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PEER REVIEW

Eco-profile for Ingeo® polylactide production

Biocatalytic vs. chemical production of alkanolamide biosurfactants

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The eco-profile for current Ingeo® polylactide production

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KEYWORDS: NatureWorks, polylactic acid, polylactide, PLA, Ingeo, life cycle assessment, life cycle analysis, LCA, life cycle inventory, eco-profile

ACRONYMS: CO_2 eq, carbon dioxide equivalents; CWM, corn wet mill; GHG, greenhouse gas(es); LCI, Life cycle inventory; MWh, megawatt-hours; PLA, polylactide; MAPP, Mid-Continent Area Power Pool, PET, polyethylene terephthalate; PS, polystyrene; PP, polypropylene

Abstract

Ingeo® polylactides are biopolymers with varied applications made entirely from annually renewable resources and produced since 2001 by NatureWorks LLC at a 140 000 tonne/yr facility in Blair, Nebraska, USA. NatureWorks' objectives include eliminating nonrenewable energy use and the emissions of greenhouse gases, as well as minimizing non-valuable co-products and reducing water use. These objectives are being accomplished through continual improvement of the Ingeo production technology.

Since 1998, NatureWorks and Cargill Inc. have worked to develop technology improvements, especially in the area of lactic acid production. In December 2008, new lactic acid production technology was implemented that resulted in a reduced environmental footprint. This paper provides the latest cradle-to-polymer-factory-gate life cycle inventory data (also referred to as an eco-profile) for Ingeo as being produced starting in 2009. It also provides a description of the 2009 Ingeo production system and compares the current energy requirements and greenhouse gas emissions with previous and future Ingeo production systems. Finally, this study benchmarks the results for these two paramaters, with data valid for a selection of fossil-based polymers.

1 Introduction

In November 2001, NatureWorks LLC started the production of Ingeo polylactide resins in its 140 000 tonne-per-year manufacturing facility in Blair, Nebraska, USA. One year later, NatureWorks started producing lactic acid in its 180 000-tonne-per-year manufacturing facility located next to the polymer plant. Today, these two plants are the only large-scale commercial production facilities for polylactide worldwide.

Ingeo is a polymer made entirely from annually renewable resources and used in a broad range of applications, including rigid packaging and films, disposable serviceware, bottles, folding boxes, cards, consumer electronics, automotive, fiberfill, wipes, carpet, apparel, feminine hygiene products, and diapers.

In 2003 NatureWorks published the first cradle-to-polymer-factory-gate life cycle inventory data (eco-profile) for Ingeo polylactide production.[1] That paper gave an introduction to the company NatureWorks, Ingeo production technology, and applications and the life cycle assessment tool as applied to Ingeo. The 2003 data was based on the plant design.

In 2007 NatureWorks published new life cycle inventory data, updated with actual data available from the production facilities, in addition to newer data for the upstream and supporting processes.[2] This 2007 paper also gave a more accurate description of the Ingeo manufacturing system and the calculation procedure used; in addition, NatureWorks reported on the use of renewable energy certificates based on wind power and the resulting impact on the calculated eco-profile.

This current paper gives the latest life cycle inventory data based on new lactic acid production technology that was implemented in December 2008. Further, the use of Renewable Energy Certificates is no longer included in the reported eco-profile. Given these significant changes, a new eco-profile has been developed and is reported here.

The data provided in this report is only valid for Ingeo (polylactides produced by NatureWorks in Blair, Nebraska, USA) and not for polylactide production in general. The life cycle inventory data for polylactides that might be produced elsewhere will be different due to different raw materials (sugar or starch source) and raw material production practices, different technologies for processing these raw materials, different fermentation and polymerization technology, and different background data for electricity/fuel mixes used.

For these reasons, the specific nomenclature "Ingeo" is used in this paper to clearly delineate wherever NatureWorks polylactide biopolymer is being referenced.

Up-to-date life cycle inventory data is needed by retailers, brand owners, and authorities to provide better insight into the performance of the Ingeo production system and to allow comparison with the petrochemical-based polymers. The objective of this paper is to provide detailed inventory data sufficient for use by LCA practitioners interested in the use of Ingeo resin for specific products.

Despite the developments in the first decade of this new century, Ingeo production is still in its infancy, compared with that of traditional polymers, and there is yet great potential to further reduce its environmental footprint. This paper will give an outlook into the future, as well.

This paper describes and assesses the life cycle performance of the Ingeo 2009 manufacturing system. This case represents the 2009 cradle-to-pellet Ingeo production system as described in *Section 2*. The data represents an annual production of 140000 tonnes of Ingeo and is valid from the cradle to the polymer factory (exit) gate in Blair, Nebraska.

2 The Ingeo production system

The simplified flow diagram for the manufacture of virgin Ingeo production is schematized in *Figure 1*.

