PACKAGING SYSTEMS

Environmental impacts of conventional plastic and bio-based carrier bags

Part 1: Life cycle production

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Abstract

Background, aim, and scope The use of bio-based products as carrier bags, packaging materials, and many other applications has been increasingly replacing conventional polymer products. One of the main driving forces of bio-plastic applications is the perceived depletion and scarcity of fossil fuels, especially petroleum. However, despite being introduced as an environmentally friendly alternative to plastics made from crude oil, the environmental benefits of bio-plastics remain debatable. This article serves to investigate whether or not bio-based materials are environmentally friendlier options compared to plastics and attempts to explain the rationale of the results.

Materials and methods The production and disposal of both conventional plastic and bio-plastic carrier bags are investigated using life cycle assessment or LCA. A typical bio-based bag (made from polyhydroxyalkanoate or PHA) from the U.S. was selected to be compared with a locally produced polyethylene plastic (PP) bag in Singapore. In the LCA system, the raw materials for making polyethylene came from crude oil imported from Middle East and natural gas piped from Natuna gas field. The refinery and PP bag production processes are based in Singapore. Bio-bag production was entirely in the U.S., and the finished product was shipped to Singapore. The impact assessment results were generated for global warming potential, acidification, and photochemical ozone formation. Next, normalized results were calculated according to the parameters of Singapore's annual emission inventory.

Results The total environmental impacts of bio-bags showed considerable differences under various energy scenarios. When the energy expenditures to make bio-bags are supplied by U.S. electricity mix, the production impacts are about 69% higher, compared to the impacts from PP bags. With coal-fired power supply, the production impacts from bio-bag production turned out to be about five times greater than those from conventional plastics. The life cycle production impacts of PP bags are comparable to bio-bags when the energy supplied to the bio-material production chain is supplied by natural gas. Bio-bags are 80% more environmentally friendly than plastic bags when clean and renewable energy (geothermal) is used throughout its life cycle production stages.

Discussions and conclusions By the use of LCA with different energy scenarios, this article sheds some light on the extent of environmental benefits (or drawbacks) of replacing plastic carrier bags with PHA bags. It was concluded that the life cycle production of bio-bags can only be considered as environmentally friendly alternatives to conventional plastic bags if clean energy sources are supplied throughout its production processes. It was also highlighted that the results should not be viewed as a global representative since the case study scope was for Singapore alone. Additional work by others on different biodegradable and compostable bags vary in results. Some of the complexities of such work lie in what is included or excluded from the scope and the adoption of different environmental impact assessment methods. Nevertheless, the authors' attempt to compare the two bags may serve as a basis for

Part 2: end-of-life options

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identifying the major environmental burdens of such materials' life cycle production.

Recommendations and perspectives Although bio-based products have been mostly regarded as a sustainable solution for replacing petroleum-based polymers, in most cases, the amounts of resources and energy required to produce them have not been taken into account. Before bio-based plastics can be recommended as a preferred option to plastics, a few challenges have to be overcome. The main issue lies in reducing the energy used in the life cycle production of the bio-material from crops. The environmental benefits and drawbacks of both materials should also be more clearly highlighted by expanding the system boundary to include end-of-life options; this is carried out in part 2 (Khoo and Tan, Int J Life Cycle Assess, in press, 2010).

1 Background, aim, and scope

This article compares the life cycle environmental impacts of plastic and bio-based plastic carrier bags for use in Singapore. The production of plastics as carrier bags starts with crude oil and natural gas extraction. These two fossil fuel resources are not available in Singapore and are imported mostly from the Middle Eastern region. Natural gas, on the other hand, is extracted from the Natuna gas field in Indonesia and piped to the country's refinery. Polypropylene is produced by the chain growth polymerization of propylene. At the refinery, cracking and distillation takes place before the production of olefins, monomers, and polypropylene plastics. Magnesium chloride and titanium chloride catalysts are added to ensure close to 100% conversion of monomers to polymers. The polymers are made into pellets, which are then used to make plastic bags.

Bio-plastics can be made from renewable feedstock without depleting natural resources. The concept to produce green environmentally products is a cyclic one, where sunlight, carbon dioxide (CO_2), and other inputs are absorbed during the growth of feedstock (crops) for making bio-plastics (Gross and Kalra 2002). After use, bio-plastic bags can be turned into natural substances, via composting and be applied as peat substitution. The main production steps involve in making bio-based bags begin with corn production, harvesting, wet milling, and finally fermentation to produce polyhydroxyalkanoates or PHA (Hatti-Kaul et al. 2007). PHA-based plastics are a suitable replacement for plastics because they can be synthesized to behave like polypropylene and exhibit the same strength and toughness characteristics (Comstock et al. 2004). However, despite

being introduced as an environmentally friendly alternative to plastics made from crude oil, the environmental benefits of bio-plastics remain debatable. This article serves to investigate whether or not bio-based materials are environmentally friendlier options compared to plastics and attempts to explain the rationale of the results.

