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ORIGINAL PAPER

Environmental assessment of biodegradable multilayer film derived from carbohydrate polymers

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Abstract Multilayer films exhibit excellent properties for food packaging. However, existing products are not biodegradable. Conventional plastics, manufactured from fossil fuels, not only consume non-renewable and finite resources, but also impact heavily on waste disposal. For this reason, a new multilayer film has been developed in the Multibio Project for the production of food packaging. In this paper, the environmental impacts of the new biodegradable multilayer film—based on modified starch and polylactic acid (PLA)—and those of the conventional multilayer film—based on PP and PA6—are quantified in the categories of climate change, fossil fuel depletion, acidification and eutrophication. Conventional multilayer film has a 90% higher impact than the Multibio multilayer film. The main difference between the LCA presented and the cited literature is the inventory data obtained in the phase of polymer processing to obtain multilayer film, and the assessment of the disposal phase of the multilayer film wastes.

Keywords Multilayer film · Biodegradable · Carbohydrate polymer · LCA · PLA · Starch

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Introduction

In recent years, multilayer films have become increasingly important for many applications, especially in the food industry, where they are mainly applied to the packaging of products such as fresh pasta, meats and cut vegetables to extend the shelf-life of goods. Commercial multilayer films currently comprise a number of layers (3–9) of different polymers. In most applications, the outer layers consist of cheap, water barrier polymers with good mechanical properties; the inner layers consist of more expensive materials, which offer good gas-barrier properties. However, existing products are not biodegradable. These conventional plastics, manufactured from fossil fuels, not only consume non-renewable and finite resources, but also impact heavily on waste disposal.

Project Multibio has tried to develop a new multilayer film for the production of food packaging. This new material includes laminates based on modified starch and polylactic acid (PLA), which exhibit good water- and gas-barrier properties, as well as being easily extruded and processed, and (bio)degraded at the end of the product's life.

This paper is focused on the life cycle inventory and environmental impact assessment (LCA) of this new material in accordance with standards EN-ISO 14040 through 14043. The environmental impact of the biodegradable multilayer film has been compared to that of the current multilayer film composed of PP–PA6–PP used to preserve fresh pasta. The functional unit considered is 1 m^2 of packaging film of similar thickness (each layer in microns): 25–200–50 for the Multibio multilayer film (68% in weight for compounding starch and 32% for PLA) and 130–20–130 for the conventional multilayer film (91% in weight for PP and 9% for PA6). In the comparison between the two multilayer films, it is assumed that quality in the preservation of pasta is not significantly lost.

When the packaging becomes waste, the different behaviours of current packaging depending on whether it is incinerated or taken to landfill have been analysed. The same two scenarios were analysed for the new biodegradable material, adding a third scenario of 'composting together with the rest of organic home waste'.

The main difference between the LCA in the Multibio Project and the cited literature is the in-depth study of the phase of polymer processing to obtain multilayer films, and the phase of disposal of the multilayer film wastes.

Life Cycle Inventory

The inventory analysis used for PP and PA6 was provided by PlasticsEurope [1], since this organisation is highly regarded in an international context. Unfortunately, more uncertainty exists regarding biodegradable materials.

The biodegradable multilayer film is composed of PLA in the two external layers and compounding of modified starch with polycaprolactone (PCL) in the inner layer. The life cycle inventory for PLA was taken from [2], with the addition of the use of fertilizers for corn cultivation that were taken from [3]. Other literature considered included [4] which provided results for energy consumption similar to results presented by [2] and the environmental impacts for maize culture in [5].

Modified starch was obtained from a blend of starches, 50% in weight of potato starch (21% amylose) and 50% in weight of Hylon VII (70% amylose) obtained from corn. Chemical modification of the starch was conducted in a laboratory test in the BioComposites Centre, following the process represented in Fig. 1 and explained in [6].

The environmental impacts of the different starches are obtained from the life cycle inventory in [7] and contrasted with the data supplied by [8]. To modify the starch, lauroyl chloride derived from vegetable oils was used. Its environmental impacts were obtained mainly from [9]. The greenhouse effect has a very high score as a consequence of N_2O emissions, about which there is great uncertainty because they depend on the type of soil, climate, etc. [9–12]. In the Multibio project, we have considered the corrections introduced by [12] to estimate the amount of N_2O emissions.