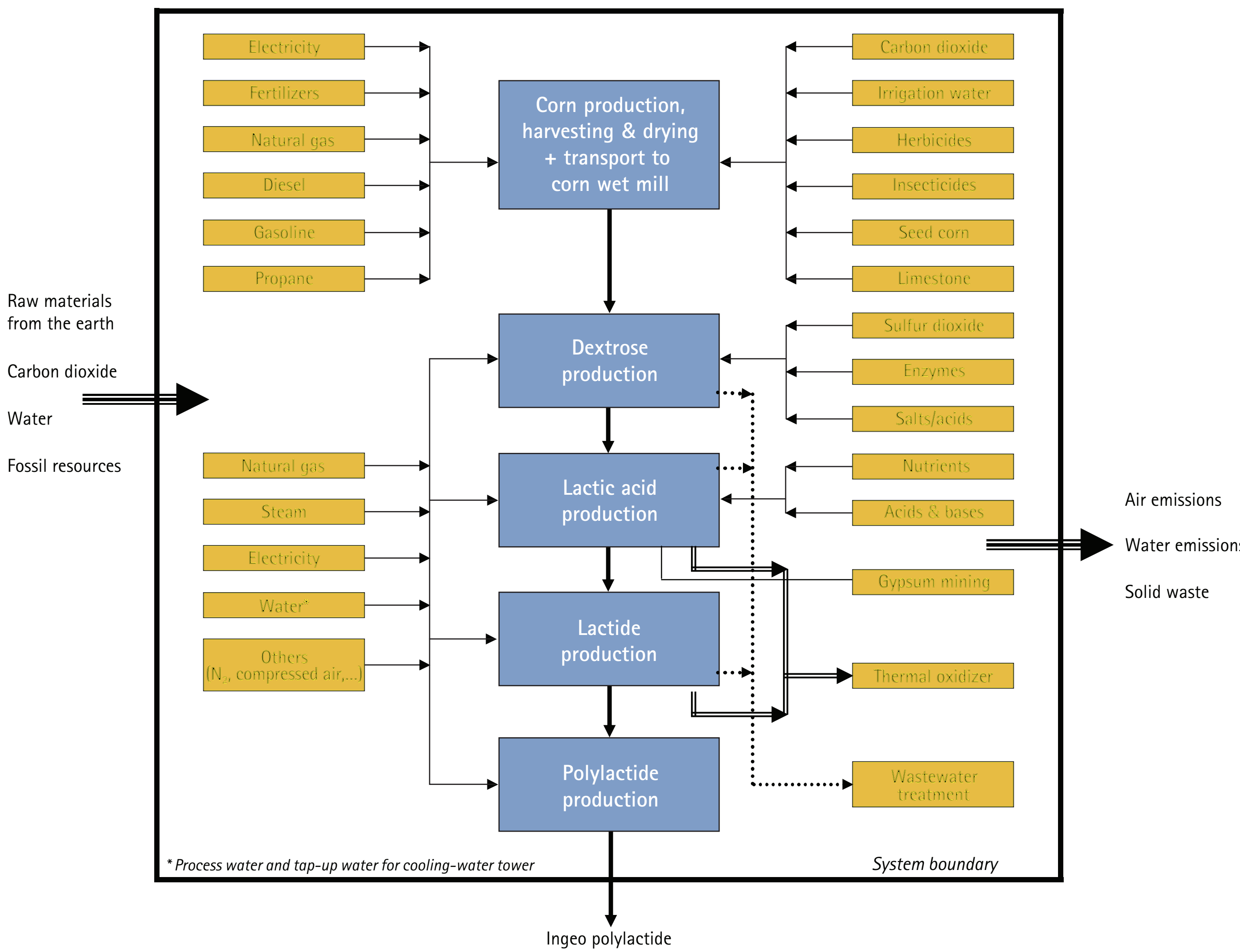


Figure 1. Flow diagram of the manufacture of Ingeo polylactide biopolymers

The cradle-to-factory-gate Ingeo production system is divided into five major steps:

1. Corn production and transport of corn to the corn processing wet mill
2. Corn processing and the conversion of starch into dextrose
3. Conversion of dextrose into lactic acid
4. Conversion of lactic acid into lactide
5. Polymerization of lactide into Ingeo polymer pellets

The primary inputs to these major steps are listed on the left and right of *Figure 1*. In the final eco-profile data, these primary inputs are traced back to the extraction of the raw materials from the earth. Only aggregated data has been provided to protect Cargill/NatureWorks proprietary information. The process-level data as well as the aggregated data were reviewed by Boustead Consulting.[3]

The life cycle of Ingeo starts with corn (maize) production. All free energy consumed by the corn plant comes from solar energy captured by photosynthesis. The basic stoichiometric equation for photosynthesis is:

$$H_2O + CO_2 \xrightarrow{\text{light}} (CH_2O) + O_2$$

In this equation, (CH_2O) represents carbohydrate, such as sucrose and starch. Therefore, all carbon, hydrogen, and oxygen found in the starch molecule or the final Ingeo molecule originated from water and carbon dioxide.

The data includes all the relevant inputs for corn production, such as production of corn seed, fertilizers, limestone, electricity, and fuels (natural gas, diesel, propane, and gasoline) used on the farm, the atmospheric carbon dioxide utilization through photosynthesis, the irrigation water applied to the cornfield, and the production of the herbicides and insecticides used to protect the corn. On the output side, emissions, including dinitrogen oxide, nitrogen oxides, nitrates, and phosphates, are taken into account. Production of the farm equipment (tractors and harvest combines) used was investigated, but their contributions are negligible.

The average life cycle data on corn production was collected from corn producers in the twenty-six counties in Nebraska and Iowa that tend to supply corn to the corn wet mill that processes corn into dextrose syrup. These counties are situated on the borderline of Nebraska and Iowa.[4]

After harvest, the corn grain is transported to a corn wet mill (CWM), where the starch is separated from the other components of the corn kernel (proteins, fats, fibers, ash, and water) and hydrolyzed to dextrose using enzymes. The dextrose solution is transported by pipeline to Cargill's lactic acid fermentation process, which is situated adjacent to the CWM. The other products of the modeled CWM are corn gluten feed, corn gluten meal, heavy steep water, and corn germ. To allocate all the inputs and outputs to these products, the CWM production process was divided as far as possible into subprocesses (11 processes were identified), and for each subprocess, allocation is based on the dry mass of the final and/or intermediate products.[5] The data includes all relevant inputs for dextrose production such as the production and delivery of natural gas, electricity, and steam, as well as the production of potable and cooling water, compressed air, chemicals (sulfur dioxide and calcium hydroxide), and enzymes.[5]

Lactic acid is produced by fermentation of dextrose received from the CWM. The process, illustrated in *Figure 2*, combines dextrose and other media, adds a microbial inoculum, and produces crude lactic acid. Prior to December 2008, the pH was controlled to near neutral by the addition of calcium hydroxide. The lactic acid broth was then acidified by adding sulfuric acid, resulting in the formation and precipitation of gypsum. This process results in near stoichiometric usage of lime and sulfuric acid, relative to the lactic acid produced, and subsequent production of gypsum. The gypsum was removed by filtration, and the lactic acid concentrated by evaporation.

Elimination of these by-products has long been a goal of NatureWorks/Cargill, and extensive research was carried out to develop an improved process. In December 2008, new fermentation technology was introduced, allowing operation of the fermentation at significantly lower pH, and thereby significantly reducing the use of calcium hydroxide and sulfuric acid, in turn resulting in significantly lower quantities of gypsum.[6,7,8] Also, less energy was required to drive the process. Small quantities of gypsum are still being produced, which are then used as soil conditioners and so replace mined gypsum. A credit is given for the avoided gypsum mining, but the impact of this is small compared to the total numbers. After final purification, the lactic acid enters the lactide/Ingeo manufacturing process.