2 Life cycle assessment

In comparing the environmental performance of two different products, life cycle assessment or LCA has emerged as a powerful method that can take into account the products' energy and resources consumed, as well as the generation of emissions and wastes, of the products entire life span from cradle to grave (Hauschild 2005; Landis et al. 2007). LCA can be applied in a wide range of scientific research and industrial areas and can bring to attention unexpected environmental outcomes. This kind of application is important to ensure that, while solving a particular environmental concern, negative impacts are not passed from one stage to another or from one environmental compartment to another. The first stage of the LCA carried out in this paper (part 1) focuses on cradle to gate. A complete LCA from cradle to grave will be discussed in part 2 (Khoo and Tan 2010) where a few end-of-life scenarios are presented.

2.1 LCA goal

The goal of the LCA is to compare the production of conventional plastic and bio-based carrier bags from cradle to gate. The LCA results serves to highlight whether or not bio-based materials are environmentally friendlier options compared to plastics and attempts to explain the rationale of the results.

2.2 LCA scope, functional unit, and system boundary

The electrical energy requirements for bio-bag production are obtained from U.S. electricity grid mix. Further analysis of the life cycle production is carried out using hypothetical options of 100% energy sourced from coal, natural gas combined cycle (NGCC) power, or geothermal power generation.

The focus of the investigation is on PHA-based bags alone. Other types of biodegradable bags (e.g., polylactide acid or PLA) are not included in the LCA. The LCA scope involves raw material extraction (fossil fuels or biomass), production, and the final delivery of the finished product, defined as a "standard bag" to the customer at the city center.

In order to ensure the relevance and fairness of the LCA, it is essential that both products provide the same service or function (Hauschild 2005). The functional unit of the LCA is defined as a "standard bag" with the dimensions 10 by

Table 1 Characteristics of PP and bio-bags

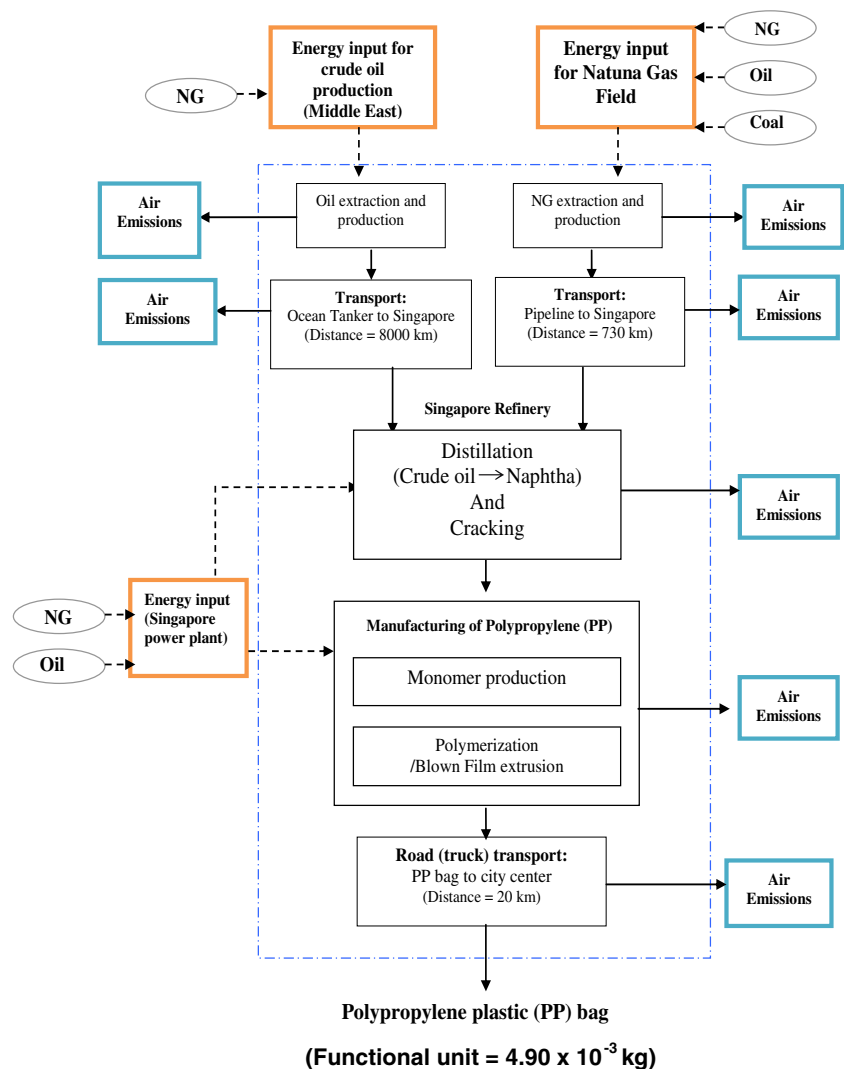| Characteristics	Dimensions of a "standard bag"			Carrying capacity (kg)	Density (g/m^3)	Mass load (kg) according to functional unit[a]
	Length (in.)	Width (in.)	Thickness (mm)			
Polypropylene plastic bag	10	14	0.06	20	9.05×10^5	4.90×10^{-3}
Bio-bag	10	14	0.06	15	1.25×10^6	9.03×10^{-3}

[a] Functional unit=one "standard bag" with carrying capacity of 20 kg

14 in., thickness 0.06 mm. The carrying capacities and densities of both bags are reported to be 20 kg and 9.05×10^5 g/m^3 for a standard plastic bag and 15 kg and 1.25×10^6 g/m^3 for a standard bio-bag made from PHA. The functional unit is selected as a "standard bag" with carrying capacity of 20 kg. From the bags' dimensions, the total volume of each is calculated as: $25.4 \times 10^{-2} \times 35.56 \times 10^{-2} \times 0.06 \times 10^{-3}$ m^3 = 5.420×10^{-6} m^3.