Derivatives of vegetable oils showed the greatest uncertainties in this study. It should also be taken into account that the oleo-chemical sector is not—generally speaking—at the same level of optimisation as the polymer sector, which means that the impacts will get lower as the former evolves. Likewise, LCA studies on the production of vegetable oils and their derivatives are significantly less widespread and optimised than those on the production of polymers.

The life cycle inventory for PCL, needed for compounding with the modified starch, was obtained mainly from [13].

The manufacturing of the biodegradable and conventional multilayer films has been tested at a pilot plant owned by AIMPLAS and the electricity consumption has been measured directly.

The manufacturing of the biodegradable film comprises the co-extrusion of the starch compound with previously dehumified PLA, after which the resulting co-extruded multilayer sheet is thermoformed to produce the packaging.

The process is similar for the conventional multilayer film, although energy requirements are higher due to the higher melting point of PP and PA6 as compared to PLA and modified starch. The energy model used was obtained from the Union for the Co-ordination of Production and Transmission of Electricity (UCPTE) for Europe [14]. The electricity consumptions for each one of the manufacturing processes studied are shown in Table 1.

Neither the impact due to transport from production plants of individual materials to processing industries nor the impact of transport to consumers has been considered. This is due to the fact that no specialisation is required to perform these tasks. However, when obtaining and processing a given material is very specialized, transport is considered, as in the case of obtaining PLA and PCL.

Impact Categories Selection

Impact assessment is a technical process aimed at characterising and evaluating the effects of the contaminants identified in the inventory phase. The steps considered in

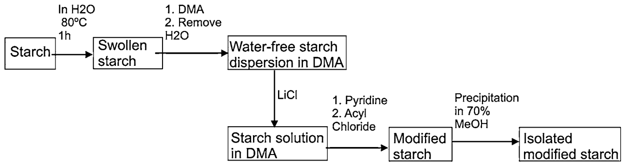

Fig. 1 Schematic diagram for esterification of starch

Table 1 Electricity consumption

Multilayer film	Weight (kg/m^2)	Dehumidification (kWh/kg)	Co-extrusion (kWh/kg)	Thermo-forming (kWh/kg)
Multibio	0.300	0.089	2.20	0.324
Conventional	0.257	0.160	2.387	0.407

this paper were classification and characterisation. In the classification step, the data from the inventory are sorted into impact categories according to their environmental effect. In the characterisation step, contaminants are weighted and aggregated within each impact category.

There is no scientific consensus regarding which impact categories should be considered when assessing the impacts of biopolymers, as can be observed in Table 2. Until the publication of the EN-ISO 14042 standard in 2000, the most broadly used methodology was the Eco-Indicator 95 [20] and its corresponding impact categories. The EN-ISO 14042 standard advises against the use of weighting for comparisons, which was contemplated in the Eco-Indicator 95 methodology. As established by EN-ISO 14042, comparisons for the public should 'only be conducted category indicator by category indicator'. Since 2003, several LCA studies of polymers have been published. In none of these studies has the weighting phase been used, and great methodological differences can be appreciated among them. They only coincide in considering greenhouse effect and non-renewable energy consumption as impact categories, and two other categories are also broadly—although not unanimously- selected, specifically eutrophication and acidification. All of the researchers except [18] use impact categories included in Guinée's list [21].

The main difference between the LCA in the Multibio Project and the other studies referenced in Table 2 is the focus on the phases of polymer processing to obtain multilayer film and disposal of the final product.

The LCA of renewable material extraction in the Multibio Project is based exclusively on bibliographical studies. The studies used exhibited great uncertainties, much like all agricultural LCAs to date. For this reason, the four most-often referenced categories in LCA of biopolymers were selected: climate change, fossil energy depletion, eutrophication, and acidification.

In the following paragraphs, the impact categories, indicators, and models are described and referenced in accordance with ISO 14042.

Abiotic Resources Depletion

Abiotic resource depletion encompasses both the use of non-renewable and renewable abiotic resources, although in this study we limit the analysis to the depletion of non-renewable energy alone. Our study uses the method proposed by [22]—based on the baseline characterisation method [21]—including modifications related to available reserves and the addition of subcategories, one of them being fossil fuels depletion. Fossil fuels include oil, natural gas and coal.