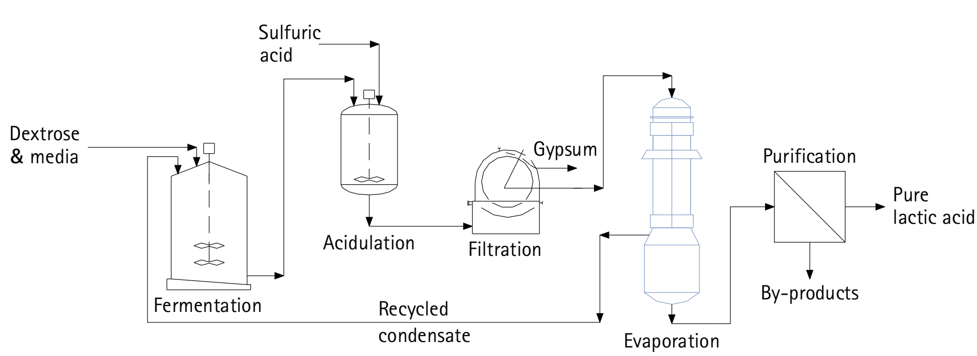


Figure 2. NatureWorks lactic acid production process

Ingeo is prepared through the polymerization of lactide to make polylactide polymer in a continuous process, illustrated in *Figure 3*. In the first step, water is removed in a continuous condensation reaction of aqueous lactic acid to produce low molecular weight prepolymer. Next, the prepolymer is catalytically converted into the cyclic dimer, lactide, and vaporized. The lactide mixture is then purified by distillation. Finally, high molecular weight Ingeo is produced using a ring-opening lactide polymerization. The process does not use any solvents. After the polymerization is complete, any remaining lactide monomer is removed and recycled within the process.[1,2,9] The polymer pellets are the final stage of the Ingeo eco-profiles. Packaging and transportation to the customer are not included.

A few additional remarks about the Ingeo manufacturing process as given in *Figure 1* are warranted.

- Steam is produced in a natural gas fired steam boiler located at the Cargill site. Make-up potable water is included in the inventory and well as electricity use by the steam boiler.
- The inventory distinguishes three types of water: irrigation water used for corn production, process water used as a transportation medium, reaction medium, or for steam production, and make-up water to compensate cooling tower losses.
- The Ingeo production process is equipped with two thermal oxidizers converting potential organic process emissions into carbon dioxide and water. The natural gas consumption of the thermal oxidizers is taken into account.
- Dextrose and lactic acid manufacturing are water-based processes. A part of the water is recycled internally and a part is drained, after purification in a wastewater treatment facility, to the surface water (river). Electricity consumption and the process emissions (to air and water) of the on-site facility are included in the inventory.

3 Methods

3.1 ECO-PROFILES VERSUS LIFE CYCLE INVENTORIES

A full life cycle inventory starts with the extraction of raw materials from the earth and covers all downstream processing until the materials are eventually disposed of as waste back into the earth. Eco-profiles, of the type reported by the European plastics manufacturing association, Plastics Europe, and NatureWorks, are cradle-to-gate rather than complete life cycle inventories. That is, the systems start with the extraction of raw materials from the earth and end with polymer resins ready for dispatch to the converter.[2]

3.2 METHODOLOGY

As a renewably derived source of plastics, Ingeo competes in the marketplace with polyethylene terephthalate (PET), polystyrene (PS), polypropylene (PP), and other petrochemical-based plastics often referred to as “traditional plastics.” In response to customer demand, PlasticsEurope published a series of eco-profiles for traditional petrochemical-based polymers over the last twenty years.[10] To allow direct comparison with traditional polymers, NatureWorks undertook the development of eco-profiles for Ingeo using the same methodology,[11] software, and core databases as used in the PlasticsEurope analyses. In addition, the results are presented in the same format used by Boustead Consulting, the organization that calculated these eco-profiles for the European plastics industry. All the calculations have been carried out in accordance with the requirements of ISO 14040 and 14044.

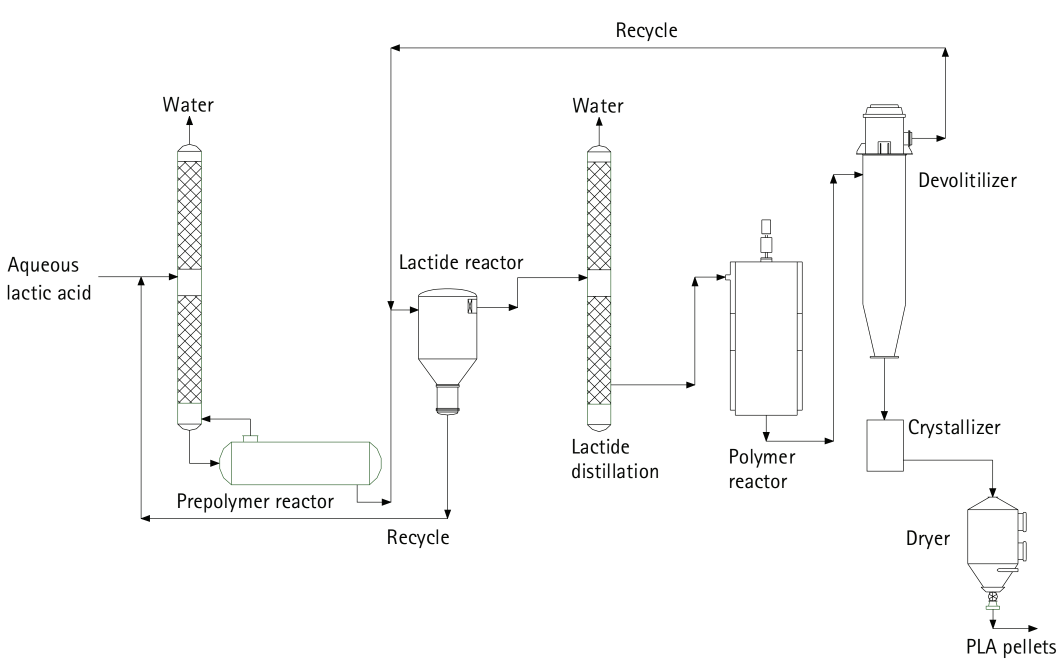


Figure 3. NatureWorks lactide formation and polylactide polymerization process

3.3 DATA SOURCES

Average corn-growing data from 26 counties on the borderline of Nebraska and Iowa, the most likely sources of corn for the Cargill corn wet mill, was collected and used for corn production.[4] Data for a modern corn wet mill representative of the Cargill corn wet mill that supplies NatureWorks was compiled and used for the dextrose production step.[5] Data for the lactic acid, lactide, and Ingeo production was developed within NatureWorks. The fossil-fuel-based electricity data was obtained from the Boustead core database[12] and is valid for the Mid-Continent Area Power Pool (MAPP) covering the US states of North Dakota, Nebraska, and Minnesota, the Canadian province of Manitoba, and parts of the states of Wisconsin, Montana, Iowa, and South Dakota. (The North American electricity grid is divided into 10 power regions in which the electric companies work together to ensure reliable and adequate power supplies by the various interconnected local utilities. MAPP is one of these 10 regional reliability councils. As a regional power pool [and "balancing area"], it is the unit of choice for estimating the emissions basis of the electrical generation in the area. A larger pool would not adequately represent the local conditions, and a smaller pool would not reflect the interconnected nature of the electrical grid.) Data for the most important process chemicals was obtained from direct suppliers whenever possible or taken from the Eco-invent database.[13] Data for the production of coal, gas, and other fuels and chemicals used in smaller quantities was taken from the core database of the Boustead model.[12] All data sources including for corn growing, corn milling, lactic acid, and lactide and Ingeo production, was peer reviewed by Ian Boustead of Boustead Consulting.[3,14]

