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Comparing the Land Requirements, Energy Savings, and Greenhouse Gas Emissions Reduction of Biobased Polymers and Bioenergy

An Analysis and System Extension of Life-Cycle Assessment Studies

Veronika Dornburg, Iris Lewandowski, and Martin Patel

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Address correspondence to:
Veronika Dornburg
Department of Science, Technology, and Society
Copernicus Institute for Sustainable Development and Innovation
Utrecht University
Padualaan 14
3584 CH Utrecht, The Netherlands
⟨V.Dornburg@chem.uu.nl⟩
⟨www.chem.uu.nl/nws/www/nws.html⟩

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Summary

This study compares energy savings and greenhouse gas (GHG) emission reductions of biobased polymers with those of bioenergy on a per unit of agricultural land-use basis by extending existing life-cycle assessment (LCA) studies. In view of policy goals to increase the energy supply from biomass and current efforts to produce biobased polymers in bulk, the amount of available land for the production of nonfood crops could become a limitation. Hence, given the prominence of energy and greenhouse issues in current environmental policy, it is desirable to include land demand in the comparison of different biomass options. Over the past few years, numerous LCA studies have been prepared for different types of biobased polymers, but only a few of these studies address the aspect of land use. This comparison shows that referring energy savings and GHG emission reduction of biobased polymers to a unit of agricultural land, instead of to a unit of polymer produced, leads to a different ranking of options. If land use is chosen as the basis of comparison, natural fiber composites and thermoplastic starch score better than bioenergy production from energy crops, whereas polylactides score comparably well and polyhydroxyalkaonates score worse. Additionally, including the use of agricultural residues for energy purposes improves the environmental performance of biobased polymers significantly. Moreover, it is very likely that higher production efficiencies will be achieved for biobased polymers in the medium term. Biobased polymers thus offer interesting opportunities to reduce the utilization of nonrenewable energy and to contribute to GHG mitigation in view of potentially scarce land resources.

Introduction

Polymers, lubricants, surfactants, and solvents account for the largest share of synthetic organic material production in contemporary economies. Today they are almost exclusively produced from fossil feedstock (with the exception of surfactants); however, they could, in principle, also be produced from renewable feedstock. This article focuses on polymers, which represent about half of the total production of synthetic organic materials (excluding bitumen) (Patel et al. 1999). A wider use of biobased polymers could thus become an important way to increase the use of renewable resources. Biobased polymers are defined here as polymers that are fully or partially produced from renewable raw material. In the 1980s and 1990s, biobased polymers began playing an increasingly important role in several applications. The environmental (and economic) performance of many biobased polymers is likely to improve in the future as a result of technological progress and economies of scale (see, e.g., Nossin et al. 2002; Vink et al. 2003). The fact that environmental considerations have been, and will continue to be, an important motivation to develop and introduce biobased polymers calls for a thorough comparative analysis of their environmental performance.

To this end, numerous life-cycle assessments (LCAs) have been prepared in the last few years for different types of biobased polymers (Patel et al. 2003). Only a few LCA studies published in the scientific literature on biobased polymers address the question of land use, however; most studies do not take it into consideration at all. In the first group of studies, the environmental impacts are mostly compared using the amount of biobased polymer as a functional unit, for example, 1 kg of polymer. Some studies report the amount of land used but do not use it as a basis for comparison of different polymers.[1]

The inclusion of demand for land in such studies is desirable because considerable efforts are currently being made to produce biobased polymers in bulk. In the longer term, this could result in a substantial demand for agricultural land. In view of land requirements for food production and policy goals to increase energy supply from biomass, the amount of available land for the production of nonfood crops is likely to become scarcer and more expensive. For example, Hoogwijk and colleagues (2003) estimated that depending on food demands, in 2050 about 0.4 to 3.2 Gha of agricultural and degraded land will be available for biomass production for energy and materials on a global scale, whereas the biomaterials production in 2050 will demand about 0.4 to 0.7 Gha. Therefore, it will become increasingly important to maximize environmental benefits from the use of land, and this requires indicators of the impacts of biomass utilization that reflect land use.

Given the prominence of energy and greenhouse issues in current environmental policy and because of the limited data that are available from LCA studies, this article only analyzes nonrenewable energy use and greenhouse gas (GHG) emissions in relation to land use. We do, however, recognize that other environmental impacts, issues of sustainable agriculture, and economical feasibility are also important criteria for ranking options. For the sake of simplicity, "nonrenewable energy" use is also referred to as "energy use" in this article.

The fact that biomass can be used both for the manufacture of materials (here: polymers) and for the production of energy commodities raises the question which of the two options is more advantageous in terms of energy use and GHG emissions. The LCA prepared by Corbière-Nicollier and colleagues (2001) indicates that the production of polymers based on starch, kenaf, and china reed offer greater opportunities for energy saving and GHG mitigation than the production of bioenergy. In contrast, Kurdikar and colleagues (2001) argued, in the case of genetically modified corn stover, that the use of stover wastes as an energy source contributes more to GHG emission reduction than the production of PHA.

During agricultural production, large amounts of agricultural residues arise; for example, in the case of corn about 50% of the total dry matter is residue (known as "stover"). The utilization of agricultural residues is usually not accounted for in LCA studies for biobased polymers. This approach is often justified because agricultural residues are typically used for low-value applications within agriculture (e.g., animal food or soil improvement); however, more and more agricultural residues are now used for energy purposes (e.g., straw combustion for district heating, as is done on a large scale in Denmark). Given this trend, it is of interest to study to what extent the utilization of agricultural residues for bioenergy generation could improve the environmental performance of biobased polymers.

Whenever a process has more than one output, allocation issues may become important in LCA studies. Examples of such by-products in the case of biobased polymers are proteins, glucose syrup, and vegetable oil. Allocation of impacts to the polymer versus the by-products can have significant effects on the calculated energy savings and GHG emission reduction for the biobased polymer. Allocation is of particular interest for biobased polymers because the by-product streams can be relatively large and different approaches are chosen in various LCA studies.

In this article, we analyze LCA studies of various biobased polymers and calculate for each study the respective energy savings and GHG emission reductions per hectare[2] of land used for biomass production, thereby assuming the substitution of biobased for petrochemical polymers. These benefits are then compared to the benefits of energy production from dedicated energy crops, hereafter referred to as "bioenergy." In other words, we use the term "bioenergy" only for the exclusive production of heat, electricity, or other mechanical power from agricultural crops. Moreover, this article assesses energy savings and GHG emission reductions per hectare resulting from the utilization of agricultural residues for energy production. This also represents a form of bioenergy use but is to be exclusively referred to in the following as "residue use" or "residue utilization" in order to avoid confusion with "bioenergy." The effect of the choice of different allocation methods and selected parameters on the results is analyzed in a sensitivity analysis.

LCA Studies of Biobased Polymers

In this assessment, we analyzed 11 LCA studies of biobased polymers (Dinkel et al. 1996; Würdinger et al. 2002; Estermann et al. 2000; Vink et al. 2003; Gärtner et al. 2002; Gerngross and Slater 2000; Heyde 1998; Diener and Siehler 1999; Wötzel et al. 1999; Pervaiz and Sain 2003; Corbière-Nicollier et al. 2001). These cover thermoplastic starch (TPS), polyhydroxyalkaonates (PHAs), polylactides (PLAs), and natural fiber reinforced composites. The studies compare biobased polymers to petrochemical polymers either as raw material or as product. The comparison at the raw material level refers to one mass unit of primary plastics (i.e., granules, pellets), whereas the comparison at the product level refers to end products, such as molded components for automobiles or blown films for packaging. The publications differ considerably in the amount of published background data and the degree of detail regarding explanations about methodology and results. A detailed description of the studies can be found in Patel et al. (2003).

Regarding system boundaries, some studies only analyze the process chain from cradle to factory gate, whereas other studies take a cradle-to-grave approach, thereby covering different types of waste treatment (e.g., incineration with or without energy recovery, recycling, composting, etc.). An important note is that the use phase has been excluded in all of the studies taken into account in this article. In this study, we decided to compare all biobased polymers equally on a cradle-to-grave basis, including incineration without energy recovery in the waste management stage. This choice has been made in view of the fact that direct landfilling of untreated waste containing organic carbon will be prohibited in many industrialized countries, especially in Europe, in the near future (EC 1999). Recycling, reuse, and other waste management options such as digestion and composting (the latter two are only relevant for biodegradable polymers) are still rarely used, and this has not appreciably changed in the last few years. As a consequence, in Europe waste incineration is likely to become the standard waste treatment technology that is applicable to all the biobased and petrochemical polymers considered. The reasons for neglecting energy recovery are that not all facilities recoup and export energy and that energy recovery yields are in general still poor. Average energy conversion efficiencies of incineration plants in Europe have been estimated at about 12% heat and 12% electricity on a lower heating value (LHV) basis of the waste input (Phylipsen et al. 2002).