Table 2 Impact categories selected in the literature

Reference	[7]	[15]	[8]	[16]	[17]	[2]	[18]	[4]	[19]
GHG	x	x	x	x	x	x	x	x	x
Ozone depletion		x	x	x					
Smog	x	x			x (n/a)				x
Acidification	x	x	x	x	x (n/a)				x
Eutrophication	x	x	x	x	x (n/a)		x		x
Non-renewable energy		x	x	x	x	x		x	x
Resource depletion							x		
Land demand			New indicators						
Human toxicity	x								
Ecotoxicity	x								
Toxicity air		x							
Toxicity water		x							
Heavy metals		x							
Carcinogenity		x							
Salinization	x	x							
Ecoindicator 95	x	x							
EPS	x								
Deposited waste	x	x							
Litter marine biodiversity							x		
Litter aesthetic							x		
Contaminants			SO_x, NH_4, particle; NO_X diesel	SO_x, NO_x, NH_4, Particulate					

Climate Change

Climate change—or greenhouse gas emissions (GHG)—is defined as the impact of anthropogenic emissions on the absorption of heat radiation by the earth's atmosphere, causing a rise in the earth's surface temperature. This is popularly referred to as the 'greenhouse effect', which may in turn have adverse impacts on ecosystem health, human health and material welfare.

To compare the impacts of emissions of different greenhouse gases, each gas has been assigned a so-called Global Warming Potential (GWP) index, expressing the ratio between the increase in infrared absorption due to the instantaneous emission of 1 kg of a given substance and that due to an equal emission of carbon dioxide (CO_2), both integrated over time.

The Intergovernmental Panel on Climate Change (IPCC) has compiled a list of 'provisional best estimates' for GWPs with time horizons of 20, 100, and 500 years, based on the expert judgement of scientists worldwide. This list of GWPs is periodically updated. The last update was published in 2001 [23]. The GWPs for 100 years are recommended as the baseline characterisation method for climate change.

Atmospheric Acidification

Acidic gases, such as sulphur dioxide, nitrogen oxides (released during the burning of fossil fuels), and other acid releases (such as sulphuric acid emissions from the production of fertilisers), contribute to acid rain and acidify soil and fresh water ecosystems. The atmospheric acidification potential of a substance is defined as the number of H^+ ions produced per kilogram substance relative to H^+ ions produced by SO_2. The category indicator for atmospheric acidification is measured in kilograms of sulphur dioxide equivalents. For the Multibio Project, the average European characterisation factors were used [24].

Eutrophication

Periodic releases of nitrates and phosphates into fresh water catchments and marine waters increase nutrient build-up. Excessive accumulation of nitrates and phosphates create algal blooms and consequently deplete dissolved oxygen content. The method adopted in the Multibio Project is the one described in [25], in which all emissions of N and P to air, water, and soil, and of organic matter to water are aggregated into a single measure, because this method allows for both terrestrial and aquatic eutrophication to be assessed. The characterisation factors in PO_4^{3-} equivalents and NO_3^- equivalents are all interchangeable. Several substances have been added to the original 1992 list.

Disposal Assessment

The environmental impact of disposing of Multibio and conventional multilayer film waste was focused on the global warming impact category because CO_2 emissions (and CH_4 emissions, to a lower extent) are the most significant in this case.

The methodology developed by the European Commission [26]—updated with the characterisation factors of [23]—was used. It was applied to three scenarios: incineration without energy recovery, landfilling without gas control, and composting in simple window systems.

Carbon dioxide is released both during the combustion of fossil fuels for energy needed in waste treatment processes and directly from the waste during treatment. Carbon in the waste itself can be either released as CO_2 or CH_4 during the treatment process or remain in the waste or waste products (e.g. compost).

For biodegradable materials, carbon will have been absorbed from the atmosphere relatively recently during plant growth. If this carbon is released again as CO_2 during the treatment process, it will re-enter the natural carbon cycle. This 'short term' carbon cycle has no net global warming impact—as the emissions have recently been offset by the uptake of an equivalent amount of carbon dioxide—and no global warming potential is associated with the emission of CO_2, since the atmospheric concentration of short-cycle carbon dioxide is relatively constant from year to year. According to [26], these emissions are reported as 'short-term CO_2' or 'biogenic CO_2' and a global warming potential of zero is given to them. However, if the emission occurs in the form of CH_4, it has a higher global warming potential than CO_2.