4 Results

4.1 ECO-PROFILE FOR INGEO 2009 PRODUCTION SYSTEM

The eco-profile data for Ingeo 2009 currently implemented technology (CIT) is found in *Tables 1–7*. All data is given per kilogram of Ingeo (at factory gate). *Table 1* gives the gross primary fuels and feedstock for the Ingeo 2009 production system. The biomass entry in the Feedstock energy column (24.97 MJ) represents the corn intake. The energy content of corn is 16.3 MJ/kg corn. *Table 2* shows the energy data expressed as masses of fuels. *Table 3* shows the demand

Table 1. Gross primary fuels and feedstock required to produce 1 kg of Ingeo 2009

Fuel type	Fuel production & delivery energy (MJ)	Energy content of delivered fuel (MJ)	Fuel use in transport (MJ)	Feedstock energy (MJ)	Total energy (MJ)
Coal	11.8048	4.8221	0.0097	0.0000	16.6366
Oil	0.1362	1.8946	0.4965	0.2132	2.7406
Gas	1.7609	18.1091	0.0120	0.0971	19.9791
Hydro	0.4694	0.1865	0.0010	0.0000	0.6568
Nuclear	2.7637	1.1117	0.0020	0.0000	3.8774
Lignite	0.0000	0.0003	0.0000	0.0000	0.0004
Wood	0.0000	0.0000	0.0000	0.0000	0.0000
Sulphur	0.0000	0.0140	0.0000	0.0578	0.0718
Biomass (solid)	0.0016	0.0007	0.0000	24.9658	24.9681
Hydrogen	0.0000	0.0477	0.0000	0.0000	0.0477
Recovered energy	0.0000	−1.1546	-0.0001	0.0000	−1.1547
Unspecified	0.0000	0.0000	0.0000	0.0000	0.0000
Peat	0.0000	0.0000	0.0000	0.0000	0.0000
Geothermal	0.0000	0.0000	0.0000	0.0000	0.0000
Solar	0.0000	0.0000	0.0000	0.0000	0.0000
Wave/tidal	0.0000	0.0000	0.0000	0.0000	0.0000
Biomass (liquid/gas)	0.0003	0.0001	0.0000	0.0000	0.0005
Industrial waste	0.0029	0.0014	0.0000	0.0000	0.0043
Municipal waste	0.0022	0.0010	0.0000	0.0000	0.0032
Wind	0.0016	0.0008	0.0000	0.0000	0.0024
TOTALS	16.9438	25.0353	0.5211	25.3340	67.8342

Table 2. Gross primary fuels used to produce 1 kg Ingeo 2009, expressed as mass	
Fuel type	Input (mg)
Crude oil	60 300
Gas/condensate	378 876
Coal	577 430
Metallurgical coal	182
Lignite	26
Peat	1
Wood	1

Table 3. Gross water consumption required for production of 1 kg Ingeo 2009			
Source	Use for processing (mg)	Use for cooling (mg)	Totals (mg)
Public supply	16 495 064	7 205 585	23 700 649
River canal	1 831	461 049	462 880
Sea	1 062	12 149	13 211
Well	48 240	0	48 240
Unspecified	21 341 920	3 220 774	24 562 694
TOTALS	37 888 117	10 899 557	48 787 674

Table 4. Gross raw materials required to produce 1 kg Ingeo 2009	
Raw material	Input in mg
Barytes	73
Bauxite	7
Sodium chloride ($NaCl$)	81 716
Chalk ($CaCO_2$)	101 703
Clay	28 593
Fe	451
Pb	3
Limestone ($CaCO_3$)	35 108
Sand (SiO_2)	10 289
Phosphate as P_2O_5	7 454
S (elemental)	7 756
Dolomite	6
O_2	180
N_2	9 152
Air	285 690
Bentonite	6
Gravel	2
Olivine	4
Potassium chloride (KCl)	14 802
S (bonded)	33 038
Biomass (including water)	314
Land use (x E^{-06} m^2)	1 727 693

Table 5. Gross solid waste associated with the production of 1 kg Ingeo 2009					
Emission	From fuel production (mg)	From fuel use (mg)	From transport (mg)	From process (mg)	Totals (mg)
Plastics	0	0	0	1 000	1 000
Unspecified refuse	601	0	0	0	601
Mineral waste	108	0	241	18 402	18 751
Slags and ash	60 239	378	94	24	60 735
Mixed industrial	393	0	12	1 381	1 785
Regulated chemicals	734	0	398	12	1 145
Unregulated chemicals	557	0	0	166	723
Construction waste	0	0	0	2	2
Waste returned to mine	113 106	0	8	5	113 119
Tailings	4	0	1 247	23	1 274
Landfilled waste (temporary; process)	0	0	0	68 374	68 374