Nonrenewable Energy Savings and GHG Emission Reduction

Nonrenewable energy savings and GHG emission reduction per kilogram[3] of biobased polymers as presented in the LCA studies, and if necessary recalculated to a cradle-to-grave basis, including incineration without energy recovery, are shown in table 1. This table allows us to compare the ranking of the different biobased polymers with regard to energy savings and GHG reduction per kilogram of polymer to the ranking with regard to benefits per hectare of cultivated biomass. The type and amount of the substituted petrochemical polymers have generally been taken as given in the original studies. To ensure a consistent comparison of the LCA, data for petrochemical polymers, that is, low-density polyethylene (LDPE), high-density polyethylene (HDPE), and expanded polystyrene (EPS), were all taken from a single source, that is, the Association of Plastics Manufacturers in Europe (APME 1999). These data sets, commissioned by the association and elaborated by the Boustead consultancy, are to our knowledge the most extensive and authoritative sources for LCA data on petrochemical polymers. Data for the conventional counterparts of natural fibers used in composites, that is, fiberglass and acrylonitrile butadiene styrene (ABS), were taken as given in the original LCA studies because no other authoritative data sets were available.

Inclusion of Land Demand and Agricultural Residues

As table 2 shows, most studies did not take into account land demand in their assessment of environmental impacts. Furthermore, four studies did not indicate a reference crop yield per hectare on which the assessment is based. In the studies, different approaches are used to account for land demand. Gärtner and colleagues (2002) included land demand in their analysis by calculating environmental impacts per hectare of biomass cultivation. Corbière-Nicollier and colleagues (2001) and Dinkel and colleagues (1996) reported the environmental impacts per kilogram of biobased polymers and the energy savings per hectare. Moreover, Dinkel and colleagues (1996) also calculated the GHG emission reductions per hectare. Würdinger and colleagues (2002) applied the concept of "natural area demand," where land is categorized into different classes of natural quality.

Table 3 summarizes whether and how agricultural residues and by-products from the material production process were accounted for in the analysis. Although many studies accounted for by-products from crop processing and polymer production, only Würdinger and colleagues (2002) and Vink et al. (2003) also considered the use of agricultural residues.

Only Gärtner and colleagues (2002) assumed that the by-products substitute for equivalent products originating from other production processes (i.e., products from sunflowers); the other authors distributed the environmental impacts among the products ("allocation" in the strict sense). Concerning agricultural residues, only Würdinger and colleagues (2002) and Vink et al. (2003) accounted for their potential value. Würdinger and colleagues (2002) assumed that corn stover, which is usually left on the field, substitutes for artificial fertilizer. Vink et al. (2003) allocated a small part of the biomass production impacts to the residues but did not specify the basis of this allocation.

Methodology

Because the different studies deal in very different ways with land use and agricultural residues, we related energy savings and GHG emissions to land demand in a consistent way and, moreover, extended the system boundary to include the use of agricultural residues for energy production. To address land use, the area of medium-quality agricultural land occupied for biomass production is used as a functional unit. Different biopolymers can then be compared with regard to their environmental performance per unit of (possibly scarce) agricultural land. Other important functions of land, for example, erosion prevention and habitat, are outside the

Table 1 Summary of LCA study results: Energy savings and CO_2 emission reduction on a cradle-to-grave basis including polymer incineration without energy recovery per kilogram of biobased polymer

Comparison: biobased versus petrochemical polymer			*Biobased polymer*					*Petrochemical polymer*	
Type of polymers	*Non-renewable energy use (MJ/f.u.)*	*GHG emissions (kg CO_2 eq./f.u.)*	*Functional unit (f.u.)*	*Product*	*Reference*	*Non-renewable energy use (MJ/f.u.)*	*GHG emissions (kg CO_2 eq./f.u.)*	*Substituted amount per functional unit*	*Reference*
TPS vs. LDPE	−55.2	−3.90	1 kg	Pellets	Dinkel et al. 1996	25.4	1.14	1 kg	APME 1999
TPS vs. LDPE	−24.5	−1.99	1 kg	Film	Dinkel et al. 1996	25.4	1.14	(150 μm) 0.62 kg	APME 1999
TPS[a] vs. EPS	−8.8	0.28	1 kg	Loose fills	Würdinger et al. 2002	18.9	1.10	(0.08 m^3) 0.33 kg	APME 1999
TPS[b] vs. EPS	−1.3	−0.76	1 kg	Loose fills	Estermann et al. 2000	36.5	0.37	(0.1 m^3) 0.45 kg	APME 1999
PLA vs. LDPE	−23.6	−1.20	1 kg	Pellets	Vink et al. 2003[c]	57	3.84	1 kg	APME 1999
PLA vs. PE	n/a	n/a	n/a	Pellets	Gärtner et al. 2002[d]	n/a	n/a	n/a	n/a
PHA vs. HDPE	1.1	n/a	1 kg	Pellets	Gerngross and Slater 2000[e]	81.0	n/a	1 kg	APME 1999
PHA vs. HDPE	−13.8	n/a	1 kg	Pellets	Heyde 1998	66.1	n/a	1 kg	APME 1999
Natural fiber/PP[f] vs. fiberglass	−45.1	n/a	1 kg	Fibers[g]	Diener and Siehler 1999	9.6	n/a	1 kg	Diener and Siehler 1999
Natural fiber/EPS vs. ABS	−72	−1.0	1 kg	Automotive parts	Wötzel et al. 1999	89	5.1	1.37 kg	Wötzel et al. 1999
Natural fiber/PP vs. fiberglass/PP	−48.5	−2.8	1 kg	Composite	Pervaiz and Sain 2003	47.9	2.8	1 kg	Corbière-Nicollier et al. 2001
Natural fiber/PP vs. fiberglass/PP	−53.7	n/a	1 kg	Transport pallet	Corbière-Nicollier et al. 2001	61.3	n/a	1.27 kg	Corbière-Nicollier et al. 2001

Note: Negative values represent energy savings and GHG emission reduction by biobased polymers relative to their petrochemical counterpart.

[a] Including 13% polyvinyl alcohol.

[b] Including 15% polyvinyl alcohol.

[c] No reference polymer is specified in the original source (Vink et al. 2003). For the preparation of this table, the petrochemical reference has therefore been assumed to be polyethylene (PE), as in Gärtner and colleagues (2002) (for TPS applications, LDPE use has been assumed).

[d] In this study, only aggregated values per hectare of biomass cultivation are presented.

[e] In this study, substitution of polyethyleneterephtalate (PET) and polystyrene (PS) is considered possible, too.

[f] PP = polypropylene.

[g] Fibers are utilized to reinforce PP; however, the functional unit of the study is the amount of natural fiber.

Table 2 Inclusion of land demand and key data on agricultural production in the LCA studies considered

Study	*Type of polymer*	*Inclusion land demand*	*Crop*	*Country*[a]	*Crop yield (Mg/[ha yr])*[b]	*Crop input*[a] *(kg crop/kg polymer)*
Dinkel et al. 1996	TPS	Energy and GHG savings calculated per hectare	Potato, corn	CH	Potato: 37.5 (fm)[c], Corn: 12.5 (dm)[d]	Potato: 2.23 + corn: 0.385
Würdinger et al. 2002	TPS	Impact category: natural area use	Corn	DE	Corn: 6.45 (dm)	0.786
Estermann et al. 2000	TPS	No	Corn	FR	Corn: 8.2 (dm)	0.971
Vink et al. 2003	PLA	No	Corn	US	Corn: 9.06 (dm)	1.74
Gärtner et al. 2002	PLA	Impacts calculated per hectare	Corn	DE	n/a	n/a
Gerngross and Slater 2000	PHA	No	Corn	US	Corn: 7.7 (dm)	5.06
Heyde 1998	PHA	No	Sugar beet	DE	n/a	n/a
Diener and Siehler 1999	Flax/PP	No	Flax	DE	n/a	n/a
Wötzel et al. 1999	Hemp/EPS	No	Hemp	DE	n/a	0.49
Pervaiz and Sain 2003	Hemp/PP	No	Hemp	CA	Hemp: 2 (dm)	0.65
Corbière-Nicollier et al. 2001	*Miscanthus*/PP	Energy savings calculated per hectare	*Miscanthus*	CH	*Miscanthus*: 17–20 (dm)	0.75

[a] International Internet country codes.