Therefore, the mass load of a plastic bag, according to its functional unit, is: $9.05 \times 10^5 \times 5.420 \times 10^{-6} = 4.90 \times 10^{-3}$ kg.

Since the carrying capacities of both bags are dissimilar, the mass load of a bio-based bag is calculated as: $1.25 \times 10^6 \times 5.420 \times 10^{-6} \times (20/15) = 9.03 \times 10^{-3}$ kg. The basis of this mass load calculation is done assuming that the bio-based bag thickness can be increased to carry the same capacity (20 kg).

The mass loads of both carrier bags, according to the selected functional unit, are compiled in Table 1. The LCA system boundary for the production of a polyethylene plastic (PP) bag starts with the extraction and production of

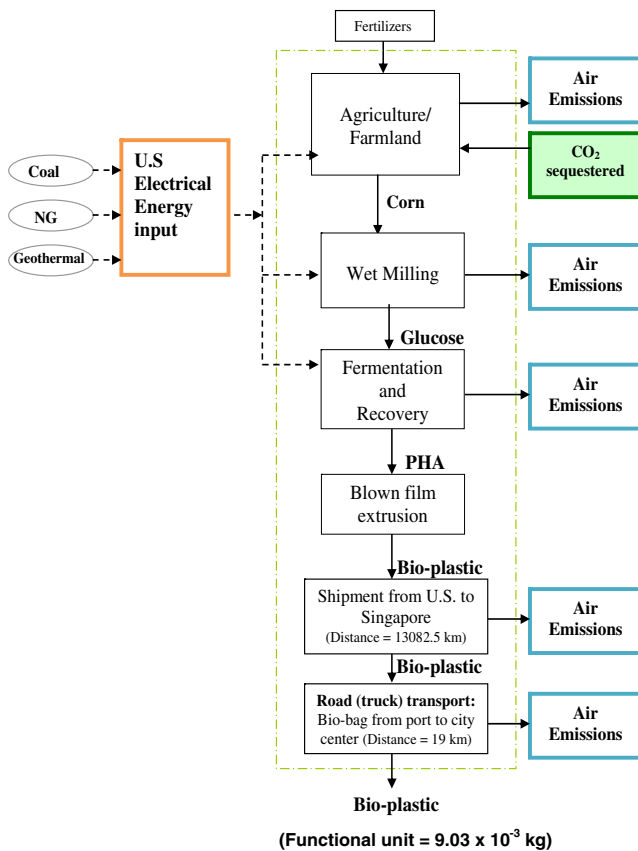**Fig. 1** Life cycle stages of polypropylene plastic bag production

Fig. 2 Life cycle stages of bio-bag production

Table 3 Direct emissions to air from fossil fuel extraction and production

Air emissions	All in kg/kg crude oil	All in kg/kg natural gas
CO_2	2.63E−02	4.10E−02
CH_4	6.77E−07	8.90E−07
NO_x	3.36E−06	1.02E−05
SO_2	7.07E−08	3.07E−08

efficient technology that blows the PP using an air jet into the shape of the carrier bag.

It is assumed that the bio-bag is produced in the U.S. and shipped to Singapore. PHAs can be produced directly from renewable resources (crops) with the help of microbes (Gross and Kalra 2002). It starts with the production of corn, wet milling to produce glucose, and last of all, the fermentation of glucose to produce PHA (Kim and Dale 2005a, b). About 1.46 kg corn is required to produce 1 kg glucose, and 3.33 kg glucose is needed to produce 1 kg PHA (Gerngross 1999). For crop production, we estimated from Akimaya et al. (2003) an amount of −1.416 kg CO_2 absorbed per kilogram of corn. Due to fertilizer use, the estimated emissions of CO_2 totaled to be 0.559 kg. Therefore, the net sequestered value is taken as −0.857 kg/kg. In the final stage, PHA is converted to bio-plastic carrier bags and delivered by ship to Singapore. The energy and fuel consumptions for the harvesting, wet milling, and fermentation stages are all supplied by the U.S. electricity grid. It is assumed that the locations of the agriculture area, wet milling, and fermentation plants are all in the same area; therefore, the transportation activities between them can be omitted from the case study. The LCA system boundary for bio-bag production is described in Fig. 2.