Table 6. Gross air emissions associated with the production of 1 kg Ingeo 2009

Emission	From fuel production (mg)	From fuel use (mg)	From transport (mg)	From process (mg)	From biomass (mg)	Totals (mg)
Dust (PM10)	8 689.0578	111.6328	14.6853	26.6177	0.0000	8 841.9936
CO	2 486.9978	1 179.5275	212.0878	288.7774	0.0000	4 167.3905
CO_2	1 652 571.5239	973 322.8604	27 884.1073	113 347.5041	-1 940 393.0000	826 733.7867
SOX as SO_2	6 026.5399	1 148.1782	68.2946	158.4648	0.0000	7 401.4775
H_2S	0.0045	0.0000	0.0303	0.1136	0.0000	0.1485
Mercaptan	0.0000	0.0004	0.0000	0.0000	0.0000	0.0004
NOX as NO_2	6 263.6776	1 803.6244	366.4538	3 877.4970	0.0000	12 311.2529
NH_3	0.0003	0.0000	0.0006	3.9538	0.0000	3.9547
Cl_2	0.0000	0.0000	0.0001	0.1603	0.0000	0.1604
HCl	345.4046	2.6515	0.0430	0.1003	0.0000	348.1994
F_2	0.0000	0.0000	0.0000	0.0001	0.0000	0.0001
HF	12.7868	0.1048	0.0048	0.0000	0.0000	12.8964
Hydrocarbons not specified elsewhere	783.4089	310.6057	58.9180	11.0203	0.0000	1 163.9528
Organics	0.0003	0.0000	0.0007	0.7001	0.0000	0.7011
Pb^+ compounds as Pb	0.0001	0.0000	0.0003	0.0001	0.0000	0.0005
Hg^+ compounds as Hg	0.0001	0.0000	0.0000	0.0001	0.0000	0.0002
Metals not specified elsewhere	0.0302	0.6090	0.0004	0.0012	0.0000	0.6407
H_2SO_4	0.0000	0.0000	0.0000	0.0138	0.0000	0.0138
N_2O	0.0000	0.0000	0.0000	370.7019	0.0000	370.7019
H_2	0.9648	0.0031	0.0043	89.4332	0.0000	90.4053
Dichloroethane (DCE) $C_2H_4Cl_2$	0.0000	0.0000	0.0001	0.0000	0.0000	0.0002
Vinyl chloride monomer (VCM)	0.0010	0.0000	0.0021	0.0000	0.0000	0.0032
Organochlorine not specified elsewhere	0.0000	0.0000	0.0000	10.2268	0.0000	10.2268
CH_4	12 592.8293	485.9704	7.5065	21.0358	0.0000	13 107.3420
Aromatic HC not specified elsewhere	0.2711	0.0000	0.5755	0.1489	0.0000	0.9954
NMVOC	0.0033	2.6748	33.7795	6.7811	0.0000	43.2388
Methylene chloride CH_2Cl_2	0.0000	0.0000	0.0000	0.0002	0.0000	0.0002
As^+ compounds as As	0.0000	0.0000	0.0000	0.0001	0.0000	0.0001
Zn^+ compounds as Zn	0.0002	0.0000	0.0005	0.0002	0.0000	0.0009
Se^+ compounds as Se	0.0000	0.0000	0.0000	0.0001	0.0000	0.0001
Ni^+ compounds as Ni	0.0000	0.0000	0.0000	0.0004	0.0000	0.0004
Fe^+ compounds as Fe	0.0000	0.0000	0.0000	0.0003	0.0000	0.0003
V^+ compounds as V	0.0000	0.0000	0.0000	0.0016	0.0000	0.0016
Al^+ compounds as Al	0.0000	0.0000	0.0000	–2.1325	0.0000	-2.1325
B^+ compounds as B	0.0000	0.0000	0.0000	0.0007	0.0000	0.0007
Manganese (process)	0.0000	0.0000	0.0000	0.0001	0.0000	0.0001
Corn dust (biomass)	0.0000	0.0000	0.0000	0.0000	76.3641	76.3641
Tin (process)	0.0000	0.0000	0.0000	0.0001	0.0000	0.0001

Table 6. Gross air emissions associated with the production of 1 kg Ingeo 2009 *continued*

Emission	From fuel production (mg)	From fuel use (mg)	From transport (mg)	From process (mg)	From biomass (mg)	Totals (mg)
Barium (process)	0.0000	0.0000	0.0000	0.0457	0.0000	0.0457
Bromine (process)	0.0000	0.0000	0.0000	0.0005	0.0000	0.0005
Cyanide (unspecified; process)	0.0000	0.0000	0.0000	0.0001	0.0000	0.0001
Helium (process)	0.0000	0.0000	0.0000	0.0496	0.0000	0.0496
VOC (process)	0.0000	0.0000	0.0000	0.0318	0.0000	0.0318
Dust (PM 2.5; process)	0.0000	1.9399	0.0000	0.0000	0.0000	1.9399
Dust (unspecified; transport)	0.0000	0.0938	8.3932	0.0000	0.0000	8.4869
Particles (<2.5 µm; process)	0.0000	0.0000	0.0000	−13.3104	0.0000	−13.3104
Particles (>10 µm; process)	0.0000	0.0000	0.0000	−138.7362	0.0000	−138.7362
Particles (<10 µm, >2.5 µm; process)	0.0000	0.0000	0.0000	−124.7004	0.0000	−124.7004

Table 7. Gross emissions to water arising from the production of 1 kg Ingeo 2009

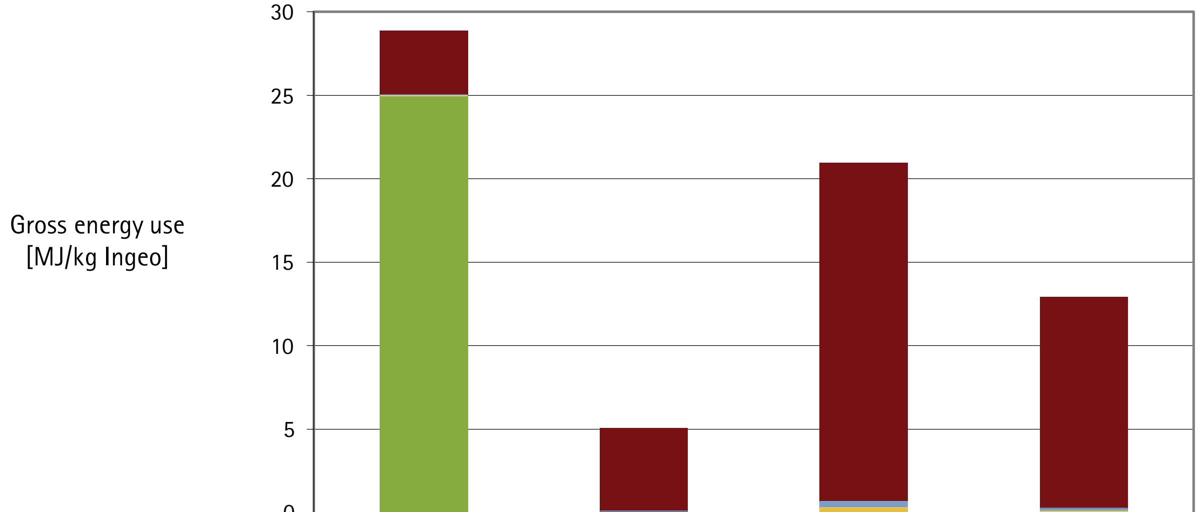
Emission	From fuel production (mg)	From fuel use (mg)	From transport (mg)	From process (mg)	Totals (mg)
COD	0.9885	0.0000	2.9824	4 891.4365	4 895.4074
BOD	0.1473	0.0000	0.3459	2.2529	2.7461
Pb^{+} compounds as Pb	0.0001	0.0000	0.0002	0.0000	0.0004
Fe^{+} compounds as Fe	0.0058	0.0000	0.0132	12.5554	12.5745
Na^{+} compounds as Na	0.1596	0.0000	0.1334	616.2524	616.5454
acid as H^{+}	0.6078	0.0000	0.0061	0.0211	0.6349
NO^{-}	0.0147	0.0000	0.0001	1 226.8562	1 226.8711
Metals not specified elsewhere	0.1507	0.0000	0.0050	0.0352	0.1910
Ammonium compounds as NH_4^{+}	0.6407	0.0000	0.0138	0.0432	0.6977
Cl^{-}	0.3407	0.0000	53.4255	1 200.4322	1 254.1985
CN^{-}	0.0000	0.0000	0.0001	0.0000	0.0001
F-	0.0006	0.0000	0.4996	0.0085	0.5087
S^{+} sulphides as S	0.0000	0.0000	0.0000	0.0000	0.0000
Dissolved organics (nonhydrocarbon)	0.2451	0.0000	0.0006	0.0608	0.3066
Suspended solids	144.3669	0.0000	24.2500	2 874.4069	3 043.0238
Detergent/oil	0.0063	0.0000	0.0144	0.0451	0.0658
Hydrocarbons not specified elsewhere	0.0604	0.0082	0.0116	0.1897	0.2699
Organochlorine not specified elsewhere	0.0000	0.0000	0.0000	0.0018	0.0018
Dissolved chlorine	0.0000	0.0000	0.0000	0.0018	0.0018
Phenols	0.0012	0.0000	0.0000	0.0060	0.0072
Dissolved solids not specified elsewhere	0.0304	0.0000	0.0560	3.4520	3.5384
P^{+} compounds as P	0.0049	0.0000	0.0000	12.1723	12.1772