[b] Yields and amounts of plants needed refer to the typically used crop part, that is, potato, tubers; corn, grain; sugar beet, beet; hemp, fibers; and *Miscanthus*, above-ground biomass.

[c] fm = fresh matter.

[d] Dry matter (dm) refers to plant as harvested with a moisture content of about 12%.

Table 3 Summary of assumptions about utilization of agricultural residues and by-products in the LCA studies considered

Study	*Crop*	*Residue*	*Accounted for residue?*	*By-products at*	*Accounted for by-products?*
Dinkel et al. 1996	Potato, corn	Foliage, stover	No	Starch production	Impacts allocated to energy content
Würdinger et al. 2002	Corn	Stover	Reduced fertilizer need	Starch, semolina production	Impacts allocated to economic value
Estermann et al. 2000	Corn	Stover	No	Starch production	Impacts allocated to energy content
Vink et al. 2003	Corn	Stover[a]	No, but inputs allocated to stover and grain	No details given	Unknown
Gärtner et al. 2002	Corn	Stover	No	Starch production	Substitution of sunflower products
Gerngross and Slater 2000	Corn	Stover	No	Glucose production	Impacts allocated, no details given
Heyde 1998	Sugar beet	Leaves	Unknown	Unknown	Unknown
Diener and Siehler 1999	Flax	Stalks	Unknown	Unknown	Unknown
Wötzel et al. 1999	Hemp	None	No	Fiber preparation	Unknown
Pervaiz and Sain 2003	Hemp	None	No	Fiber preparation	No
Corbière-Nicollier et al. 2001	*Miscanthus*	None	No	Fiber preparation (grinding)	Penalty for energy use of disposal

[a] Stems, husks, leaves, and so on.

scope of this study. Schemes for the systems studied are presented in figure 1 and are explained below in more detail.

Energy Savings and GHG Emission Reduction without Utilization of Residues

To determine energy savings of biobased polymers without residue use, the nonrenewable energy use for the production of a biobased polymer (left box in figure 1, top) is compared to the nonrenewable energy use for the production of a (functionally equivalent) petrochemical polymer (right box in figure 1, top). Energy use within the system includes direct energy inputs for crop production, crop processing and polymer production (process energy and feedstock energy), and indirect energy inputs that are energy inputs for the supply of materials needed for production, for example, machines and fertilizers. These energy requirements lead to GHG emissions. Moreover, non-CO_2 GHG process emissions (N_2O and CH_4) that mainly result from agricultural crop production are also taken into account. Data on these energy uses and GHG emissions were taken from the LCA studies reviewed (table 1).

The amount of biobased polymer (x_1) that can be produced from 1 ha of biomass cultivation substitutes for an amount of petrochemical polymer (x_2) that can fulfill the same function (e.g., a certain amount of pellets, volume of loose fill, or an automotive component). The quantities x_1 and x_2 can be the same, but this is not necessarily the case. For example, less favorable material properties for a given thermoplastic biobased polymer may result in the need for more material

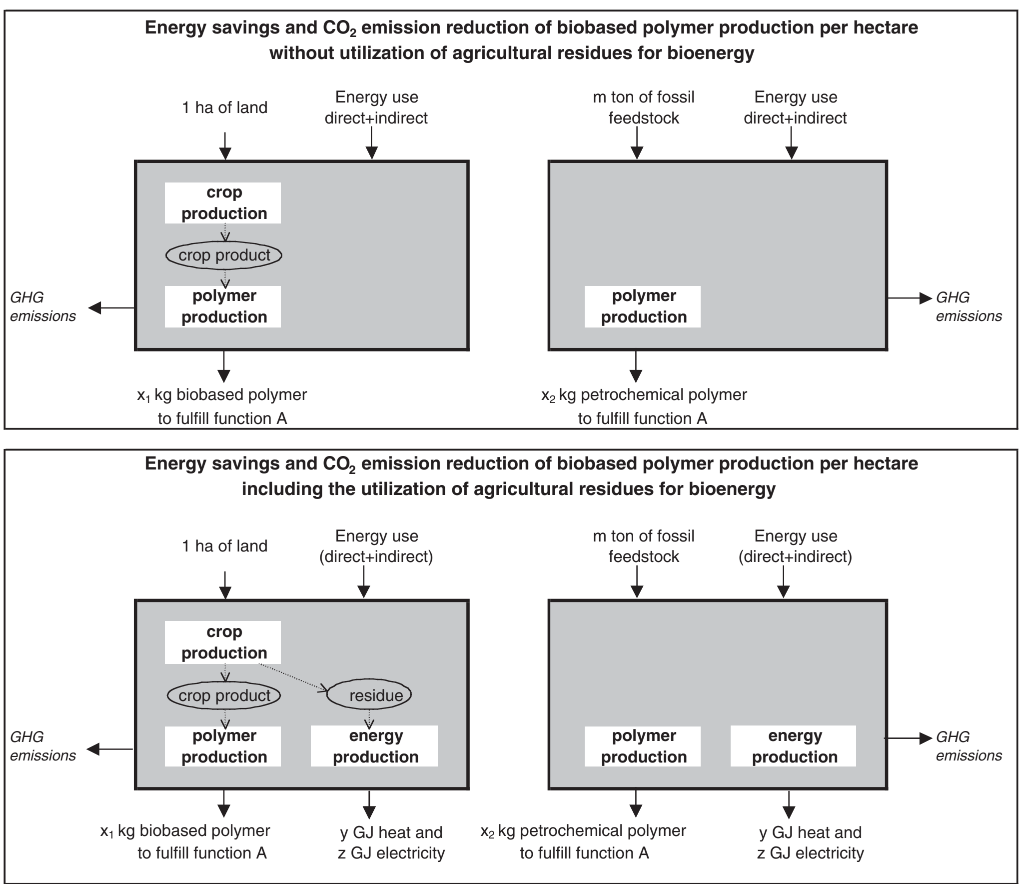

Figure 1 Systems studied to determine energy savings and CO_2 emission reduction of biobased polymer production per hectare of agricultural land.

(mass) than its petrochemical counterpart in order to fulfill the same function. This may occur for starch polymers in certain applications. On the other hand, natural fiber composites are typically lighter than the substituted material, that is, fiberglass composites.

The results of environmental impacts caused by the production of biobased polymers as found in the 11 LCA studies can be expressed per unit of land demand (in hectares). This approach has been applied earlier by Gärtner and colleagues (2002), Corbière-Nicollier and colleagues (2001), and Dinkel and colleagues (1996). To correct for regional differences in agricultural productivity, we recalculated the key results of the LCA studies using a uniform crop yield drawn from the agricultural literature. This value is computed as the average of the "medium yield" shown in table 4 (hereafter referred to as "medium yield"). We thereby assume that the LCA studies refer to good-practice agricultural production methods on land of average fertility, as no exceptional cases have been mentioned. In practice, however, yields per hectare can vary significantly depending on local conditions, for example, climate and soil quality. The influence of this yield variation on the energy savings (and GHG emission reduction) per hectare of land is analyzed in a sensitivity analysis.

Even if total land requirements were compared, the land use in the petroleum-based reference systems would be negligible. Therefore, land requirements are taken into account only for the biobased polymers (figure 1). If a biobased polymer is compared to another biobased polymer or bioenergy, however, the land demand for each of these biobased products is 1 ha. Alternative use of the land in question as set aside or for food production is not considered here.

Energy Savings and GHG Emission Reduction by Utilization of Residues

If the agricultural residues are used for energy production, then this energy is assumed to substitute heat and power from an average energy mix in Europe (see figure 1, bottom). The GHG emission reduction is determined on the same basis.

In practice, agricultural residues often remain on the field. When studying the effect of residue removal on energy use and GHG emissions, three aspects need to be taken into account: (1) the withdrawal of nutrients from the field, (2) the energy requirements and the emissions related to the collection of the residues on the field and their transportation to the energy conversion installation, and (3) the conversion of residues to secondary energy that substitutes for fossil energy.

The amount of agricultural residue can be calculated on the basis of the yield of the crop utilized for biobased polymer production and the harvest index, that is, the proportion of different crop components, as found in the agricultural literature (see table 4). The amount of nutrients

Table 4 Yield classes of crops and agricultural residues

Crop[a]	*Medium-level yield (Mg/[ha yr])*	*Low-level yield (Mg/[ha yr])*	*High-level yield (Mg/[ha yr])*	*Residue*	*Proportion crop: residue*
Potato (tubers, fm)	35–50	25–35	50–60	Foliage (fm)	5:4
Corn (grain, dm)	6.5–8	5–6.5	8–9.5	Stover (dm)	1:1.3
Sugar beet (beet, fm)	50–70	40–50	70–80	Leaves (fm)	4:3
Flax (fibers, dm)	1.4–1.6	1–1.4	1.6–2	Straw (dm)	1:4
Hemp (fibers dm)[b]	1.5–2.25	1.25–1.5	2.25–2.5	Straw (dm)	1:4
Miscanthus (dm)	12–20	6–12	20–30	Grinding res. (dm)	1:0.3

Source: Hydro Agri Dülmen (1993); Scheer-Triebel et al. (2000); Lewandowski et al. (2000); Nova-Institut (1996); Corbière-Nicollier et al. (2001).