Several assumptions have been made in the course of this study. These assumptions are listed as follows:

- Only the main resources for each type of plastics are considered.
- For the production stages, the air emissions of CO, CO_2, CH_4, N_2O, NO_x, SO_x, and nonmethane volatile organic compounds (NMVOC) are considered, mostly from energy requirements and partially from direct emissions.

crude oil from Middle East and natural gas from Natuna gas field (described in Fig. 1). Next, crude oil is transferred to a Singapore refinery by ocean tanker, whereas natural gas is piped from Natuna to Singapore. At the refinery, crude oil and natural gas are processed to produce olefins, which are then turned to polypropylene. Next, the plastic carrier bag is produced. The final stage is the delivery of the PP bag from the manufacturer to the city center by truck. In general, about 1.22 kg of crude oil (typically 45 MJ/kg) and 0.4 kg of natural gas (typically 54 MJ/kg) is required for the production of 1 kg polypropylene product (BUWAL 1991; Narita et al. 2002). From 1 kg PP, 1 kg PP monomer can be yielded by using magnesium chloride and titanium chloride catalyst. The final process, blown film molding, is a very

Table 2 Energy requirements for PP bag production

Fossil fuel production (including other fossil fuel inputs; treatment/processing; compression of natural gas at station)		
Off-shore crude oil exploration and production	24.3	MJ/kg crude oil
Natural gas exploration and production	11.34	MJ/kg natural gas
Refinery processes		
Crude oil distillation + natural gas cracking	4.92	MJ/kg crude oil
PP bag manufacturer		
Monomer production and polymerization (PP)	19.05	MJ/kg PP monomer
Blow film extrusion to produce PP bag	Negligible	

Table 4 Air emissions from energy supplied to PP bag production

Emissions (kg/MJ)	Singapore electricity mix: for supply of energy to refinery and plastic manufacturer	Malaysia electricity mix: for supply of energy for natural gas exploration and production	Natural gas-fired power: for supply of energy for crude oil exploration and production
CO	4.94E−05	1.11E−05	7.50E−07
CO_2	1.56E−01	1.60E−01	2.06E−01
CH_4	2.26E−06	1.00E−06	5.33E−06
N_2O	8.42E−07	n.a.	1.41E−06
NO_x	2.04E−03	1.94E−03	2.64E−05
SO_x	3.31E−04	5.83E−07	5.56E−07
NMVOC	6.03E−06	5.83E−06	2.78E−06

Table 5 Pipeline and marine transport emissions

Emissions (g/ton km)	Nonroad transport		Emissions (g/km)	Road transport
	Pipeline (distance=730km)	Shipment (distance=8,000km)		EURO 4 truck (distance=20km)
CO	0	1.20E−01	CO	6.30E−01
CO_2	1.00E+01	3.00E+01	CO_2	3.51E+01
CH_4	2.00E−02	4.00E−02	CH_4	6.00E−02
NO_x	2.00E−02	4.00E−01	NO_x	3.30E−01
VOC	2.00E−02	1.00E−01	VOC	4.00E−02

Table 6 Direct emissions to air from agriculture and wet milling stages

Air emissions	Agriculture (kg/kg corn)	Wet milling (kg/kg glucose)
CO_2	−0.857 (sequestered)	3.5E−01
N_2O	6.51E−04	0

Table 7 Energy requirements for bio-bag production

Agriculture/farming	
Corn production	2.5 MJ/kg corn
Wet milling	
Corn→glucose	4.9 MJ/kg glucose
Fermentation and recovery	
PHA	52.53 MJ/kg PHA
Blow film extrusion to produce bio-bag	Negligible

Table 8 Air emissions from energy supplied to bio-bag production

Emission parameters (kg/MJ)	Energy supply scenarios to U.S. agriculture, wet milling, and PHA production (fermentation)			
	U.S. energy mix	Coal-fired power	NGCC	Geothermal
CO	1.97E−05	3.72E−05	7.50E−06	0
CO_2	1.88E−01	2.69E−01	1.03E−01	2.25E−02
CH_4	5.04E−06	7.44E−04	1.22E−05	2.08E−04
N_2O	2.93E−06	1.70E−06	2.03E−07	0
NO_x	4.19E−04	8.44E−04	2.64E−05	0
SO_x	8.71E−04	1.78E−03	5.56E−07	8.33E−06
NMVOC	2.73E−06	4.40E−06	2.78E−06	0

- Transport pollution includes CO, CO_2, CH_4, NO_x, and volatile organic compounds (VOC) only.
- The energy supplied for natural gas production is supplied by the Malaysian national grid, which has approximately the same fuel mix (coal, gas, and oil) as Indonesian power plants.
- Electrical energy requirements for Singapore refinery and plastic manufacturer are from Singapore national grid mix.
- Coproducts (e.g., gasoline, diesel, asphalt base, heating oil, kerosene) from the refinery and wet milling of corn (e.g., corn gluten meal, corn oil) are not included in the system boundary.
- Allocation for both products was done according to mass load in all cases.
- The energy requirement for blow film extrusion (shaping of carrier bag) is exactly the same for both bags and is considered negligible.