Table 7. Gross emissions to water arising from the production of 1 kg Ingeo 2009 *continued*

Emission	From fuel production (mg)	From fuel use (mg)	From transport (mg)	From process (mg)	Totals (mg)
Other nitrogen as N	0.1364	0.0000	0.0050	133.0750	133.2164
Other organics not specified elsewhere	0.0003	0.0000	0.0006	0.3167	0.3175
$(SO_4)^{2-}$	0.0214	0.0000	0.0453	137.1732	137.2400
Vinyl chloride monomer (VCM)	0.0000	0.0000	0.0000	0.0000	0.0001
K^+ compounds as K	0.0001	0.0000	0.0003	0.1726	0.1730
Ca^+ compounds as Ca	0.0004	0.0000	0.0009	128.3759	128.3772
Mg^+ compounds as Mg	0.0000	0.0000	0.0001	0.9485	0.9487
Cr^+ compounds as Cr	0.0000	0.0000	0.0000	0.0018	0.0018
ClO^{3-}	0.0002	0.0000	0.0006	0.0601	0.0609
BrO^{3-}	0.0000	0.0000	0.0000	0.0003	0.0003
TOC	0.0003	0.0000	1.2465	9.9312	11.1780
Al^+ compounds as Al	0.0002	0.0000	0.0005	0.0127	0.0134
Zn^+ compounds as Zn	0.0000	0.0000	0.0001	0.0005	0.0006
Cu^+ compounds as Cu	0.0000	0.0000	0.0000	0.0004	0.0004
Ni^+ compounds as Ni	0.0000	0.0000	0.0000	0.0003	0.0003
CO^{3-}	0.0000	0.0000	0.0191	0.2461	0.2652
As^+ compounds as As	0.0000	0.0000	0.0000	0.0001	0.0001
Mn^+ compounds as Mn	0.0000	0.0000	0.0000	0.0036	0.0037
Ba^+ compounds as Ba	0.0000	0.0000	0.0000	0.0010	0.0010
Sr^+ compounds as Sr	0.0000	0.0000	0.0000	0.0037	0.0037
Ca^{2+}(process)	0.0000	0.0000	0.0000	251.8245	251.8245
$(PO_4)^{3-}$ (process)	0.0000	0.0000	0.0000	0.0316	0.0316
Chromium (III) (process)	0.0000	0.0000	0.0000	0.0010	0.0010
Chromium (VI) (process)	0.0000	0.0000	0.0000	0.0001	0.0001
Chlorine, dissolved (process)	0.0000	0.0000	0.0000	0.0007	0.0007
Fluorine (process)	0.0000	0.0000	0.0001	0.0000	0.0002
Neutral salts (process)	0.0000	0.0000	0.0000	0.0033	0.0033
Halogenated organics (process)	0.0000	0.0000	0.0000	0.0101	0.0101

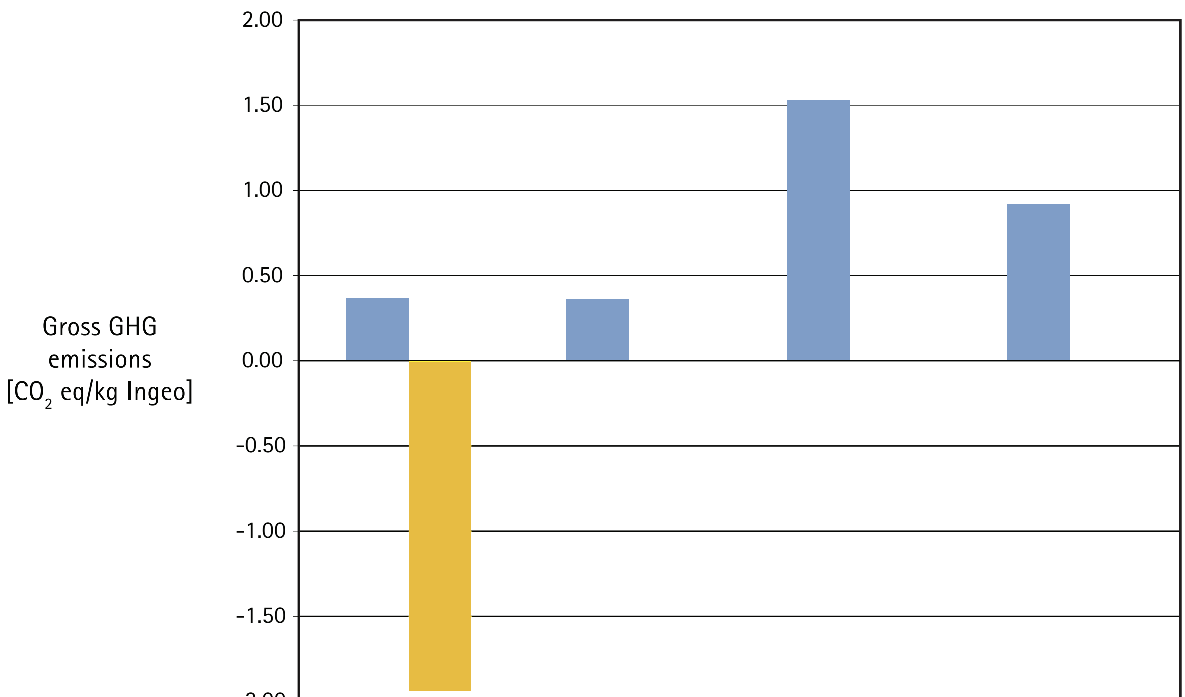
for water. The entry "Unspecified" in the "Use for processing column" mainly represents the irrigation water use during corn production. *Table 4* shows the raw material requirements. The bottom entry gives "Land use"; the net land use is 1.7 m^2/kg Ingeo. *Table 5* shows the solid waste generated. The bottom entry, "Landfilled waste," is a temporary landfilled waste stream that will be incinerated with energy recovery, starting 2 to 3 years from now. The gypsum produced is sold for soil conditioning and is replacing mined gypsum in the marketplace. A credit is given equal to the avoided gypsum mining. *Table 6* shows the air emissions, and *Table 7* the emissions to water. The interpretation of these tables is described by Boustead.[11]

