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HOW 'GREEN' ARE BIOPOLYMERS?

Daniel Garraín[1], Rosario Vidal[1], Pilar Martínez[2], Vicente Franco[1], Rosa González[2]
[1]GID, Engineering Design Group, Dpt. EMC, Universitat Jaume I, Castellón, Spain
[2]AIMPLAS, Technological Institute of Plastics, Valencia, Spain

ABSTRACT

An increasingly pronounced degradation of the environment caused by human beings has fostered the development of an environmental consciousness in product design. The design of more ecological products is aimed at reducing the environmental impact caused by products and their manufacturing processes, as is the case of the development of bioplastics as an alternative to conventional materials. The accomplishment of this objective has not been sufficiently demonstrated due to two reasons:

- The lack of optimisation of new bioproduct processing techniques as opposed to production processes used for conventional products.
- The assessment criteria employed do not realistically reflect the environmental impact caused.

The most widely used tool for evaluating environmental impact is the Life-Cycle Assessment Methodology (LCA). The impact categories most often developed in LCAs on plastics and biopolymers are global warming, acidification, eutrophication, ozone layer depletion, smog or fossil resource depletion, while other relevant categories that would lead to a more detailed and therefore more realistic assessment are left aside. These categories include land use regarding aesthetic impact, waste treatment or impact on biodiversity and soil productivity.

Keywords: Life-Cycle Assessment, biopolymers, impact categories, land use, landscape aesthetic impact, waste disposal

1 INTRODUCTION

Interest in biodegradable materials has developed as a consequence of increasing social awareness of environmental degradation and the possibilities of reducing it by selecting more environmentally-friendly products.

In the early 1900s most non-fuel industrial products, like plastics, were made from biobased resources. By the 1970s petroleum-derived materials had replaced, to a large extent, those materials derived from natural resources. Recent developments are raising the prospects that naturally derived resources will once again be a major contributor to the manufacturing of industrial products. Currently, these biobased products are being optimized. At the same time, environmental concerns are intensifying the interest in agricultural and forestry resources as alternative feedstocks. Sustained growth of this industry will largely depend on the development of new markets and cost- and performance-competitive biobased products [1].

An undeniable advantage of biopolymers is their biodegradability. This allows a significant reduction of their aesthetic impact especially when their disposal is not correct. Moreover, they can be composted with the rest of organic material in municipal solid waste. Composting avoids global warming gas emissions that happen when plastics derived from petroleum are incinerated. It also decreases the need for peat extraction, which reduces the environmental impact globally.

Some authors have remarked that biodegradable materials are, in some cases, less "ecological" than conventional ones, among other reasons, because of the high degree of optimisation in conventional industries. Gärtner & Reindhardt [2] and Braschkat *et al.* [3] have carried out LCAs of different biobased products comparing them to conventional ones. They have stated that, in many cases, biobased products save fossil energy resources and prevent greenhouse gas emissions. However, they cause more acidification, eutrophication and ozone layer depletion. Moreover, the outcome of the assessment of biobased products strongly depends on agricultural production, the usage pattern of biobased products, the use of co-products and the kind of disposal. The results by Patel *et al.* [4] show

that biobased polymers can contribute to the reduction environmental impacts associated to the use of materials in terms of saving energy resources or mitigating greenhouse gas emissions. In spite of this, it is not possible to make conclusion on whether biobased plastics should be preferred to petrochemical polymers from an environmental point of view. This is due to the fact that none of the biopolymers studied performs better than its fossil fuel-based counterparts in all categories. Scott [5] points out that the use of waste polymers by mechanical recycling and incineration has serious ecological limitations.
Biopolymers obtained from renewable sources are still in an incipient state of development when compared to petroleum-derived plastics. Even though the environmental impact of biopolymers is higher nowadays, they should not be rejected because of this. Instead, further research on their optimisation towards their environmental improvement should be conducted [6].
A number of international projects comparing the environmental impact associated to the use of biopolymers against conventional materials have been developed in this work. In one of these projects (DOLFIN project), different polymeric compounds comprising a matrix of recycled high-density polyethylene (HDPE) or recycled polypropylene (PP) blended with natural fillers and fibres obtained from agricultural waste (such as rice husks) or industrial waste (cotton lint) were developed as an alternative to wooden structures. In another project (MULTIBIO project), an innovative 100% biodegradable multilayer sheet obtained from potato and corn starch was developed for its application to disposable food packaging, as an alternative to the existent non-biodegradable containers.
When designing a new product composed of biodegradable materials, every relevant environmental impact category must be taken into account to properly assess the environmental impact associated to its production, use and disposal. The most usual impact categories developed in LCAs carried out by several authors on the subject of plastic products and processes were global warming, acidification, eutrophication, ozone layer depletion, smog and fossil resource depletion [3, 4, 7-13] (see Table 1). So far, assessments made considering the usual impact categories alone have shown that products involving agricultural resources are either less sustainable or show little differences in terms of sustainability with conventional products, chiefly due to the use of fertilizers.
Taking a closer look at the LCA methodology followed by most authors, one can observe that impacts such as the land use of biodegradable materials or the visual impact of a crop field are not taken into account. Does a cornfield make a better neighbour than a factory? Can the difference in visual impact between agriculture and plastic industry be quantified? Hence, less developed but yet significant categories arise, such as land occupation and transformation by industries and crops [14], aesthetic impact [12] or land take of biodegradable and non-biodegradable waste [15-16]. In this article, these new categories are developed or discussed in order to quantify annoyance as an additional factor in LCAs. This will allow for fair comparisons between biodegradable products (or products including biodegradable parts) and their conventional counterparts.