Fossil fuel reserves constitute an almost-permanent sink for carbon. Combustion of fossil fuels releases the stored carbon into the atmosphere as fossil-derived CO_2. These emissions are reported as 'fossil CO_2' and have the usual CO_2 global warming potential of one.

However, if the carbon is sequestered in a form which is unavailable to the natural carbon cycle over a sufficiently long time period, then it could be argued that a 'sink' for carbon has been created [26]. The two main routes for carbon storage in waste management are landfilling and composting applied to soil.

The key to determining CO_2 emissions is the calculation of C concentrations in the waste and the amounts of fossil, short-cycle and sequestered CO_2. The concentration for each one of the plastic materials has been calculated considering their chemical formulations and that the material (1 kg) is dry in both cases.

The main non-carbon greenhouse gas of interest to waste management is N_2O. Nitrous oxide is formed in trace amounts from nitrogen gas in the air and from compounds of the element present in waste during combustion in incinerators, landfill gas flares, and combustion engines.

Incineration

Organic carbon compounds are oxidised to CO_2 and water vapour, which are discharged to the atmosphere in the stack gas. The incineration of conventional plastics makes a net positive contribution to global warming, but the incineration of biobased materials as short-cycle carbon compounds is neutral in global warming terms.

Emissions of nitrous oxide from incinerators have also been estimated at 0.05 kg/t [26]. The results of the greenhouse gas fluxes from incineration are shown in Table 3.

Landfilling

In a landfill site, decaying wastes use up the oxygen entrained within the waste, thus creating anaerobic conditions. The waste continues to degrade to produce landfill gas, which contains roughly 50% methane and 50% carbon dioxide. Carbon dioxide is assumed to be all short-cycle as only biogenic materials will degrade. In landfills with no gas control, the gas migrates to the surface and is released.

In addition to CH_4, small amounts of N_2O may also be released from landfills. These emissions are considered to be too small to make a significant contribution and have therefore been omitted.

The key parameters in disposal emissions are:

- Degradable organic carbon content (DOC): the fraction of the waste made up of biodegradable carbon.
- Dissimilable DOC (DDOC): the fraction of the DOC that dissimilates to CO_2 and/or CH_4. The remainder is assumed not to degrade to gaseous products under landfill conditions within the 100-year horizon.

Estimates of the degradable organic carbon content (DOC) have been derived from estimates of the total carbon content of the waste, along with estimates of the proportion of this total carbon which is biogenic and therefore degradable (see Table 4).

To explore the sensitivity of the results to the assumption of DDOC, two alternatives were considered: 30% and 50% of DOC is dissimilable. The biogenic carbon locked up in landfills can be considered to have been removed from the natural carbon cycle, thus reducing global carbon dioxide emissions.

Results of the greenhouse gas fluxes from landfill are shown in Table 4.

Composting

Composting is the aerobic degradation of waste to produce compost, which can be used as a soil improver. The end product of decomposition, compost, consists of materials resistant to decomposition, such as polymers formed from the remains of the biomass, along with humus. Humus is the term for highly condensed aromatic structures of high molecular mass which are highly resistant to further decomposition. Humus is the source of the humic acids that contribute to the dark colour of most soils. Soil humus plays an important role in soil fertility.

Table 3 Greenhouse gas fluxes (kg of CO_2 eq.) for incineration of 1 kg of material

Emissions in kg for 1 kg of material incinerated	% C	CO_2 short cycle GWP = 0	CO_2 fossil GWP = 1	N_2O GWP = 296	CO_2 fossil energy GWP = 1	Total GHG
PP–PA6–PP	84	0	3.072	0.00005	0.008	3.095
PLA–Compounding–PLA	59	2.165	0	0.00005	0.008	0.023

GWP ratio for 100 years

Table 4 Greenhouse gas fluxes (kg of CO_2 eq.) for landfilling of 1 kg of material

