fermentation. *Polym. Degrad. Stabil.* 80, 183–194.
- Asrar, J., Grys, K.J., 2002. Biodegradable Polymer (BIOPOL®). In: Doi, Y., Steinbüchel, A. (Eds.), *Biopolymers, Polyesters III: Applications and Commercial Products* (Vol. 4). Wiley-VCH, Münster, pp. 53–90.
- Baker, C.G.J., McKenzie, K.A., 2005. Energy consumption of industrial dryers. *Dry. Technol.* 23 (1–2), 365–386.
- Botha, T., 2006. A comparison of the environmental benefits of bagasse-derived electricity and fuel ethanol on a life-cycle basis. *Energ. Policy* 34, 2654–2661.
- Boustead, I., 2000. Eco-profiles of plastics and related intermediates, Association of Plastics Manufacturers in Europe (APME). Brussels, Belgium.
- Chen, G.Q., Zhang, G., Park, S.J., Lee, S.Y., 2001. Industrial scale production of poly(3-hydroxybutyrate-co-3-hydroxyhexanoate). *Appl. Microbiol. Biot.* 57, 50–55.
- Crank, M., Patel, M., Marscheider-Weidemann, F., Schleich, J., Hüsing, B., Angerer, G., 2004. Techno-economic Feasibility of Large-scale Production of Bio-based Polymers in Europe (*PRO-BIP*). European Commission, Institute for Prospective Technological Studies (IPTS), Sevilla, Spain.
- Delft, 2004. Industrieel Ontwerpen – Delft [online], Delft University of Technology, Available from: [http://www.io.tudelft.nl/research/dfs/idemat/Onl\\_db/Typ113.htm](http://www.io.tudelft.nl/research/dfs/idemat/Onl_db/Typ113.htm), [Accessed 14 October 2005].
- Dennis, J.S., 2000. Protease production, MS-Excel spreadsheet, selected data.
- Doi, Y., 1990. *Microbial Polyesters*. VCH Publishers, New York.
- DSMZ, 2006. Bacterial Nomenclature up-to-date (approved lists, validation lists), Deutsche Sammlung von Mikroorganismen und Zellkulturen GmbH, April 2006, Available from: <http://www.dsmz.de/download/bactnom/bactname.pdf>, [Accessed 5 May 2006].
- Engler, C.R., 1985. Disruption of microbial cells. In: Moo-Young, M. (Ed.), *Comprehensive Biotechnology: The Principles, Applications & Regulations of Biotechnology in Industry, Agriculture and Medicine*, Vol.2, The Principles of Biotechnology: Engineering Considerations. Pergamon Press, New York, Chapter 20.
- Frischknecht, R., Suter, P., 1996. *Öko-inventare von Energiesystemen*, third ed. ETH-ESU.
- Gerngross, T.U., 1999. Can biotechnology move us toward a sustainable society? *Nat. Biotechnol.* 17, 541–544.
- Gerngross, T.U., Slater, S.C., 2000. How green are green plastics? *Sci. Am.* 2000, 36–41.
- Godbole, S., Gote, S., Latkar, M., Chakrabarti, T., 2003. Preparation and characterization of biodegradable poly-3-hydroxybutyrate-starch blend films. *Bioresour. Technol.* 86, 33–37.
- Grothe, E., Moo-Young, M., Chisti, Y., 1999. Fermentation optimization for the production of poly(3-hydroxybutyric acid) microbial thermoplastic. *Enzyme Microb. Tech.* 25, 132–141.
- Harrison, S.T.L., 1990. The extraction and purification of *Alicoligenes eutrophus*, PhD dissertation, Cambridge University.
- Heijungs, R., Guinée, J.B., Huppes, G., Langkreijer, R.M., Udo de Haes, H.A., Wegner Sleswijk, A., Aasems, A., Eggels, P.G., van Duin, R., de Goede, H.P., 1992. *Environmental Life Cycle Analysis of Products: Backgrounds and Guide*. Centre of Environmental Science, Leiden University, Leiden.