2 BIOPOLYMERS AS ALTERNATIVE TO CONVENTIONAL PRODUCTS

2.1 Selection of impact categories

The research projects which are going to be taken as a reference are MULTIBIO and DOLFIN projects, both financed by the European Commission in the 5th and 6th Framework Programme respectively. The aim in DOLFIN was to develop different composite materials from recycled polymer materials and agricultural (rice husks) and industrial (cotton lint) wastes. The aim of MULTIBIO was to develop an innovative 100% biodegradable multilayer sheet obtained from potato and corn starch. In both projects an alternative to the conventional materials has been used, thus reducing environmental impacts. For the assessment of the environmental impact associated to each product, up-to-date life-cycle inventory data was entered to SimaPro v7.0 software.
There is no scientific consensus regarding which impact categories should be considered when assessing the impacts of biopolymers, as illustrated in Table 1. Until the publication of the ISO 14042 norm in 2000, the most broadly-used methodology was Eco-Indicator 95 [17] with its corresponding impact categories. The aforementioned norm advises against the use of weighting factors for comparisons, which were included in the Eco-Indicator 95 methodology. As stated in ISO 14042, comparisons shall only be conducted between same categories. Since 2003, several LCA studies on polymers have been published [3, 4, 7-13]. Wide methodological differences can be appreciated among them. They do coincide in considering greenhouse effect and non-renewable energy

consumption as impact categories. Two other categories are also broadly –if not unanimously- selected, namely eutrophication and acidification. All of the authors except [12] use impact categories included in Guinée's list [18].

Table 1. Impact categories selected in the literature

Reference	[3]	[4]	[7]	[8]	[9]	[10]	[11]	[12]	[13]
Greenhouse gases	X	X	X	X	X	X	X	X	X
Ozone depletion	X			X	X				
Smog		X (n/a)	X	X		X			
Acidification	X	X (n/a)	X	X	X	X			
Eutrophication	X	X (n/a)	X	X	X	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					
Eco-indicator 95			X	X					
EPS			X						
Deposited waste			X	X					
Litter marine biodiversity								X	
Litter aesthetic								X	
Contaminants	SO_x, NO_x, NH_4, particulate				SO_x, NO_x, NH_4, diesel particle				

The LCAs studied show a high level of uncertainty. This is a common trait of agricultural LCAs performed to date. For this reason, the four most-cited categories in biopolymer LCAs were selected to be used in our own LCA, namely global warming, abiotic resource depletion, eutrophication, and acidification. The characterization model employed was CML 2000 by the Institute of Environmental Sciences of Leiden (The Netherlands), which has been extensively used by the international scientific community. The normalisation set selected was Western Europe, 1995 [19].

2.2 Ecoprofiles of biopolymers versus conventional products

The DOLFIN project entailed the analysis and environmental assessment of plastic and biocomposite materials using the LCA methodology. These were used as substitutes for wood in the construction of platforms. The proposed alternatives included a platform formed by polymeric material tubing in virgin PP and HDPE thermoplastics instead of wooden logs, along with other platforms built using biocomposite materials. These materials featured a recycled HDPE and PP matrix phases and a reinforcement phase made from agricultural and industrial wastes (rice husk powder, cotton lint pellets). Four different biocomposite compounds were considered, each one having a different reinforcement/matrix combination with diverse sources for thermoplastics and cotton lint. Overall, six platforms were modelled for comparative purpose:

- Conventional eucalyptus wood platform (W).
- Virgin HDPE and PP platform (VP).
- Biocomposite platform with plastic matrix coming from recycled urban post-consumer waste and reinforcement of rice husks and cotton lint from crop waste (UW&CC).