2.3 Life cycle inventory

The database for the production of raw materials and energy are sourced from various reports and available data-base. Sheehan et al. (1998) reported an input of 0.54 MJ/MJ crude oil extraction; this translates to 24.3 MJ energy input per kilogram crude oil extracted (for energy value of 45 MJ/kg crude oil). The life cycle energy efficiency for the production of natural gas is reported to be 21% (Spath and Mann 2000a, b); this can be translated to 11.34 MJ required for every kilogram of natural gas produced (for 54 MJ/kg natural gas). Both estimated energy requirements include the resource inputs of coal, gas, heavy fuel oil, and diesel during exploration, drilling, and well injection/pumping. Also, the energy inputs for natural gas include treatment, processing, and transmission to the station for compression before pipeline transport. The energy requirements for the main processes involved in PP bag production, from cradle to gate, are compiled in Table 2. Emissions to air from fossil fuel extraction and production are shown in Table 3. Refinery energy requirements are sourced from Jimenez-Gonzalez and Overcash (2000). At the refinery, mass-based allocation is used to determine the energy requirements and associated emissions of products. The energy requirements for crude oil extraction and production in the Middle East region is supplied by natural

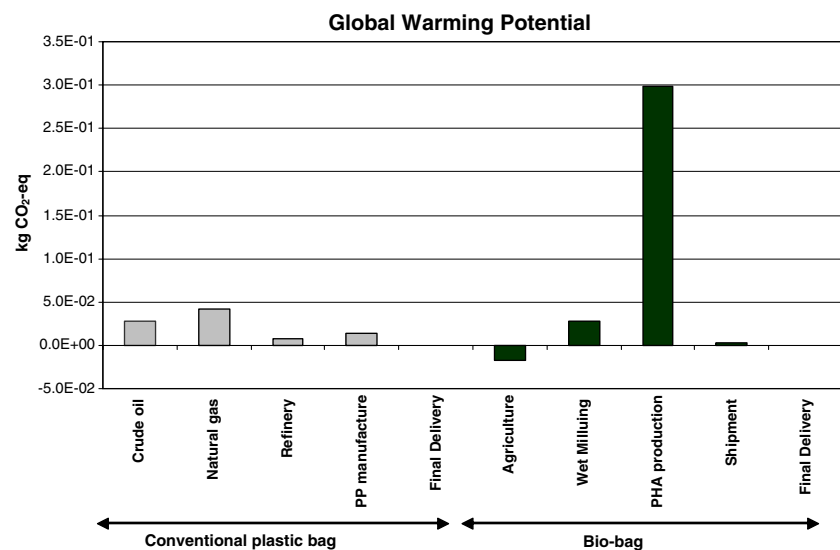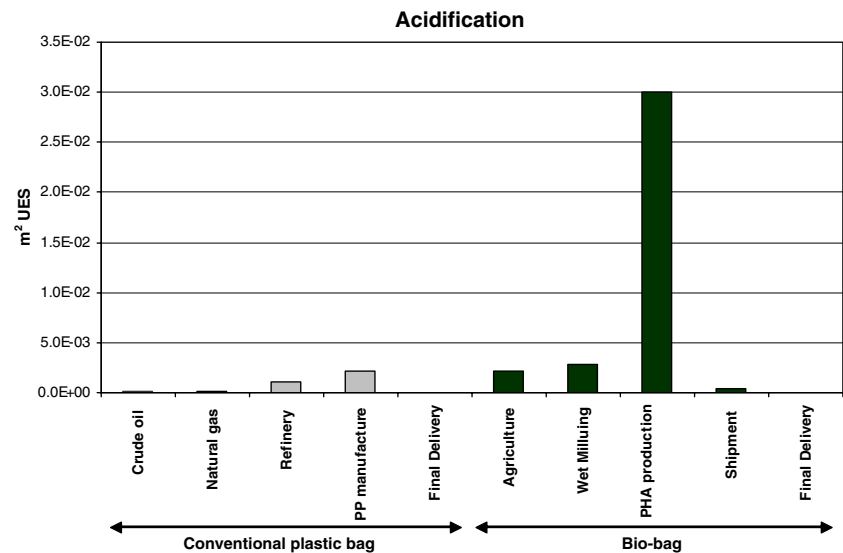**Fig. 3** GWP results: from cradle to gate

Fig. 4 Acidification results: from cradle to gate

gas power plants. The greenhouse gas emissions (in kilograms per megajoule) for this is taken as Middle East average for power production, and the rest of the data are extracted from a typical natural gas-fired power producer (Widiyanto et al. 2004; International Energy Agency (IEA) 2007). For natural gas extraction and production, the energy requirement is estimated from power plants using coal, gas, and oil fuel mix from the region (Chen and Hussein 2005). The emissions generated from cradle to gate due to the types of energy supply are compiled in Table 4.

The source of natural gas, from the Natuna gas fields, is piped to Singapore. The distance of the pipeline is reported to be 730 km. The distance from the oil field in the Middle East region to Singapore is estimated to be 8,000 km. Finally, the distance from plastic producer to city center (customer) is estimated to be 20 km for PP bag and from port to city center is 19 km for bio-bag. Marine and pipeline transportation emissions are taken from Hetch (1997). The

emission factors for road are determined from class II of diesel-powered trucks using the EURO 4 standards. These are compiled in Table 5.