- Heyde, M., 1998. Ecological considerations on the use and production of biosynthetic and synthetic biodegradable polymers. *Polym. Degrad. Stabil.* 59, 3–6.
- Khanna, S., Srivastava, A.K., 2005. Recent advances in microbial polyhydroxyalkanoates. *Process Biochem.* 40, 607–619.
- Kim, B.S., 2000. Production of poly(3-hydroxybutyrate) from inexpensive substrates. *Enzyme Microb. Tech.* 27, 774–777.
- Kurdikar, D., Paster, M., Gruys, K.J., Fournet, L., Gerngross, T.U., Slater, S.C., Coulon, R., 2001. Greenhouse gas profile of a plastic derived from a genetically modified plant. *J. Ind. Ecol.* 4 (3), 107–122.
- Lee, S.Y., 1996. Plastic bacteria? Progress and prospects for polyhydroxyalkanoate production in bacteria. *Trends Biotechnol.* 14, 431–438.
- Lee, S.Y., Choi, J., 1998. Effect of fermentation performance on the economics of poly(3-hydroxybutyrate) production by *Alcaligenes latus*. *Polym. Degrad. Stabil.* 59, 387–393.
- Luck, T., 1996. Feasibility-Studie Polyhydroxyfettsäuren – Kurzdarstellung der Ergebnisse der Studien ‘Feasibility-Studie zur Abschätzung des Marktpotentials neuer Polyhydroxyfettsäuren (PHF)’ und ‘Abschätzende Ökobilanzen zu Polymerwerkstoffen auf der Basis biologisch erzeugter Polyhydroxyfettsäuren’, Fraunhofer Institut für Lebensmitteltechnologie und Verpackung (ILV), Freising, Germany. Cited Patel et al. 2002.
- Nonato, R.V., Mantelatto, P.E., Rossell, C.E.V., 2001. Integrated production of biodegradable plastic, sugar and ethanol. *Appl. Microbiol. Biot.* 57, 1–5.
- Ogorkiewicz, R.M. (Ed.), 1970. *Engineering Properties of Thermoplastics*, Imperial Chemical Industries (ICI) Ltd., Plastics Division. Wiley-Interscience, London.
- Patel, M., Bastioli, C., Marini, L., Würdinger, E., 2002. Life-cycle assessment of bio-based polymers and natural fibre composites. In: Steinbüchel, A. (Ed.), *Biopolymers, General Aspects and Special Applications* (vol. 10). Wiley-VCH, Münster.
- Perry, R.H., Green, D.W., Maloney, J.O. (Eds.), 1984. *Perry’s Chemical Engineers’ Handbook*, sixth ed. McGraw-Hill, International edition.
- Reddy, C.S.K., Ghai, R., Rashmi, Kaliav C., 2003. Polyhydroxyalkanoates: an overview. *Bioresour. Technol.* 87, 137–146.
- Steinbüchel, A., Fächtenbusch, B., 1998. Bacterial and other biological systems for polyester production. *Tibtech* 16, 419–427.
- Sudesh, K., Abe, H., Doi, Y., 2000. Synthesis, structure and properties of polyhydroxyalkanoates: biological polyesters. *Prog. Polym. Sci.* 25, 1503–1555.
- Theka, E., 2002. A life-cycle assessment of ethanol produced from sugarcane molasses, M.Sc. dissertation, Department of Chemical Engineering, University of Cape Town.
- Wang, F., Lee, S.Y., 1997. Poly(3-hydroxybutyrate) production with high productivity and high polymer content by a fed-batch culture of *Alcaligenes latus* under nitrogen limitation. *Appl. Environ. Microbiol.* 63 (9), 3703–3706.
- Yu, S.T., Lin, C.C., Too, J.R., 2005. PHBV production by *Ralstonia eutropha* in a continuous stirred tank reactor. *Process Biochem.*, 40–2734.
- Zinn, M., Witholy, B., Egli, T., 2001. Occurrence, synthesis and medical application of bacterial polyhydroxyalkanoates. *Adv. Drug Deliver. Rev.* 53, 5–21.