- Biocomposite platform with plastic matrix coming from recycled industrial waste and reinforcement of rice husks and cotton lint from crop waste (IW&CC).
- Biocomposite platform with plastic matrix coming from recycled urban post-consumer waste and reinforcement of rice husks and cotton lint from textile waste (UW&RC).
- Biocomposite platform with plastic matrix coming from recycled industrial waste and reinforcement of rice husks and cotton lint from textile waste (IW&RC).

Figure 1 illustrates the results of the comparison in terms of environmental impact between all platforms.

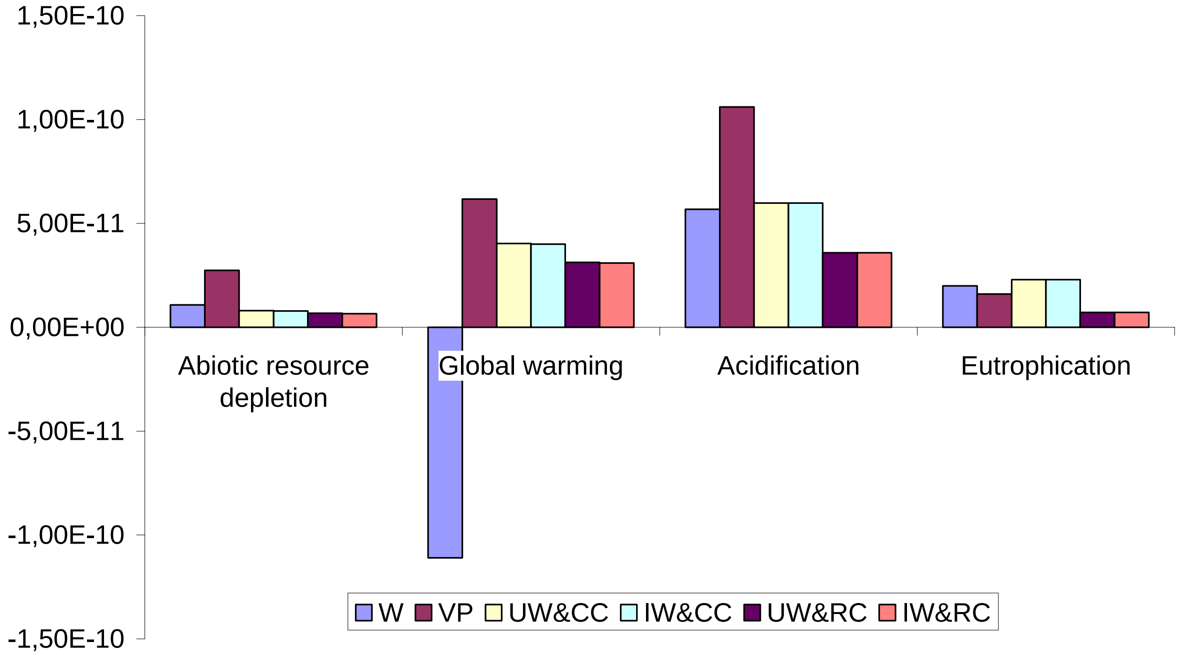

Figure 1. Ecoprofile of platforms made of different materials

It can be concluded that none of the alternative platforms made of plastic has an advantage over conventional wooden ones from an environmental preservation perspective. The platform made of virgin polymers has the greatest environmental impact. The platform with plastic matrix coming from recycled industrial waste and reinforcement of rice husks and cotton linters from textile waste is the most ecological alternative among plastic platforms.

Wooden platforms yield large negative results in the global warming category due to the fact that eucalyptus trees act as carbon dioxide sinks until they are cut down. However, it should be taken into account that the validity of these results is subject to the creation and maintenance of forest masses for timber extraction. Furthermore, environmental impacts associated to wood are probably higher, mostly due to the application of chemical products for weather protection treatment. On the other hand, biocomposite platforms will have longer life cycles given their superior resistance.

MULTIBIO project, which also involved biopolymers, was aimed at the development of an innovative 100% biodegradable multilayer sheet for its application in single-use food packaging obtained from potato and corn starch as an alternative to the existent non-biodegradable containers. The material developed within the project was composed of three layers: two outer layers made from PLA (Polylactic acid) and one inner layer from compounding of modified starch, PCL (Polycaprolactone) and glycerol mosterate (PLA-Starch-PLA). This was compared to a functionally similar multilayer PP - PA6 (Polyamide Nylon 6) - PP sheet. The functional unit considered was one square meter of packaging material of identical thickness.

The impacts associated to each one of the materials were obtained from literature as detailed in the technical report by Vidal *et al.* [20]. Figure 2 illustrates the environmental impact as result of the LCA of each multilayer sheet.