For PHA production, the air emissions and process energy for each stage (agriculture, wet milling, and fermentation) are obtained from mainly from Akiyama et al. (2003)and Shapouri et al. (2003) and supplemented by Kim and Dale (2005a, b). They are compiled in Tables 6 and 7. The total energy expenditures from Table 7 agrees with the reported total amount of energy required (81 MJ) for the cradle-to-gate production of 1 kg PHA (Gerngross 1999). A few energy supply options are available for bio-bag production. The LCA will first and foremost take into consideration energy supplied from U.S. energy mix, which is 49% coal and 20% natural gas, and the rest from virtually zero-pollution sources (e.g., nuclear, geothermal, wind) (Gerngross 1999). For further comparisons, various energy scenarios will be taken into account: coal-fired power,

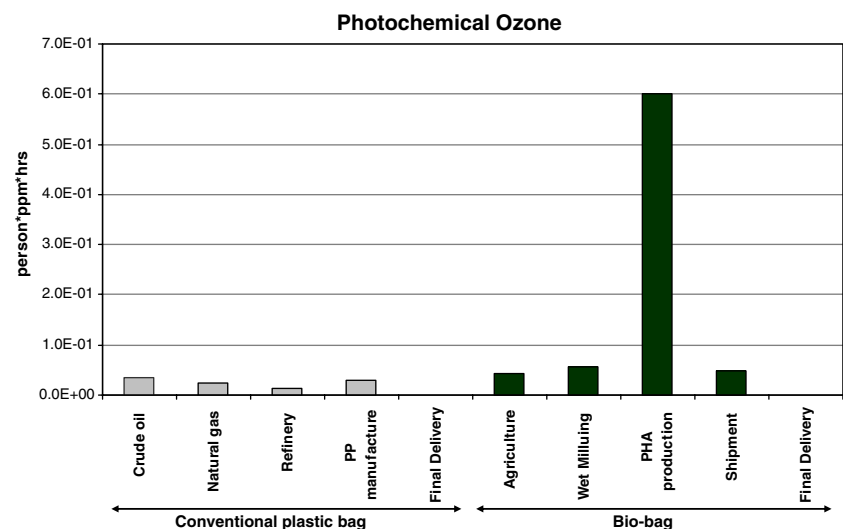**Fig. 5** Photochemical ozone results: from cradle to gate

Table 9 Normalized and weighting values adjusted for Singapore

Impact category	Normalization values for Singapore data
Global warming	6,200 (CO_2 eq/capita/year)
Acidification	894 (UES m^2/capita/year)
Ozone photochemical formation	85,600 (person ppm h/capita/year)

NGCC, and geothermal power production. The life cycle inventory (LCI) data for these are from various energy databases (Spath et al. 1999; Spath and Mann 2000a, b; Bertani 2002; Reed and Renner 2004). The air emissions for the different types of energy, from cradle to gate, are displayed in Table 8.

3 Impact assessment results: production

The Environmental Development of Industrial Products 2003 impact assessment method is used to generate the environmental impact results. Three impact categories were selected based on their relevance to the LCI emissions of both bags. The categories are: global warming potential (GWP), which is caused mainly by CO, CO_2, CH_4, and N_2O; acidification, caused by acidic emissions of SO_x and NO_x; and photochemical ozone formation cause by CO, CH_4, NO_x, NMVOC, and VOC (Hauschild and Potting 2003). The characterized results for the stages involved in the cradle-to-gate production of both bags are displayed in Fig. 3 (GWP), Fig. 4 (acidification), and Fig. 5 (photochemical ozone). For the results shown in Figs. 3, 4, and 5, all energy supplied for bio-bag production is by U.S. electricity grid mix.
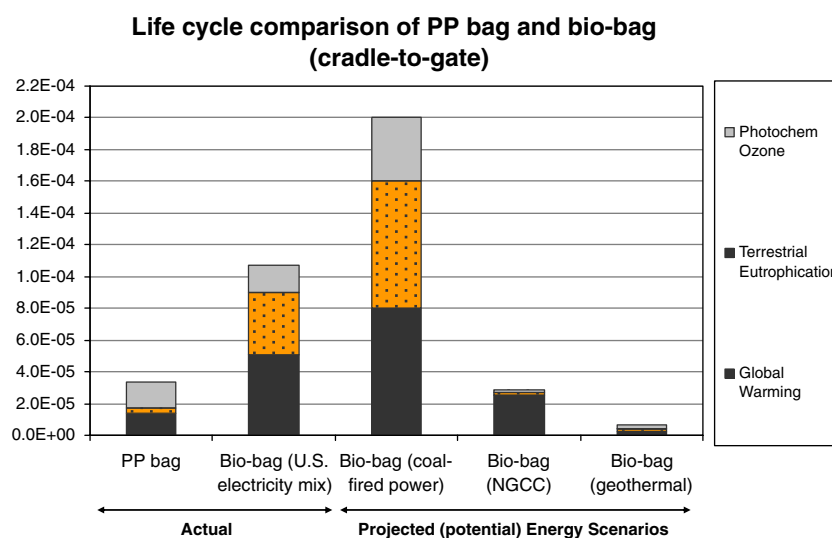
From Fig. 3, it can be observed that, for PP bags, the highest contribution to global warming is primarily from natural gas production and distribution and, next, crude oil

extraction. The results are from both energy requirements and direct emissions from oil and gas extraction processes. Emissions from the refinery and manufacturer are less significant. Figure 3 also shows that the GWP result from PHA production is extremely significant—nearly six times the amount of greenhouse gasses generated from PP bag production processes. The amount of carbon dioxide sequestered in the agriculture of corn pales in comparison to the amount generated from the energy requirements for making bio-bags. For both types of bags, the final delivery by truck to the city center hardly contributes to global warming.