Emissions in kg for 1 kg of material landfilled	% C	% DOC	% DDOC	DDOC	CH_4 GWP = 23	CO_2 short cycle GWP = 0	CO_2 sequestred short cycle GWP = –1	CO_2 fossil Energy GWP = 1	Total GHG
PP–PA6–PP	84	0		0	0	0	0	0.008	0.008
PLA–Comp.–PLA	59	59	30	17.7	0.118	0.325	1.515	0.008	1.209
PLA–Comp.–PLA	59	59	50	29.5	0.197	0.541	1.082	0.008	3.452

GWP ratio for 100 years

Carbon dioxide emissions were based on an analysis of the carbon content of the waste, and estimates of the proportion of this carbon which will degrade. These involved estimating degradable organic carbon or DOC and then dissimilable organic carbon (DDOC).

Compost may provide a useful source of soil organic matter, contributing to improvements in soil physical structure and fertility. Some regions are particularly short of soil organic matter—for example, soils in the Mediterranean basin-. A recent study review concluded that organic waste re-use through compost applications seems to be the best way of improving the organic matter content of such soils [27].

The estimated organic carbon stored in soil as a result of compost application will only be considered to be sequestered if it remains locked up in the soil for at least 100 years. Estimating a precise lifetime for soil organic matter derived from compost addition is very difficult, because of the large number of inter-converting pools of carbon involved [26].

We have adopted a compost carbon turnover time in soil of 40 years. The turnover time selected is similar to the 42 years estimated from the Rothamsted carbon data. It corresponds to 8.2% of added carbon persisting in the soil 100 years after application, the remaining 91.8% being mineralised to CO_2 [26].

The use of compost may replace other materials, or alternatively new markets may open up to absorb compost in its own right, rather than as a replacement for other materials. If other materials are displaced by compost, we need to consider what impact this replacement would have on the overall greenhouse gas fluxes. Two classes of materials may be displaced by composts:

- plant growing media and soil conditioners (including peat)
- inorganic fertilizers, which may be at least partly displaced by nutrients in the compost

The carbon in peat derives from plants as old as the last glaciation—some 10,000 years ago—and for this reason it will be treated as fossil carbon. The use of peat results in the mineralization of this carbon, leading to the release of CO_2, and therefore to a net positive contribution to global warming. Each cubic metre of peat replaced by compost would save the emission of about 247 kg of CO_2.

Compost generally contains significant concentrations of the three plant macro-nutrients: nitrogen (N), phosphorus (P) and potassium (K). Although the concentrations in compost are low in comparison with inorganic fertilizers, they may still be of value to crops and reduce the need for inorganic fertilizer applications. N is the plant nutrient required in greatest quantities, for nearly all of the N present in compost is incorporated into organic compounds. This N only becomes available for uptake by plants after micro-organisms have converted the organic N into inorganic forms, namely ammonium (NH_4^+) and nitrate (NO_3^-) ions. The concentration of N, P and K is very low in the biodegradable materials of the Multibio Project. Thus, the displacement of fertilizers by compost has not been considered.

Results of the greenhouse gas fluxes from composting are shown in Table 5.

Disposal

Table 6 compares the CO_2 equivalent emissions of a functional unit of 1 m^2 of multilayer plastic material for the

Table 5 Greenhouse gas fluxes (kg of CO_2 eq.) for composting of 1 kg of material

Emissions in kg for 1 kg of material composted	% DOC	% DDOC	CO2 GWP = 0	% DOC mineral as compost mineralised	CO2 compost use GWP = 0	CO2 sequestered short cycle GWP = –1	CO2 fossil energy GWP = 1	CO2 fossil avoided peat GWP = –1	Total GHG
PP–PA6–PP	0	0	0	0	0	0	–	0.000	–
PLA–Comp.–PLA	59	30	0.649	38	1.394	0.124	0.021	0.145	–0.248
PLA–Comp.–PLA	59	50	1.082	27	0.996	0.089	0.021	0.145	–0.213

GWP ratio for 100 years

Table 6 Greenhouse gas fluxes (kg of CO_2 eq.) for 1 m^2 in different disposal scenarios

1 m^2	GHG (kg of CO_2 eq.)					
	Weight (kg)	% C	% DDOC	Incineration	Landfill	Composting
Conventional	0.2566	84	0	0.794	0.002	–
Multibio	0.3	59	30	0.007	0.363	–0.074
Multibio	0.3	59	50	0.007	1.036	–0.064

three waste scenarios analysed: incineration, landfilling, and composting.