The data in *Tables 1–7* give the gross eco-profile data per kg Ingeo 2009. *Figure 4* gives the gross energy use per production segment. The gross nonrenewable energy use (for process and feedstock) from the cradle to the polymer factory gate is 42.2 MJ/kg Ingeo 2009. For the correct interpretation of this figure, an example is offered: The gross nonrenewable energy use for the lactic acid production segment is 20.57 MJ/kg Ingeo. This 20.57 MJ represents the total or gross energy used to produce and deliver the nonrenewable energy required (electricity, natural gas, and steam) in the lactic acid production process, and the energy required to produce and deliver all kinds of operating supplies (water, acids, nutrients, compressed air), as well



	Corn	Dextrose	Lactic acid	Polymer
Nonrenewable used as process energy	3.85	5.00	20.30	12.69
Renewable used as process energy	0.01	0.08	0.39	0.18
Nonrenewable used as feedstock	0.03	0.00	0.27	0.07
Renewable used as feedstock	24.97	0.00	0.00	0.00

Figure 4. Gross energy use per production segment



	Corn	Dextrose	Lactic acid	Polymer
$GWP_{(100\ year)}$: gross emissions	0.37	0.36	1.53	0.92
$GWP_{(100\ year)}$: net harnassed	-1.94	0.00	0.00	0.00

Figure 5. Gross greenhouse gas take-up and emissions per production segment

Figure 6. Cradle to polymer factory gate nonrenewable energy use for the various Ingeo production systems

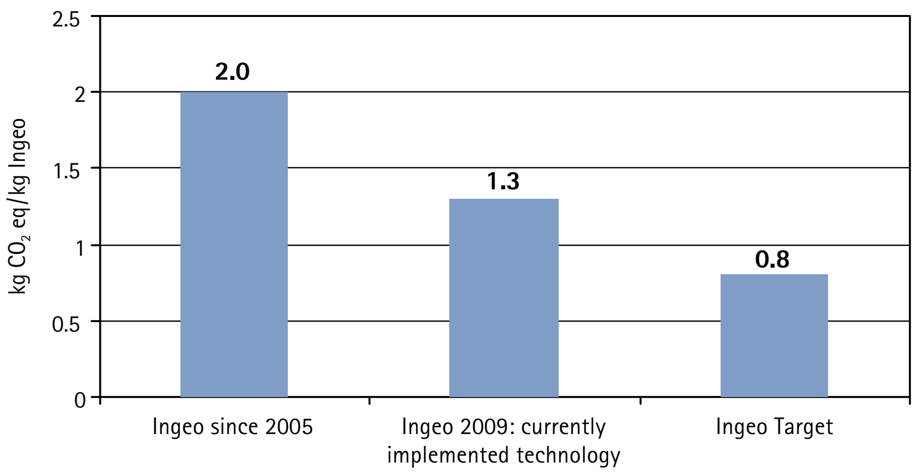


Figure 7. Cradle to polymer factory gate greenhouse gas emissions for the various Ingeo production systems

as the energy required for processing the air and water emissions generated by the lactic acid production facility.

Figure 5 gives the gross greenhouse gas take-up (1.94 kg CO_2 eq/kg Ingeo of which 95% is build into the polymer backbone) and the gross greenhouse gas emissions (total 3.18 kg CO_2 eq/kg Ingeo) per production segment, resulting in a *net* GHG emission of 1.24 (rounded to 1.3) kg CO_2 eq/kg Ingeo.

4.2 THE INGEO 2009 ECO-PROFILE IN PERSPECTIVE

NatureWorks has produced Ingeo biopolymers since 2001 in its large-scale facility in Blair, Nebraska. Between 2001 and 2005, data was collected to calculate the first eco-profile. This eco-profile was called Ingeo 2005 (or PLA5) and was the basis for the 2007 publication.[2] Since 1998, NatureWorks has been developing new lactic acid production technology, with the objectives of developing a process with higher yields, better economics, lower carbon footprint, lower energy use, lower water use, and less waste. During this period, a package of technology improvements was developed, part of which were implemented in December 2008. The changes implemented in lactic acid production technology led to an update of the Ingeo 2005 eco-profile, called Ingeo 2009 (often, again, also referred to as Ingeo 2009 CIT). The eco-profile of Ingeo 2009 is given in this paper. However, more technology improvements are possible in the Blair facilities, and with further investments, the environmental footprint (expressed as the eco-profile) can be further reduced. This eco-profile is called Ingeo Target. There are various routes to reach this target, depending on technological and economic parameters. A comparison of these three Ingeo eco-profiles is given in *Figures 6*, *7*.

To calculate the total greenhouse gas emissions, the following global warming potential ($GWP_{(100\ year)}$) values were used: carbon dioxide = 1; methane = 23, and nitrous oxide = 296. (The Global Warming Potential, or GWP, is a measure of how much a given mass of greenhouse gas is estimated to contribute to global warming or global climate change. It is a relative scale that compares the gas in question to that of the same mass of carbon dioxide [whose GWP is, by convention, equal to 1]. A GWP is calculated over a specific time interval; the commonly used interval is 100 years.)

There are many more potential improvements. One can switch from agricultural crops (starch- or sugar-based) to agricultural waste stream (cellulosics-based feedstock) as a source for the required sugar.[1] As new plants are built, the energy supply (electricity and heating needs) can be optimized by installing, for example, biomass-fueled heat/power installations. Wind power can also be an attractive alternative. In the meantime, process optimization of lactic acid and polymer production will be continued as well. Exactly how these improvements will affect the overall life cycle inventory in the future cannot be meaningfully projected at this point, but it is clear that fossil energy requirements, greenhouse gas emissions, and other indicators will be further reduced in next-generation Ingeo production facilities.