[a] fm = fresh matter, dm = dry matter.

[b] For hemp, yield classes were determined from average yields (Nova-Institut 1996) assuming same proportions as for flax.

removed when residues are recovered is determined by assuming typical residue nutrient content in terms of nitrogen (N), phosphorous (P), potassium (K), and calcium (Ca). Next, we assume that synthetic fertilizers must be used to replace the withdrawn nutrients and that the environmental impacts of fertilizer production must be accounted for in the analysis. Energy use and related GHG emissions during harvest and transportation of the agricultural residues are based on the necessary machinery use and average transport distances. Furthermore, for every agricultural residue a representative commercial conversion technology has been defined: Relatively dry agricultural residues (10% to 50% moisture content) are assumed to be combusted in small-sized combined heat and power (CHP) plants. Wet agricultural residues (50% to 90% moisture content) are digested on a small scale, and the biogas is converted to heat and power by a gas engine. The heat and electricity produced from agricultural residues is assumed to replace heat and electricity from an average European energy mix (see table 8) because most LCA studies considered were prepared for Europe.

Comparison with Bioenergy

Finally, the replacement of fossil fuels by either biobased polymers or bioenergy is compared on the basis of land area units. This is done by comparing energy savings and GHG emission reduction of bioenergy production from dedicated energy crops to the results from biobased polymers. For bioenergy, a selection of ethanol, CHP, and power production processes have been considered. Energy savings and GHG emission reduction of bioenergy relative to respective reference energy commodities (i.e., gasoline, heat, and power) were taken from the published literature.

In detail, for ethanol production from corn and short-rotation woody crops (SRWCs), production efficiencies were taken from an energy balance for the United States and Europe, respectively (Shapouri et al. 2002; Faaij et al. 2000). The amount of ethanol produced per hectare is converted to energy savings and GHG emission reduction by the substitution of gasoline on an LHV basis. For ethanol from sugar beet and CHP from perennial grasses, energy savings and GHG emission reduction per hectare are derived from a German LCA, where the energy carriers were compared to an average energy mix (Kaltschmitt and Reinhardt 1997). For power production in a biomass-integrated gasification system with combined cycle fueled by SRWCs, power generation efficiencies are derived from Faaij and colleagues (1998). The power produced is converted to energy savings and GHG emission reductions by substitution of the average European electricity mix.

Agricultural Production and Energy Use of Agricultural Residues

This section presents all complementary data that we used for our calculations of the environmental impacts per area of land used and the use of agricultural residue for energy production (as described in figure 1).

The different yield classes (low, medium, high) as shown in table 4 refer to Germany, being representative of the temperate climate in central Europe.[4] The medium-level yield has been used in our calculations.

In general, we assumed that 100% of the agricultural residues can be removed; however, the final effect of residue removal on soil fertility is a complicated issue and is the subject of intense debate at the moment (see discussion). Table 5 presents the nutrient and energy content of residues. Because fiber plants, that is, flax, hemp, and *Miscanthus*,[5] are usually harvested as a whole crop and no residues are left on the field, no credits for avoided fertilizer use have been introduced for these plants. The energy contents given in table 5 are stated as an LHV if the residues are combusted directly and an LHV of biogas production if the residues are digested.

The energy use and GHG emissions due to the removal of agricultural residues are summarized in table 6. Energy use and GHG emissions due to synthetic fertilizer were derived from research by Kaltschmitt and Reinhardt (1997) and were combined with the nutrient contents in table 5. Residues of hemp, *Miscanthus,* and flax are

Table 5 Characteristics of agricultural residues: Average nutrient and energy content

Residue	Nutrient content kg/Mg residue (fm) N^a	P	K	Ca	Water content (%)	Energy content
Potato foliage	2.4	0.44–0.87	4.1–5.8	19.9	75	15.8 $GJ_{LHV\text{-}biogas}/Mg_{dm}$
Corn stover	4.2	2.18–3.06	12.4–20.7	3.6–5.0	14	15.7 GJ_{LHV}/Mg_{dm}
Sugar beet leaves	1.7	0.35–0.48	3.3–5.8	5.0–10.0	84	12.9 $GJ_{LHV\text{-}biogas}/Mg_{dm}$
Flax straw	N/a	N/a	N/a	N/a	N/a	16.9 GJ_{LHV}/Mg_{dm}
Hemp straw	N/a	N/a	N/a	N/a	N/a	15.6 GJ_{LHV}/Mg_{dm}
Miscanthus straw	N/a	N/a	N/a	N/a	N/a	16.9 GJ_{LHV}/Mg_{dm}

Source: Hydro Agri Dülmen (1993); LWK (2002); Kuhn (1995); Kaltschmitt and Reinhardt (1997); Kaltschmitt and Hartmann (2001).

[a]Amount of nitrogen that is available for plant growth and can replace fertilizer if agricultural residues are left on the field; this is about 60% of the total content.

Table 6 Nonrenewable energy use and GHG emissions due to the removal of 1 Mg of agricultural residue

	Nonrenewable energy use (MJ/Mg residue)				GHG emissions (kg CO_2 eq./Mg residue)			
	Fertilizer[a]	Harvest[b]	Transport[c]	Total	Fertilizer[a]	Harvest[b]	Transport[c]	Total
Potato foliage	168.0	58.5	65.4	292	25.8	4.3	4.9	35
Corn stover	345.3	61.1	112.2	519	39.7	4.5	8.3	53
Sugar beet leaves	122.8	58.5	65.4	247	16.6	4.3	4.9	26
Flax straw	N/a	N/a	16.1	16	N/a	N/a	1.2	1
Hemp straw	N/a	N/a	16.1	16	N/a	N/a	1.2	1
Miscanthus straw	N/a	N/a	16.1	16	N/a	N/a	1.2	1

Source: Kaltschmitt and Reinhardt (1997); own assumptions.

[a]Penalty to account for the removal of nutrients together with the residue.

[b]Collection of the residue on the field.

[c]Transportation from the field to a decentralized energy conversion facility.

usually removed from the field. Therefore, no extra energy use or emissions were included for their removal.

To calculate impacts related to the collection of residues, machine hours and fuel use for a large field of approximately 40 ha were taken from the research of Kaltschmitt and Reinhardt (1997). We have assumed that the collection of corn straw is comparable to the collection of wheat straw. Machine hours for clearing and collecting sugar beet leaves were derived from research by PAV (2000). No data were available for the harvesting of potato foliage because it is a very uncommon operation. As potato foliage is relatively wet and has to be cleared and collected from the field like sugar beet leaves, the same process has been assumed.[6]

Energy use and GHG emissions related to transportation have been derived from the fuel use of trucks per megagram[7] and kilometer[8] with an empty return. Data were taken from research by Kaltschmitt and Reinhardt (1997). Sugar beet leaves and potato foliage were assumed to be utilized in a small-scale digestion facility converting the biogas (mainly CH_4) to heat and power in a small-scale gas engine. Hence, truck capacity and transportation distances are assumed to be small, that is, 7.5 Mg and 15 km. Corn straw is assumed to be utilized for CHP generation in a medium-scale combustion facility (ca. 20 MW thermal input on an LHV basis). Given the necessity of transport from several farms, the results for corn stover in table 6 are based on a medium truck capacity of 23 tons and an average transportation distance of 50 km. Finally, residues of flax, hemp, and *Miscanthus* occur in large quantities at fiber-processing plants. Thus, the truck capacity for transport of these residues is the largest possible, that is, 40 tons. We assumed that the CHP plant for utilization is located relatively nearby (15 km).

Table 7 shows the average efficiencies of the energy conversion plants that were assumed for the utilization of agricultural residues. Table 8 presents average European Union data (for 1998) for conventional power production. For the production of heat, the replacement of small central heating systems (50% oil and 50% gas) was assumed. For comparison, the respective values for the United States are 2.62 GJ/GJ_e and 205 kg CO_2 equivalent/GJ_e. At the other extreme, in Switzerland only about 1.31 GJ/GJ_e and 11 kg CO_2 equivalent/GJ_e are substituted due the country's high share of hydroelectric and nuclear power (UBA 2002). Characteristics of bioenergy production are presented in table 9. Note that some of these processes use only part of the crops and thus do not include residue utilization, whereas other processes use the whole crop.