Also from Fig. 4, the highest contributions to acidification are first of all from PHA production. The only significant contribution to acidification for PP bag is from the refinery and PP manufacturing, which is still considerably lower than those from PHA production. The acidic gasses from agriculture, wet milling, and crude oil and natural gas production are comparable. The rest—crude oil and natural gas production, shipment of bio-bags, and delivery by truck transportation—hardly imposes any impacts. The same pattern is observed for Fig. 5, "photochemical ozone" environmental category. The life cycle impacts of PP bag production stages are all moderate. A considerably higher amount of environmental impacts are observed from the shipment of bio-bags from the U.S. to Singapore. This is due to the emissions of VOC from marine transportation (Hetch 1997). The rest of the results (agriculture, wet milling, and shipment) are about 90% less than PHA production.

4 Normalized results

In this final life cycle impact assessment step, the previous characterized results are divided by their respective normalized values that give the relative importance of the particular

Fig. 6 Final normalized and weighted impact results

Life cycle comparison of PP bag and bio-bag (cradle-to-gate)

impact category. The normalized values have been adjusted according to Singapore national annual emission records (Ohara et al. 2007; United Nations Statistics Division 2007) and divided by the country population, which is 4.59 million in June 2007 (Government of Singapore 2008). The normalized parameters used for Singapore are shown in Table 9. The normalized results of bio-bags are calculated for the following energy supply scenarios:

- energy supplied by U.S. electricity grid mix,
- energy supplied by coal-fired power production,
- energy supplied by NGCC power plant,
- energy supplied by geothermal plants.

The final results are displayed in Fig. 6.

5 Discussions and conclusions

It can be observed that the type of energy supplied to the product's life cycle has a dramatic effect on the total environmental impacts. When the energy expenditures to make bio-bags are supplied by U.S. electricity mix, the production impacts are about 69% higher, compared to the impacts from PP bags. With coal-fired power supply, the production impacts from bio-bag production turned out to be about five times greater than those from conventional plastics. The life cycle production impacts of PP bags are comparable to bio-bags when the energy supplied to the bio-material production chain is supplied by natural gas. Bio-bags are 80% more environmentally friendly than plastic bags when clean and renewable energy (geothermal) is used throughout its life cycle production stages.

Akimaya et al. (2003) conducted a near similar study of LCA on the production of PHA from crops and concluded that the environmental performance of PHA-based plastics is better than that of conventional plastics. The author's investigation considered wind power as a replacement to grid electricity in the refinery and bio-energy from corn stover to generate steam. On the other hand, studies conducted by Gerngross (1999) claimed that, due to the high energy expenditure of the fermentation process of making PHA, plastics made from fossil fuels are preferred. In addition to this, corn is an energy-intensive crop which requires the input of fertilizers (Landis et al. 2007; Shapouri et al. 2003). Two of the graphs from Fig. 6 agree with Gerngross (1999).

It should be highlighted, however, that the results in the investigation are not meant to be viewed as a global representative, as the case study scope was limited to Singapore alone. Apart from Akimaya et al. (2003) and Gerngross (1999), further work carried out for various other kinds of biodegradable and compostable bags tend to display different results (James and Grant 2005), thus making a justifiable comparison of LCA studies impracti-

cable. Some of the complexities of such work lie in what is included or excluded from the LCA system boundary, as well as the adoption of differing environmental impact assessment methods (Murphy and Bartle 2004).

6 Recommendations and perspectives

Although bio-based products have been mostly regarded as a sustainable solution for replacing petroleum-based polymers, in most cases, the amounts of resources and energy required to produce them have not been taken into account. Before bio-based plastics can be recommended as a preferred option to plastics, a few challenges have to be overcome. One of the main concerns is reducing the energy used in the life cycle production of the bio-material from crops. Part of the limitations of the LCA lies in obtaining data from secondary sources (Kim and Dale 2005a, b; Gerngross 1999; Akiyama et al. 2003). Future work focusing on primary data from bio-material producers, along with verification from third-party or independent reviewers, will offer more robust studies of the life cycle production impacts of such materials. Nevertheless, the authors' attempt to compare petroleum-based and bio-based bags may serve as a basis for identifying the main environmental problem areas during the production stages of plastics and bio-materials. A full cradle-to-grave analysis will also provide a complete overview of the life cycle of PP and bio-bags.

Part 2 of the article will look into end-of-life options (Khoo and Tan 2010).