4.3 BENCHMARKING ON POLYMER PELLET BASIS.

Basically, LCA should always take a full “cradle to grave” perspective, but since there are so many different polymers, numerous differ-

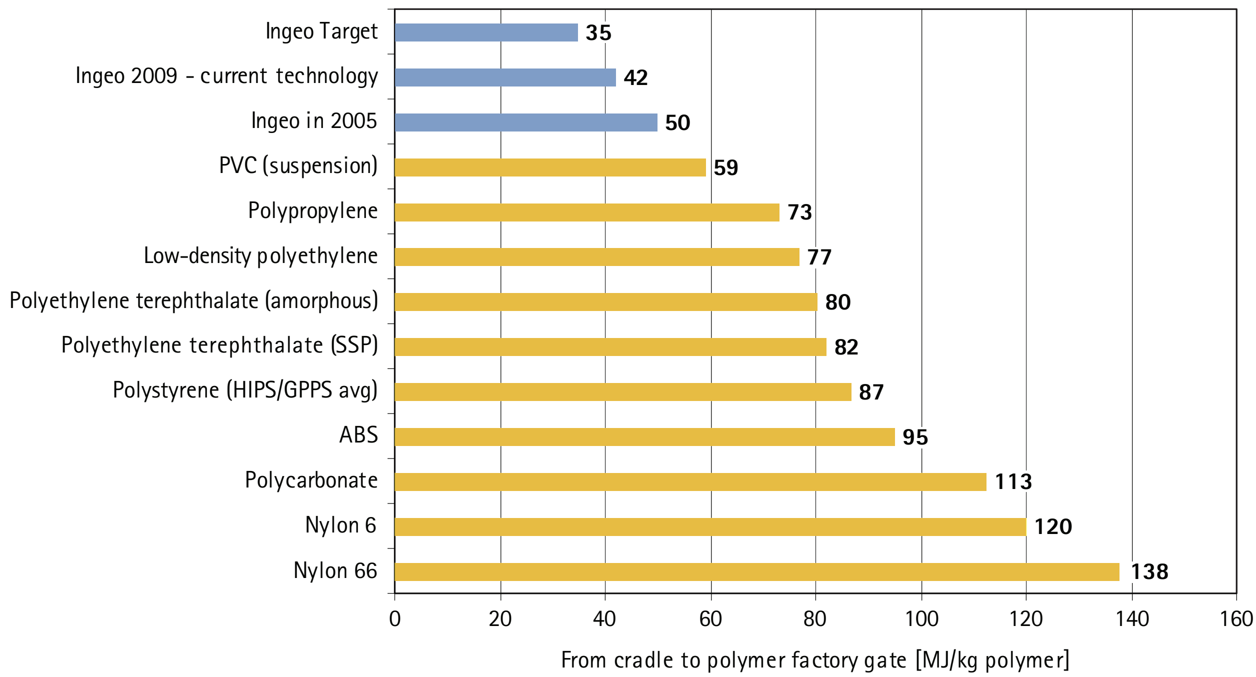


Figure 8. Benchmarking for nonrenewable energy use

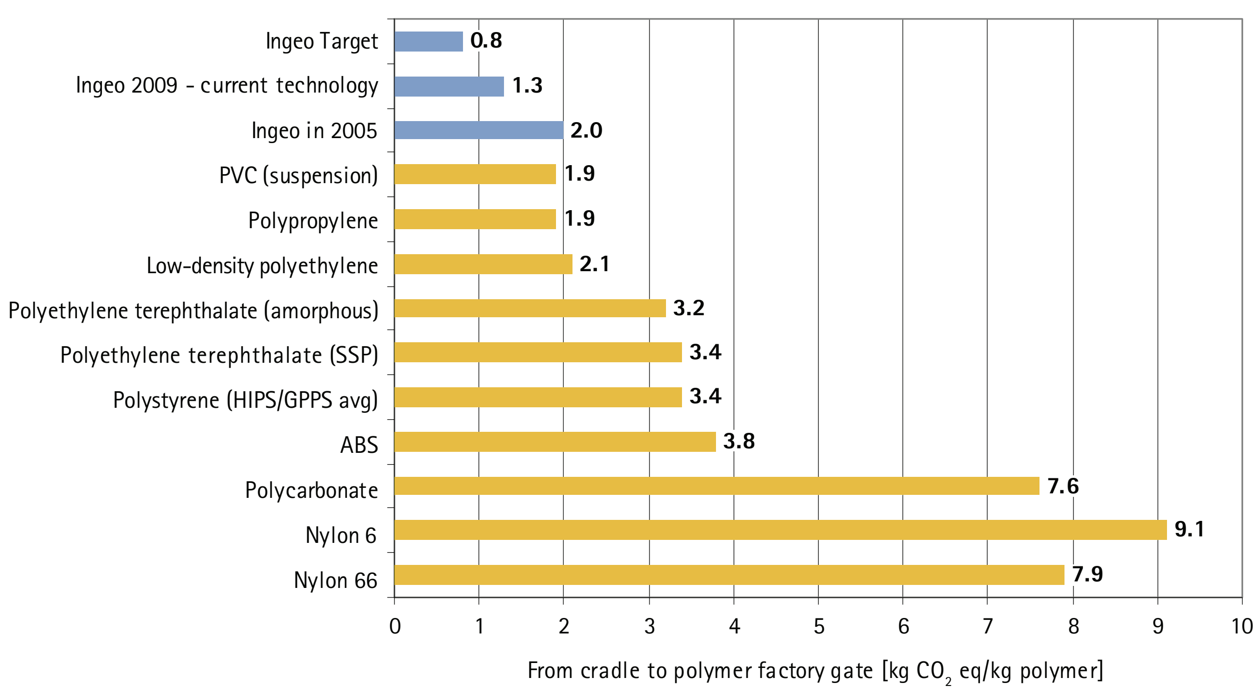


Figure 9. Benchmarking for greenhouse gas emissions

ent production locations (with different fuels mixes), many different applications, as well as different end-of-life options, it is infeasible to perform all these studies. There is thus a need to adopt some simplifications. Benchmarking on a "polymer pellet" basis can be done and will give a *relative good first impression* as to how Ingeo biopolymer performs given that:

- in many applications (packaging, bottles), the polymer weight is similar
- in most packaging LCAs, the contribution of specific impact categories is dominated by the processes up through the polymer pellet production
- energy requirements for conversion are relatively small and do not differ to a large extent

The recovery or final disposal route can cause (very significant) differences between polymers, and these must be accounted for when completing an LCA.

Figures 8 and *9* give the benchmarking results for Ingeo biopolymers compared with a selection of fossil-based polymers. The data for these polymers is being published by PlasticsEurope.[10]

Acknowledgment

During the development process of the current Ingeo eco-profile, Dr. Ian Boustead of Boustead Consulting reviewed all the process-level data which was the basis for the current Ingeo eco-profile. The final review report may be downloaded from the NatureWorks website.[3]

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