Results

Figure 2 shows the annual energy savings and GHG emission reductions per hectare for biobased materials (polymers and composites) relative to their petrochemical and mineral counterparts. The results both with and without the utilization of agricultural residues are presented. The figure also shows the net benefits of using bioenergy instead of conventional (mainly fossil) energy commodities.

Energy Savings and GHG Emission Reduction per Hectare

Nonrenewable energy savings of the different biobased polymers on a per-hectare basis have a broad range from about 1,100 to −2 GJ/(ha yr), with the highest value achieved by *Miscanthus* transportation pallets. On the other hand, PHA and TPS loose fills offer comparatively low nonrenewable energy savings of less than 30 GJ/(ha yr).

The outstanding performance of the *Miscanthus* composite can be explained by the very high yield of *Miscanthus* and the large part of the harvested biomass (ca. 70%) that is usable for composite production. By contrast, in the case of hemp and flax, only about 25% of the harvested biomass (i.e., the fibers) is utilized in composite production.

For PLA, two studies (a and b) are considered. Energy savings per hectare that result from these studies differ considerably. In the case of the first study (Vink et al. 2003), based on the current production technology of Cargill Dow, the energy savings per hectare have been calculated as explained in the methodology. In the case of the second study (Gärtner et al. 2002), only aggregated energy savings per hectare were published, with very little additional information. Therefore, it is not possible to explain whether the differences relative to Vink and colleagues (2003) are as a result of methodological or empirical discrepancies, for example, lower crop yields.

As the differences between the white and black bars in figure 2 show, the utilization of agricultural residues increases the nonrenewable energy savings per hectare considerably. Additional benefits are in the range of up to 190 GJ/(ha yr). For the production of PLA and PHA, these benefits are even larger than the benefits of polymer production.

In table 10, the biobased polymers are ranked on the basis of energy savings per hectare and on the basis of energy savings per kilogram of biobased polymer, both with and without residue use for energy production. The table shows that the rankings computed on these bases differ significantly. This is due to two factors: (1) the polymer

Table 7 Energy conversion efficiencies for the utilization of agricultural residues

Conversion technology	*Residues*	*Net efficiency, power (%)*	*Net efficiency, heat (%)*
Digestion	Potato, sugar beet	25 (biogas LHV)	55 (biogas LHV)[a]
Combustion	Corn, hemp, flax, *Miscanthus*	18 (biomass LHV)	64 (biomass LHV)

Source: Rösch and Wintzer (1997); Kaltschmitt and Reinhardt (1997).

[a] Own estimate: total efficiency of gas engine = 80%.

Table 8 Conventional heat and power production (assumed to be substituted by energy from agricultural residues)

Nonrenewable energy use, power (GJ/GJ_e)	*Nonrenewable energy use, heat* (GJ/GJ_{th})	*GHG emission factor, power* (*kg* CO_2 *eq.*/GJ_e)	*GHG emission factor, heat* (*kg* CO_2 *eq.*/GJ_{th})
2.48	1.36	126	87

Source: UBA (2002).

Table 9 Characteristics of processes of bioenergy production compared to biobased polymer production

Bioenergy	*Crop*	*Crop yield* (*Mg*/[*ha**yr*])	*Technology*	*Conversion efficiency*
Ethanol[a]	Corn (grain)	7.3 (dm)	Fermentation	86% of max. ethanol[h]
Ethanol[b]	Sugar beet (beet)	56.2 (fm)	Fermentation	86% of max. ethanol
Ethanol[c]	SRWC (whole plant)[e]	10.0 (dm)	Pretreatment + ferment.	46% ethanol, 4% power
CHP[b]	Grass (whole plant)[f]	16.7 (dm)	Combustion + steam cycle	18% heat, 64% power
Power[d]	SRWC (whole plant)[g]	10.0 (dm)	BIG/CC	43% power

[a] From Shapouri et al. (2002). This is a cradle-to-gate energy balance for U.S. ethanol production plants. Values per hectare are estimated with the average yields used in this study.

[b] From Kaltschmitt and Reinhardt (1997). Data are taken from this complete bioenergy LCA.

[c] From Faaij et al. (2000). Net energy yields of crops and energy conversion rates are converted by our own calculation with the energy factors from table 8 and a substitution factor of 74.1 kg CO_2/GJ ethanol derived from gasoline.

[d] From Faaij et al. (1998); for calculation, see footnote c.

[e] SRWC = short-rotation woody crop, which includes fast-growing trees, for example, poplar and willow, with a rotation time of usually 3 to 4 yr.

[f] Fast-growing perennial grasses, for example, *Miscanthus* and switchgrass.

[g] BIG/CC = biomass-integrated gasification with combined cycle.

[h] Maximum ethanol yield is the complete conversion to ethanol; value corresponds to an assumed starch content of 64%.

yield (kilogram polymer per kilogram of biomass input) differs for the different kinds of biobased polymers (table 1), and (2) the polymers are produced from crops with very different yields (table 4). *Miscanthus* transportation pallets, which already have quite high savings per kilogram, score even better than hemp/EPS composites and TPS with regard to energy savings per hectare both with and without energy use of residues. Also, all TPS materials improve their relative position when ranked by savings per hectare. PHA from sugar beet (Heyde 1998) scores less well on a per-hectare basis compared to a per-kilogram basis.

The difference in results between the area-based versus the mass-based approach is particularly large if agricultural residues are used for the production of heat/electricity (table 10). This drastically improves the reported environmental performance if expressed relative to one mass unit of biobased polymer. This can be observed, for example, in the PHA production from corn case (see line 7 of table 10). The amount of corn needed to produce 1 kg of PHA is relatively high. Consequently, the amount of agricultural residue and the amount of energy that can be produced from it are quite high as well. At the other extreme, for *Miscanthus*-reinforced polypropylene (PP), only small amounts of *Miscanthus* are needed, and hence only small amounts of residues are generated. That is, relative to other biopolymers, less fuel is created per kilogram of biobased polymer. Therefore, *Miscanthus*-reinforced PP scores relatively poorly relative to other biopolymers when compared on a per-kilogram basis with the utilization of residues for energy included. Thus, a mass-based metric may lead to