References

Akiyama M, Tsuge T, Doi Y (2003) Environmental life cycle comparison of polyhydroxyalkanoates produced from renewable carbon resources by bacterial fermentation. Polym Degrad Stab 80:183–194

Bertani R (2002) Geothermal power generating plant CO₂ emission survey. International Geothermal Association News No. 49

BUWAL (1991) Eco-balance of packaging materials. Environment Report No. 132, Bern, Switzerland

Chen SS, Hussein WM (2005) Development of life cycle assessment activities in Malaysia. Proceedings of the International Workshop on LCA: Capacity Building in APEC Economies, December 15–16, Bangkok, Thailand

Comstock K, Farrell D, Godwin C, Xi Y (2004) From hydrocarbons to carbohydrates: food packaging of the future. Available at http://depts.washington.edu/poeweb/gradprograms/envmgt/2004symposium/GreenPackagingReport.pdf/. Accessed August 2008

Gerngross TU (1999) Can biotechnology move us toward a sustainable society? Nat Biotechnol 17:541–544

Gross RA, Kalra B (2002) Biodegradable polymer for the environment. Science 297:803–807

Hatti-Kaul R, Törnvall U, Gustafsson L, Börjesson P (2007) Industrial biotechnology for the production of bio-based chemicals—a cradle-to-grave perspective. Trends Biotechnol 25:119–124

Hauschild MZ (2005) Assessing environmental impacts in a life cycle perspective. Environ Sci Technol 39:905–912

Hauschild M, Potting J (2003) Spatial differentiation in life cycle impact assessment—the EDIP2003 methodology. Institute for Product Development Technical University of Denmark

Hetch J (1997) The environmental effects of freight. Organisation for Economic Co-operation and Development (OECD), Paris

International Energy Agency (IEA) (2007) Electricity information database 2007 and CO_2 emissions from fuel combustion database 2006. International Energy Agency, Paris, Available at http://www.iea.org/. Accessed August 2008

James K, Grant T (2005) LCA for biodegradable plastic bags. Centre for Design, RMIT, Australia. Available at http://www.cfd.rmit.edu.au/programs/life_cycle_assessment/lca_of_degradable_plastic_bags. Accessed April 2009

Jimenez-Gonzalez C, Overcash M (2000) Life cycle inventory of refinery products: review and comparison of commercially available databases. Environ Sci Technol 34:4789–4796

Khoo HH, Tan RBH (2010) Environmental impacts of conventional plastic and bio-based carrier bags—part 2: end-of-life options. Int J Life Cycle Assess (in press)

Kim S, Dale BE (2005a) LCA study of biopolymers (PHA) derived from no-tilled corn. Int J Life Cycle Assess 10:200–210

Kim S, Dale BE (2005b) LCI information of the United States electricity system. Int J Life Cycle Assess 10:294–304

Landis AE, Miller SA, Theis TL (2007) Life cycle of the corn-soybean agroecosystem for bio-based production. Environ Sci Technol 41:1457–1464

Murphy R, Bartle I (2004) Biodegradable polymers and sustainability: insights from life cycle assessment. Imperial College, London, Available at http://www.oakdenehollins.co.uk/pdf/biodegradable_polymers.pdf. Accessed April 2009

Narita N, Sagisaka M, Inaba A (2002) Life cycle inventory analysis of CO_2 emissions manufacturing commodity plastics in Japan. Int J Life Cycle Assess 7:277–282

Ohara T, Akimoto H, Kurokawam J, Horii N, Yamaji K, Yan X, Hayasaka T (2007) An Asian emission inventory of anthropogenic emission sources for the period 1980–2020. Atmos Chem Phys 7:4419–4444

Reed M, Renner J (2004) Environmental compatibility of geothermal energy. In: Sterrett FS (ed) Alternative fuels and the environment. Lewis, Boca Raton, p 25

Shapouri H, Duffield JA, Wang M (2003) The energy balance of corn ethanol revisited. Am Soc Agr Eng 46:959–968

Sheehan J, Camobreco V, Duffield J, Graboski M, Shapouri H (1998) Life cycle inventory of biodiesel and petroleum diesel for use in an urban bus. National Renewable Energy Laboratory, NREL/SR-580-24089 UC Category 1503

Government of Singapore (2008) Statistics Singapore. Available at http://www.singstat.gov.sg/. Accessed August 2008

Spath PL, Mann MK (2000a) Life cycle assessment of a natural gas combined-cycle power generation system. National Renewable Energy Laboratory, NREL/TP-570-27715

Spath PL, Mann MK (2000b) Life cycle assessment of a natural gas combined-cycle power generation system. Report no. NREL/TP-570-27715. National Renewable Energy Laboratory, Washington

Spath PL, Mann MK, Kerr DR (1999) LCA of coal-fired power production. National Renewable Energy Laboratory (NREL), National Technical Information Service (NTIS), U.S. Department of Commerce, Washington, DC

United Nations Statistics Division (2007) Environment statistics country snapshot: Singapore. UN Publications Board

Widiyanto A, Maruyama N, Kato S (2004) Life cycle analysis for electricity grid systems in Japan. Proceedings of 2nd International Energy Conversion Engineering Conference, August 16–19, Rhode Island, New England, USA