The biodegradable multilayer film is the one that performs best at disposal. The environmental impact is the lowest when waste is composted. The environmental impact is higher when the multilayer film uses plastics derived from petroleum. This worsening is more significant if waste is incinerated.

Only in the case of disposal of waste to landfill does the biodegradable multilayer film show a worse environmental behaviour than the conventional material. Methane emissions increase the impacts in the global warming category, whereas conventional multilayer film is not degraded in landfill, so no emissions are produced.

Environmental Assessments of the Multilayer Film

The final comparison between Multibio and conventional multilayer films is expressed in the area unit m^2, although for the mid-way results the impact of 1 kg of each of the materials analysed has been considered.

The environmental assessment was done using the software SimaPro [28] regarding four impact categories: climate change, fossil fuels depletion, acidification and eutrophication, as described above.

Multilayer Film with Conventional Polymers

The environmental impacts of PP and PA6 were calculated using the data published by PlasticsEurope [29] (see Table 7).

Multilayer Film with Biopolymers

The biodegradable multilayer film is made mainly from starch (potato starch and hylon VII), PLA, and PCL. The sources for each material are referred in the Life Cycle Inventory section. Table 8 shows the impact scores for 1 kg of each of these materials.

Table 7 Environmental impacts for 1 kg PP and PA6 present in conventional multilayer film

Impact category	Unit	PP	PA6
Global warming (GWP100)	kg CO_2	1.88	8.6
Acidification	kg SO_2	0.00571	0.0371
Eutrophication	kg PO_4^{3-}	0.00051	0.00521
Fossil energy depletion	MJ	74.2	124

Comparative Assessment

The functional unit selected—1 m^2 of multilayer film—implies different weightings for the conventional material and for the biodegradable material. Table 9 shows the environmental impact of the production of 1 m^2 of both Multibio and conventional multilayer films.

The life cycle assessment of the PP–PA6–PP multilayer film (Table 9) includes the production of pellets for each of the polymers, the dehumidification processes for PA6, the co-extrusion of the three layers, the thermo-forming and the incineration at disposal. In the case of biodegradable multilayer films, besides considering the production of each material, we have also included: the dehumidification of PLA, the chemical modification of starch, the compounding of modified starch with PCL, the co-extrusion of the three layers, the thermo-forming and the composting of the packaging at disposal. The transport from production centres to consumers has not been considered for either of the two multilayer films.

The production of multilayer film from petrochemical polymers exhibits higher environmental impacts than the production of biodegradable multilayer film. The biodegradable multilayer film has lower global warming and fossil energy depletion impacts than the conventional multilayer film. Differences in the acidification category are relatively small. Eutrophication is the sole category for which the conventional multilayer film exhibits a lower impact. This impact is produced by the use of fertilizers for the production of renewable polymers, and could be reduced with the improvement of agricultural practices.

Table 9 Life cycle assessment of 1 m^2 of multilayer film from cradle to grave

Impact category	Unit	Multibio	Conventional
Global warming (GWP100)	kg CO_2 eq.	1.07	2.04
Acidification	kg SO_2 eq.	0.00706	0.00548
Eutrophication	kg PO_4^{3-} eq.	0.000671	0.00028
Fossil energy depletion	MJ	29.1	33.6

Table 8 Environmental impacts for 1 kg of each material present in biodegradable multilayer film

Impact category	Unit	Starch (potato)	Hylon from corn	PLA	PCL
Global warming (GWP100)	kg CO_2 eq.	1.02	0.988	1.77	0.872
Acidification	kg SO_2 eq.	0.00693	0.0139	0.00167	0.00803
Eutrophication	kg PO_4^{3-} eq.	0.00458	0.00439	0.00225	0.00059
Fossil energy depletion	MJ	14.2	14.7	55.7	84.3

In order to consider the relative importance of these impacts, characterisation values of Table 9 are normalised with regard to the values corresponding to West Europe (1995) for the categories of global warming, acidification and eutrophication, and to the world (1999) for the category of fossil fuels depletion. Normalised impacts are represented in Fig. 2.

Global warming is the most significant impact with regard to normalised values. The results for this impact category are favourable to the Multibio multilayer film. Eutrophication is significantly the least important category.