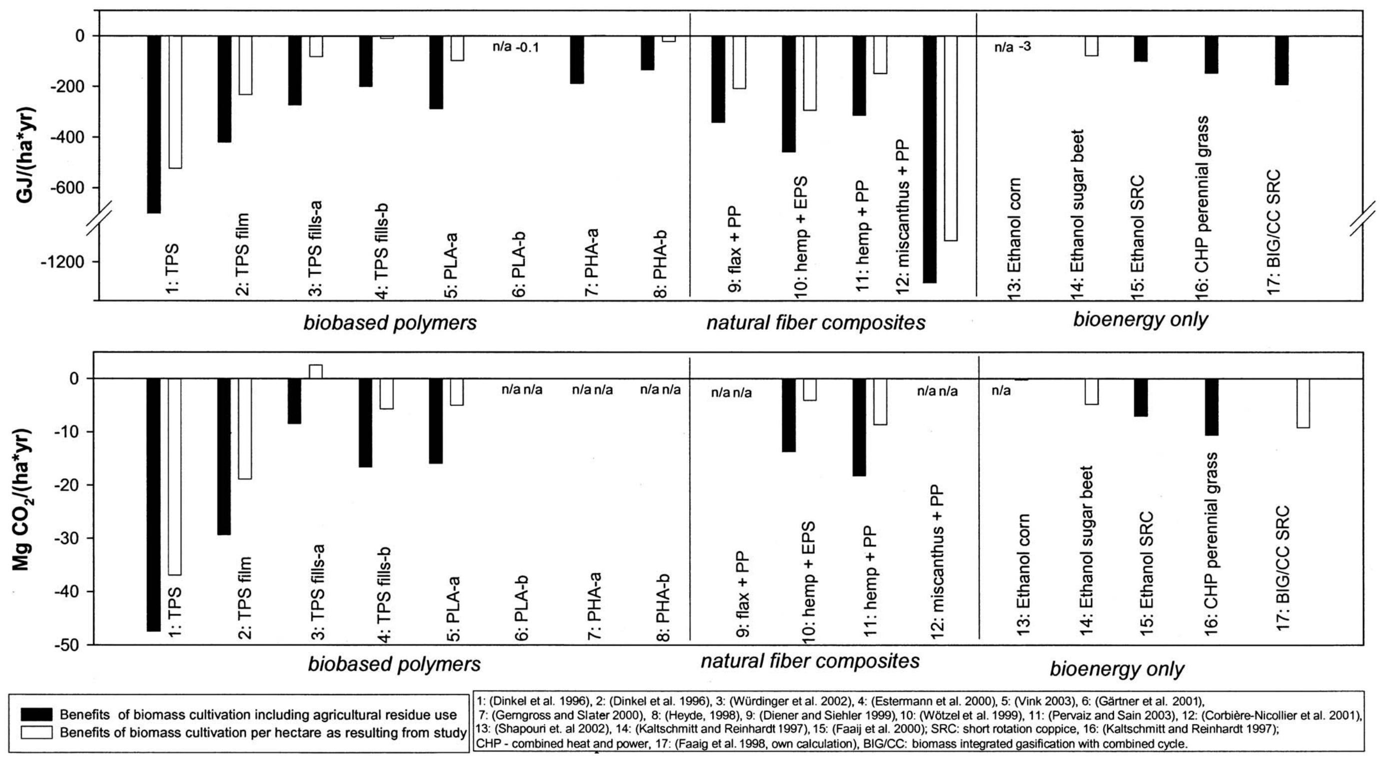

Figure 2 Nonrenewable energy use and GHG emissions of biobased polymers relative to their fossil counterparts, cradle to grave including incineration without energy recovery. The results are presented per hectare of biomass cultivation with medium crop yields as achieved in central Europe. Negative values represent energy savings or GHG emission reductions compared to use of fossil-fuel-based alternatives.

Table 10 Comparison of ranking of energy savings of biobased polymers on basis of area of biomass production and kilogram of biobased polymer

	Ranking with residue use		*Ranking without residue use*	
Biobased polymer[a]	*Based on GJ/ha yr*	*Based on GJ/kg*	*Based on GJ/ha yr*	*Based on GJ/kg*
1: TPS pellets	2	5	2	2
2: TPS film	4	9	4	6
3: TPS fills, study a	8	10	8	9
4: TPS fills, study b	9	11	10	10
5: PLA, study a	7	7	7	7
7: PHA, study a	10	1	11	11
8: PHA, study b	11	4	9	8
9: Flax + PP	5	6	5	5
10: Hemp + EPS	3	2	3	1
11: Hemp + PP, study a	6	3	6	4
12: *Miscanthus* + PP	1	8	1	3

Note: A value of 1 indicates the highest energy savings. See table 1 for energy savings per kilogram of biobased polymers without residue use.

[a] Row numbers correspond to figure 2 (including references).

misinterpretation in the case of systems with large energy use of residues.

The levels of GHG emission reduction from the biobased polymers relative to their petrochemical counterparts also change significantly when computed on a per-hectare basis. Values range from about −37 to 3 Mg CO_2 equivalent/(ha yr) without including the utilization of residues for energy. Fewer results are available for GHG emission than for renewable energy use. The highest GHG emission reductions per hectare are achieved by TPS pellets and TPS films. The utilization of residues reduces carbon emissions further to around 47 Mg CO_2 equivalent/(ha yr). The small number of materials for which GHG emission data are available makes a comparison of rankings between the surface-based and the mass-based approach less significant. As a consequence, the results are not discussed here.

Comparison of Biobased Polymers and Bioenergy Only

The benefits, that is, energy savings and GHG emission reductions, per hectare from exclusive bioenergy production based on dedicated energy crops and the subsequent substitution for fossil fuels are shown on the right-hand side of figure 2. Nonrenewable energy savings per hectare of biomass cultivation can be up to a factor of 6 higher for the production of biobased polymers (*Miscanthus* composites) than for the production of bioenergy. This is because most biobased polymers replace petrochemical polymers that are more energy intensive than fossil energy generation. Not all biobased polymers achieve higher benefits per hectare than bioenergy, however. Including residue utilization, both records for PHA and PLA as calculated by Gärtner and colleagues (2002) still have lower energy savings per hectare than bioenergy. Contrary to this, according to Vink and colleagues (2003), PLA without residue utilization is comparable to bioenergy production. Similarly, whereas TPS loose fills score better than bioenergy if the residues are utilized, they score worse without residue use.

Comparing bioenergy and biobased polymers on the basis of GHG emission reduction per hectare produces different results than the comparison based on energy savings. This is probably because of the use of different carbon emission factors for energy consumption, that is, different emission factors for primary energy, electricity, and heat (units of kilogram CO_2 equivalent per gigajoule) in the various studies of biobased polymers. Including residue utilization, all biobased polymers, except for TPS loose fills (Würdinger et al. 2002), result in GHG emissions reductions comparable to bioenergy applications. Without agricultural residue utilization, PLA, hemp-EPS, and all TPS loose fills have lower GHG emission reductions than bioenergy production. No GHG emission data are available for PHA.[9]

For ethanol, figure 2 shows a wide range of values both for (nonrenewable) energy and (fossil) GHG emissions (see numbers 13 to 15). The benefits of corn-based ethanol in the United States (based on Shapouri et al. [2002]) are very low compared to all the other bioenergy production routes. This finding corresponds to a net energy value of 21,000 Btu/gal. Furthermore, Shapouri and colleagues (2002) compared nine other studies of ethanol production in which net energy values ranged from −34,000 to 30,000 Btu/gal.[10] Based on reported data, ethanol from sugar beet (data refer to western Europe) is clearly better than corn-based ethanol. In the longer term, even larger benefits might become available by making use not only of the starch yield from corn (figure 2, number 13) but also of the lignocellulosic crop parts, that is, the corn stover. In the United States, current major research and development (R&D) projects are focusing on this option (for example, Dale [2002]). Energy efficiencies of ethanol production from stover are about 49% with an additional coproduction of 5% electricity (Atherton et al. 2002). If methods of using lignocellulosic plant components are successfully developed, fast-growing SRWCs could also be used as a feedstock for ethanol production. Yields of SRWCs and corn stover are comparable, amounting to about 10 Mg/(ha yr). For the advanced production of ethanol from SRWCs, Faaij and colleagues (2000) estimated energy yields of about 53% ethanol and 8% electricity. This would allow savings on the order of about 130 GJ/(ha yr) and 9 kg CO_2 equivalent/(ha yr). Comparing these values to the energy savings and GHG emission reductions of biobased polymers as presented in figure 2, it can be concluded that the production of most polymers from biomass is more advantageous than advanced bioethanol production with pretreatment, that is, conversion of lignocelluloses to fermentable sugars from SRWCs or corn stover.

In general, energy savings of bioenergy production are limited by crop yields. For a high-yield crop such as *Miscanthus*, average yields in central Europe are about 270 GJ/(ha yr). In an ideal situation, biomass can substitute for fossil fuel on a 1:1 basis,[11] which leads to energy savings of about 270 GJ/(ha yr). The energy savings related to biobased polymers can exceed this value as the results for TPS, hemp-EPS, and *Miscanthus*-PP composites in figure 2 show. This is due to the fact that the energy requirements (i.e., feedstock and process energy) for petrochemical polymers can be much higher than for the corresponding biobased polymers.

Sensitivity Analysis

Measures of biopolymer performance such as energy savings and GHG emission reduction per hectare of biomass cultivation are highly sensitive to crop yield. Crop yields vary depending on local conditions and agricultural practices. Whereas medium crop yields were used for the calculations discussed above, sensitivity analyses using high and low crop yields are now presented.[12] Accounting for the possible range of yields due to different agricultural conditions in western Europe changes the overall result by a factor of 2, as shown in table 11. This range of results exceeds by far the maximal benefits from agricultural residue utilization. Even with low crop yields, however, *Miscanthus* pallets and TPS pellets are still much better in terms of energy savings than bioenergy production, whereas the performance of other TPS products, PLA, and hemp/flax composites is comparable to that of bioenergy production when low crop yields are assumed.

Another uncertain factor is the amount of agricultural residues that can be removed from the field. The mechanisms determining the final effect of residue removal on soil fertility are very complex and are currently the subject of debate (Sheehan et al. 2002). For the results in figure 2, we assumed that 100% of the agricultural residues can be removed without any long-term adverse effects on soil fertility, provided that the lost nutrients are replaced by artificial fertilizer. Kurdikar and colleagues (2001), however, argued that only 60% of corn stover can be removed or soil quality decreases. Reduction in the fraction of residue recovered results in a proportionate reduction in the added benefits of residue recovery relative to the nonrecovery cases as shown in figure 2.