The following figures show the characterisation impacts for the two multilayer films organised by materials production, film processing, and disposal method:

- In materials production, it should be noted that the production of agricultural raw materials, the biopolymers processing industry, and the oleo-chemical industry are lagging behind in their optimisation degree as compared to the industry of petroleum and its derivatives. Therefore, lower fossil energy consumptions and lower emissions relative to acidification and eutrophication will likely be reached in the future. Moreover, it should be added that LCA studies regarding biodegradable materials are scarce and their reliability is uncertain.
- Processing of the Multibio multilayer film includes the dehumidification of PLA, the co-extrusion of the three layers and the thermo-forming and composting of the packaging at disposal. For the conventional multilayer film, the film processing includes the dehumidification processes for PA6, the co-extrusion of the three layers and the thermo-forming.
- Composting of biodegradable plastics and incineration of conventional plastics were considered for each individual waste from both packaging materials.

The global warming impact category has been the focus of study of the scientific community because of its effects on climate change. On this regard, the level of equivalent emissions of CO_2 can be considered the most reliable key parameter (Fig. 3). For this category, the new multilayer biodegradable film shows a significant reduction in this impact. Conventional multilayer film has a 90% higher impact than the Multibio multilayer film.

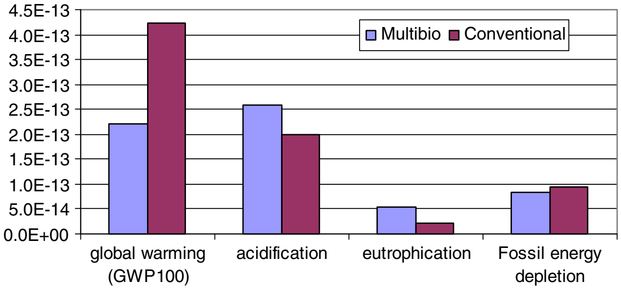

Fig. 2 Normalised life cycle assessment of 1 m^2 of multilayer film

Incineration of materials derived from petroleum, like polyolefins, has a high impact in global warming because all the fossil carbon is discharged as CO_2. However, composting biodegradable multilayer film has no estimated effect in the balance of CO_2 because the carbon released re-enters the natural carbon cycle when absorbed during plant growth.

Impacts of the co-extrusion and thermoforming processes are estimated to be slightly lower for Multibio materials in this pilot study, due to a lower electricity consumption figure per kilogram of biodegradable multilayer film. This lower energy consumption is largely offset by the higher density of the Multibio multilayer film analysed in this report (Fig. 4). The same comment is valid for the acidification impact (Fig. 5).

The eutrophication impact is a consequence of the use of fertilizers (for the production of renewable polymers) and of the emissions during the extraction of crude oil and polyolefin processing (for the conventional polymers, see Fig. 6).

Improvements in the industry of agricultural raw materials production and optimisation of the biopolymer pro-

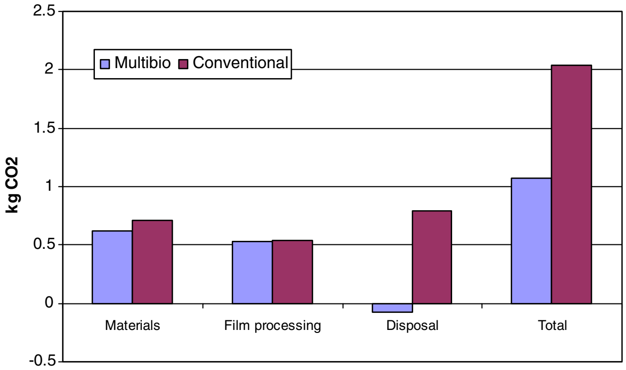

Fig. 3 Global warming for 1 m^2 of multilayer film

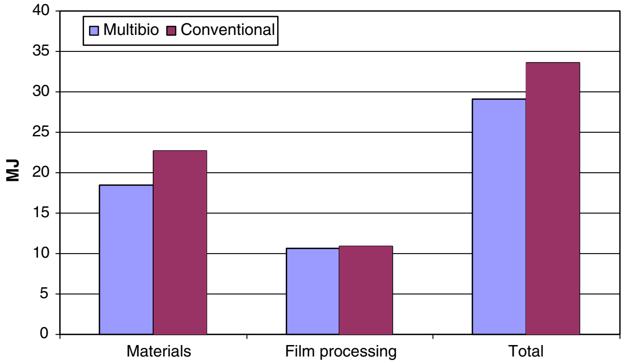

Fig. 4 Fossil fuel depletion for 1 m^2 of multilayer film

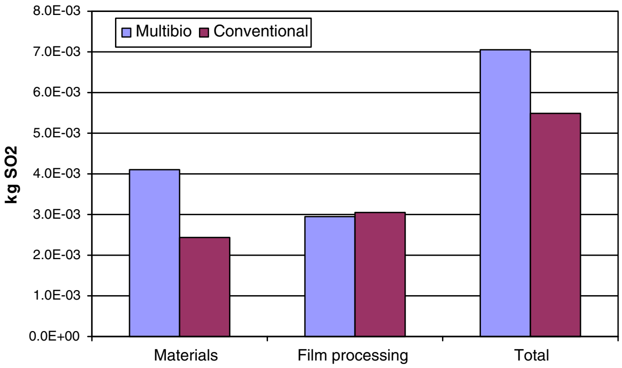

Fig. 5 Acidification for 1 m^2 of multilayer film

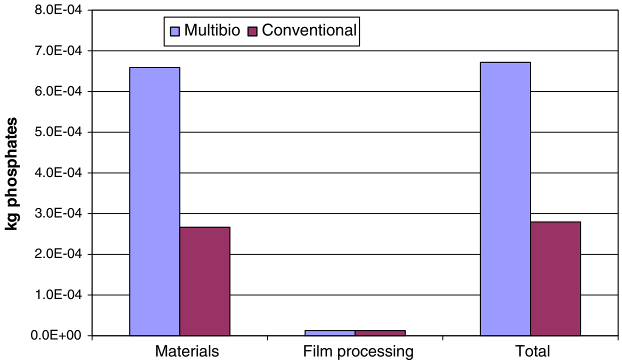

Fig. 6 Eutrophication for 1 m^2 of multilayer film

cessing and oleo-chemical industries should significantly reduce the impacts in this category.

Conclusions

The production of multilayer film from petrochemical polymers exhibits a higher environmental impact than the production of biodegradable multilayer film. Global warming is the most significant impact category (as a normalised value). The performance of the Multibio multilayer film compares favourably to that of conventional multilayer film in this category. Eutrophication is significantly the least important category impact, so even though the Multibio multilayer film does not perform as well in this category, its overall performance is hardly affected.

The biodegradable multilayer film has lower global warming and fossil energy depletion impacts than the conventional multilayer film. Differences in the acidification category are relatively small. The eutrophication category, with the least relative importance, is the only one for which the conventional multilayer film presents significantly lower impact.

The next remarks are needed to justify the above conclusions:

1. The polyolefin production industry now works with a high efficiency rate. The environmental impacts of polyolefins by PlasticsEurope (Association of Plastics Manufacturers) reflect improvements of 45% in energy consumption over the past 10 years.
2. Raw materials and biopolymers used in biodegradable multilayer film production have been estimated to produce high impacts, due to the following reasons:

a. Manufacturing and use of fertilizers for crop plants, leading to eutrophication (PO_4^{3-}). Agricultural practices, and particularly climate and local differences, should be more accurately known to improve the analysis.
b. The oleo-chemical industry, supplying chemicals like acyl halide, for modification and compounding in biopolymer production, has a lower optimisation degree than the commodity polyolefin industry.
c. Moreover, there is insufficient analysed environment data available in the literature for these phases of the life cycle.

3. Impacts of the co-extrusion and thermoforming processes are estimated to be slightly lower for Multibio materials in this pilot study, due to lower electricity consumption per unit of weight.
4. Regarding the global warming category, conventional multilayer film has a 90% higher impact than the Multibio multilayer film.
5. Incineration of materials derived from petroleum—like polyolefins—causes a high impact in global warming because all of the fossil carbon is discharged as CO_2. However, composting biodegradable multilayer film has no estimated effect in the balance of CO_2 because the carbon released re-enters the natural carbon cycle, after having been absorbed during plant growth.

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