Table 11 Sensitivity analysis of benefits of biopolymers per hectare including utilization of agricultural residues with different crop yields per hectare

	Nonrenewable energy use (GJ/ha yr)			*GHG emissions ($Mg\ CO_2$ eq./[ha*yr])*		
	Base case[a]	*With low*[b] *crop yield*	*With high*[b] *crop yield*	*Base case*[a]	*With low*[b] *crop yield*	*With high*[b] *crop yield*
1: TPS pellets	−711	−452	−966	−51	−32	−69
2: TPS film	−420	−267	−571	−33	−21	−45
3: TPS fills, study a	−273	−188	−357	−12	−9	−16
4: TPS fills, study b	−200	−138	−262	−21	−14	−27
5: PLA, study a	−288	−199	−378	−20	−14	−26
7: PHA, study a	−188	−130	−247	n/a	n/a	n/a
8: PHA, study b	−134	−89	−179	n/a	n/a	n/a
9: Flax + PP	−342	−228	−455	n/a	n/a	n/a
10: Hemp + EPS	−458	−286	−573	−17	−11	−21
11: Hemp + PP, study a	−313	−196	−392	−22	−13	−27
13: *Miscanthus* + PP	−1253	−470	−2350	n/a	n/a	n/a

Note: References for the information in this table can found in figure 2.

[a] Including the use of agricultural residues; results as presented in figure 2.

[b] Low and high crop yields are the extremes of yield classes given in table 4.

Apart from data uncertainties, methodological choices made when preparing an LCA study also need to be considered. In the case of multiproduct processes, the allocation of impacts to a certain product and its by-products can have significant effects on the environmental performance calculated. As mentioned earlier, the allocation can be based on mass flows, energy contents, monetary values, or other indicators. Although not all of the LCA studies specify exactly the procedure applied, it is still obvious that different allocation methods have been used (table 4).

Lack of information on the exact allocation procedure did not allow us to recalculate the results using a common approach (this proved not to be a limiting factor for the conclusions, as is discussed below). Therefore, the original results as calculated in the respective studies were used. Moreover, for the sake of simplicity and comparability, we allocated all land use to the biobased polymers. It is interesting, however, to consider the consequence of applying a more detailed allocation procedure that allocates parts of the land used for biomass cultivation to the various by-products. In this case, the benefits per hectare would be even greater than those reported in figure 2. Hence, our simpler approach can be regarded as conservative, tending to underestimate the true benefits.

This is shown in table 12, which presents the results if the total area of land is allocated to the different by-products according to the allocation methods that were used in the respective study. These methods are either (1) no allocation (i.e., all impacts are assigned to the biobased polymer being the main product), (2) allocation on the basis of energy contents, or (3) allocation based on economic values of products and by-products (table 3). Table 12 contains only those biobased polymers for which the allocation method used in the original study is known. The allocation key used for TPS pellets and films by Dinkel and colleagues (1996) assigns the least impacts of starch production to the biobased polymer. If the same allocation procedure is applied to the area of land used, the energy savings and GHG emission reduction per hectare increase by about 70% for TPS pellets and TPS films (rows 1 and 2 of table 12). For TPS loose fill, the sensitivity to the allocation of a hectare of biomass cultivation to by-products is lower (0% to 25%).

Moreover, the kind of allocation method used to assign life-cycle flows to by-products also plays a role. Table 13 shows the energy savings and GHG emission reduction for TPS pellets with

Table 12 Sensitivity analysis of benefits of biopolymers per hectare with and without allocation of area of biomass cultivation to by-products within the production process

	Energy savings (GJ/ha yr)		GHG emission reduction (Mg CO_2 eq./[ha yr])	
	Base case (without agricultural residues use, no allocation of hectare)	*Results including allocation of hectare to by-products*	*Base case (without agricultural residues use, no allocation of hectare)*	*Results including allocation of hectare to by-products*
1: TPS pellets	−523	−888	−37	−63
2: TPS film	−232	−392	−19	−32
3: TPS fills, study a	−81	−100	3	3
4: TPS fills, study b	−10	−10	−6	−6

Note: Allocation process are as used in the respective studies (table 3). References for the information in this table can found in figure 2. TPS = thermosplastic starch.

Table 13 Energy savings and GHG emission reduction of TPS (Dinkel et al. 1996) relative to its petrochemical counterpart with different allocation methods (applied to energy use, GHG emission, and area of biomass cultivation)

	Energy savings (GJ/ha yr)				GHG emission reduction (Mg CO_2 eq./[ha yr])			
Allocation method	*No allocation*	*Energy content*	*Economic value*	*Mass*	*No allocation*	*Energy content*	*Economic value*	*Mass*
1: TPS pellets	−460	−888	−580	−944	−34	−63	−42	−67

different allocation methods. The results can differ by about a factor of 2. The by-products associated with other biobased materials were not sufficiently well known to perform a similar sensitivity analysis for those materials.

Discussion

Methodological Differences between the LCA Studies

This article discusses the results of various LCA studies of biobased polymers with one surface unit of land (1 ha) as the basis of comparison. The LCA studies used for the analysis presented here vary considerably both in scope and detail. Although the LCAs of Würdinger and colleagues (2002) and Dinkel and colleagues (1996) are very detailed, other studies are less explicit about methodology and data used. Moreover, the studies differ with regard to the methodologies used and also contain several data uncertainties.

In this article, we standardized several assumptions. First, to ensure a uniform basis for comparison, we used one single data source for LCA data on petrochemical polymers (APME 1999), although the data used in the studies differ considerably.[13]

Second, we assumed common crop yields that represent medium values for western and central Europe. Yields can vary considerably, even within the same geographic region, and sensitivity analyses show that the influence of variation in yield on the savings per hectare is very significant. In the case of the United States, the average crop yields can differ considerably from those in central Europe, but average corn yields in the United States, that is, 7.6 Mg/(ha yr) (Shapouri et al. 2002), are more or less comparable to the medium yields in central Europe that we assumed, that is, 7.3 Mg/(ha yr). Many European studies assume a crop yield slightly above or below the medium yields we assumed here, however. The advantage of assuming uniform crop yields as done in this article is that the different biobased polymers can be compared among one another with regard to efficient land use.[14]

Third, we chose to compare only one method of waste management within the cradle-to-grave system boundaries, that is, waste incineration without energy recovery. Some of the LCA studies also include a variety of waste management technologies. Although it can be very useful to evaluate biobased polymers in a specific waste management regime appropriate for a specific polymer or a specific region, it is more appropriate to assume uniform waste treatment for this initial comparison. A further investigation of the influence of waste management technologies and especially of those predetermined for biodegradable polymers, that is, composting and digestion, is desirable, however.

On the other hand, it was not possible to make a correction for all methodological differences found in the LCA studies. Because the fuel mix for power generation is country specific, the studies assume different carbon emission factors for electricity, which has not been corrected. Another important aspect in this context is that different allocation methods have been applied in the LCA studies. This can have a substantial impact on the results (table 13). Moreover, it was not possible to allocate land demand to the by-products, and therefore the benefits per hectare of land tend to be underestimated (table 12). The lack of data made it impossible to apply one uniform allocation method. The results presented in this study provide a first conservative estimate of the performance of biobased polymers on a per-hectare basis. Further research in this context is necessary.

Patel and colleagues (2003) carried out an analysis of 20 studies on biobased polymers containing most of the studies considered in this article. In spite of different approaches, end products, allocation methods, and system boundaries of the LCA studies reviewed, the results of this meta-analysis show a uniform picture for different biobased polymers. We are therefore confident that the energy savings and GHG emission reduction per hectare calculated from the original study results per kilogram of biobased polymers provide a reliable overall picture.

Removal of Agricultural Residues

A few more aspects have to be considered when interpreting the results. First, the data used to calculate the penalties for residue removal are uncertain. This is because several assumptions had to be made, that is, machine use for harvest, amount of nitrogen in the residues that is available to plants, and the transportation distances to the energy conversion facility. Total penalties do not play an important role on the overall energy balance, however, as they are less than 3% of the energy savings per hectare due to agricultural residue utilization.

Much more important, and controversial, are the amounts of residues that can be removed without significant losses in soil fertility. As the base case, we assumed 100% removal. This reflects agricultural practice for certain crops; for example, fiber crops are typically harvested as whole plants (excluding roots) and sugar beet leaves are sometimes used as fodder. Kurdikar and colleagues (2002) assumed in their study on biobased polymers from genetically modified corn in the United States, however, that only 60% of the residues can be harvested. On the other hand, Sheehan and colleagues (2002) argued that soil carbon would only slightly decrease (less than 3 metric tons of carbon equivalent per hectare [MTCe/ha] in 100 years) if corn stover were completely removed. Without stover removal, soil carbon would increase (about 30 MTCe/ha in 100 years) and the soil would be rebuilt. According to Linden and colleagues (2000), it depends on local climate and soil conditions whether corn stover removal decreases or increases corn yields; however, if residues are well incorporated into the soil, and fertilizer application is adjusted, leaving residues on the field would generally have positive effects on soil fertility. We consider the removal of all residues to be a good base-case assumption to indicate maximal benefits from agricultural residue utilization. Nevertheless, it should be noted that this removal is not possible in all cases, not only for soil fertility reasons but probably also because of the extra costs incurred for collection and logistics. As shown in the sensitivity analysis, this can considerably decrease the savings per hectare of agricultural land use. Therefore, a more detailed study of the local agricultural circumstances and the implications of residue removal today and in the long term is necessary in order to determine the possible benefits of residue utilization in specific settings.

Technological Development

A successful development of pretreatment technology, where pretreatment refers to conversion of lignocelluloses to fermentable sugars, would not only offer new opportunities for bioethanol production but also for biobased polymers. For example, Cargill Dow intends to use pretreated lingocellulose for PLA production in the future.[15] This is expected to clearly improve the environmental performance (Vink et al. 2003); however, the overall environmental performance of pretreatment may depend on whether and how genetically modified organisms are used.

Moreover, it should be emphasized that the material properties, and hence the possible applications of the biobased polymers covered in this article, are not comparable. Because of their sensitivity to moisture and other disadvantageous material properties, starch polymers have a more limited range of applications than PHA and PLA. This generally limits starch polymers to niche applications. Regarding natural fiber composites, the studies considered cover products that are in different stages of development. Although the use of hemp and flax composites has been successfully adopted by the automotive sector, the technical feasibility of *Miscanthus* transportation pallets has not yet been proven.

Secondary Savings

Finally, it needs to be pointed out that the use phase has been excluded from this analysis. Depending on the application area, however, so-called "secondary savings," that is, savings during the use phase, can be very important. These are especially important for natural fiber composites used for transportation applications, as they are typically lighter than their glass-fiber-reinforced counterparts. For example, secondary savings associated with the *Miscanthus* pallets can be about 90% of the energy required of their production if a transport distance of 5,000 km is assumed (Corbière-Nicollier et al. 2001). Thus, the inclusion of secondary savings could increase the energy savings and GHG emission reduction per hectare of natural fiber composites considerably.

Conclusions

In this article, nonrenewable energy savings and GHG emissions reductions per kilogram of biobased polymers (relative to the petrochemical polymers that they replace) are compared to the same savings computed on the basis of the area of land used for biomass production. These benefits are based on state-of-the-art production data. Comparing biopolymers on the basis of energy savings and GHG emission reduction per hectare of biomass cultivation changes their ranking relative to a ranking referring to 1 kg of biobased polymer. *Miscanthus* composites and TPS pellets rank higher, whereas PHA, PLA, hemp composites, and flax composites are comparatively less good. For the polymers studied, most changes in the ranking are moderate, although some changes are quite large.

The utilization of agricultural residues can increase the benefits per hectare of biomass cultivation significantly [by about 190 GJ/(ha yr) and 15 Mg CO_2 equivalent/(ha yr)] but does not change the ranking of biomass polymers. Depending on local circumstances (soil, climate, etc.) that influence soil carbon contents and economic considerations, however, it might not be possible to remove 100% of residues, and the benefits of residue utilization would thus be lowered by the percentage of residues that remain in the field. Further research is required regarding the amount of residue that can be removed under a sustainable regime.

Referring energy savings and GHG emission reduction of biobased polymers to a unit of agricultural land used, instead of to a unit of polymer produced, can lead to a different ranking of options (table 10). Therefore, referring these benefits to a unit of land area provides additional insights into the performance of biobased polymers. Moreover, it can help to optimize the use of agricultural land if it is scarce and expensive. A consistent allocation method is needed to more accurately compare biobased polymers and should be used in future research.

If compared on a hectare basis and without residue utilization, most biobased polymers score better in terms of energy savings and GHG emission reduction than bioenergy production from energy crops. This is clearly the case for natural fiber composites and TPS pellets and films. Energy savings and CO_2 emission reduction for PLA on a per-hectare basis are in the range of the benefits for bioenergy production and are worse than bioenergy applications only in the case of PHA. If compared on a per-hectare basis *with* residue utilization, even the benefits of PHA production are in the range of the benefits of bioenergy production. Biobased polymers such as PLA are in an early stage of commercial development, however, and PHA is just about to reach the stage for bulk polymer applications. On the other hand, many bioenergy technologies have already reached commercial status.

Therefore, in the medium to long term, technological progress will therefore most likely lead to higher efficiency gains for biobased polymers than for bioenergy production, and as a consequence, this would also result in higher energy savings and GHG emission reductions. This has mainly to do with technological progress, the long process chain for biobased polymers (compared to bioenergy), and developments in waste management. We therefore conclude that the production and use of biobased polymers offer very interesting opportunities to reduce the utilization of nonrenewable energy and to contribute to GHG mitigation.

Furthermore, the amount of land that can be used for the production of nonfood crops is limited and might not be sufficient to supply the total energy demand (Goldemberg 2000). Energy in the form of fuels, electricity, and heat can also be supplied by renewable sources other than biomass, although chemical feedstock cannot. For this reason, the production of biobased polymers seems a good strategy to reduce the overall use of nonrenewable energy, provided that it can compete on economic terms.

Nomenclature

BIG/CC	biomass-integrated gasification, combined-cycle plant
CHP	combined heat and power
dm	dry matter
EPS	expanded polystyrene
f.u.	functional unit
fm	fresh matter
GHG	greenhouse gas
HDPE	high-density polyethylene
LCA	life-cycle assessment
LDPE	low-density polyethylene
LHV	lower heating value
PHA	polyhydroxyalkaonates
PLA	polylactic acid
PP	polypropylene
SRWC	short-rotation woody crop
TPS	thermoplastic starch

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Notes

1. Van den Broek and colleagues (2001) compared environmental impacts of three different land-use strategies, that is, organic agriculture, set-aside land, and bioenergy production. In their approach, system extension is used to provide the same amount of food and electricity and to use the same amount of land in all systems. With respect to acidification, energy carrier depletion, and climate change, the strategies producing bioenergy score best.
2. One hectare $= 10{,}000\ m^2 \approx 2.47$ acres.
3. One kilogram ≈ 2.204 lb.
4. These yields are also possible in parts of the United States and Canada with a very broad range of climatic conditions and consequently

widely varying crop yields. The studies concerning biobased polymer production in the United States and Canada (Vink et al. 2003; Gerngross and Slater 2000; Pervaiz and Sain 2003) do not specify yields for agricultural production, however. For comparability reasons, the same yield data have been used to calculate environmental impacts per hectare of land demand in this article.

5. *Miscanthus* is a tall perennial grass that is widely being investigated as a bioenergy crop.
6. Potato foliage can be cleared mechanically, chemically, or thermally. Thermally, foliage is burned on the field and is consequently not available for utilization. Chemically treated foliage is quite dry, but contaminated with herbicides. Therefore, a mechanical clearance is assumed here.
7. One megagram = 1 metric ton ≈ 1.102 short tons.
8. One kilometer ≈ 0.621 mi.
9. Kurdikar and colleagues (2001) investigated the production of PHA from genetically modified corn. The agricultural residue, that is, stover, is used for PHA extraction, and the process waste is converted to energy. This results in an emission reduction of about 5.4 Mg CO_2 equivalent/(ha yr), which is comparable to the lower results for TPS loose fills but lower than bioenergy production.
10. Editor's note: See also the discussion of this issue by Kim and Dale (2003) in this issue of the *Journal of Industrial Ecology*.
11. Even slightly higher substitution rates are possible if biomass is used as solid fuel in a more efficient energy conversion process than the reference.
12. In this analysis, only the crop yields are varied to account for site difference, but no variations due to site-specific crop production methods are taken into account.
13. For a comparative overview of life-cycle energy and CO_2 data for chemical products across various sources, see research by Patel and colleagues (2003), and for a discussion of the influence of inventory data sets on LCA results, see the work by Peereboom and colleagues (1998).
14. This is justified because we suppose that all of the studies assume comparable agricultural production methods.
15. Editor's note: For a description of the Cargill Dow joint venture, see the corporate profile by Rábago (2003) in this issue of the *Journal of Industrial Ecology*.

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About the Authors

Veronika Dornburg is a Ph.D. student, **Iris Lewandowski** is a senior researcher, and **Martin Patel** is an assistant professor in the Department of Science, Technology, and Society of the Copernicus Institute for Sustainable Development and Innovation at Utrecht University in the Netherlands.