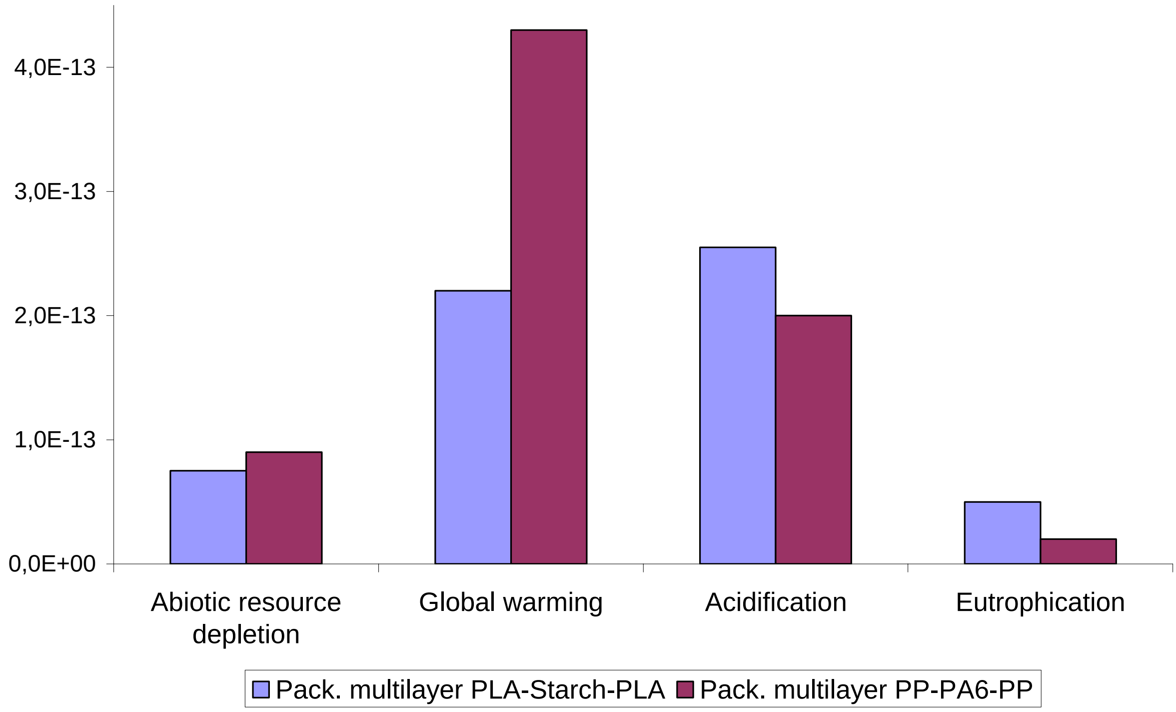

Figure 2. Ecoprofile of 1 m² of multilayer food-packaging sheet made with biodegradable materials versus conventional plastic sheet

The food-packaging product made with biodegradable materials has a higher environmental impact in the acidification and eutrophication categories. The main reason for this is that biopolymers obtained from renewable sources are still in an incipient state compared to plastics derived from petroleum. Agricultural processes for obtaining raw materials, the biopolymer processing industry, and the oleo-chemical industry are trailing behind in terms of optimisation degree when compared to the petroleum product industry. This ecological disadvantage of biopolymers is further increased by the use of fertilizers needed to obtain starch. However, biopolymers are clearly more ecological in terms of abiotic resource depletion and global warming. Thus, we conclude that further optimisation is needed in the biopolymer production chain in order to attain plastic products that perform well in every impact category.

3 NEW IMPACT CATEGORIES

As noted in the introduction, the most usual impact categories developed in LCAs of plastic and biodegradable products and their production processes are global warming, acidification, eutrophication and fossil resource depletion. Ozone layer depletion and smog are developed to a lesser extent.

When designing a product made of biodegradable materials, all of the impacts associated with the product along its life cycle -“from cradle to grave”- should be taken into account. The replacement of conventional materials by biopolymers entails modifications of environmental impacts which are not always evident or easy to quantify. Existing LCA studies of biopolymers have often neglected the land use impact category, with some exceptions [9].

Given that the organic fraction of biodegradable products often comes from agricultural waste, several environmental issues concerning the impact of crops arise, namely land occupation and transformation or aesthetic impact on landscape. Additionally, when replacement of conventional plastics by biodegradable polymers is under consideration, other topics come up, such as the environmental assessment of the disposal methods. These matters are outlined next.

3.1 Land occupation and transformation by crop fields

Should biodegradable materials have great market success, it is possible that additional land would have to be transformed into crop fields, therefore causing land occupation and transformation impacts. In order to quantify these effects in the long run, the impact caused by a one-hectare potato field has been assessed. Two areas in Spain possessing different soil characteristics were chosen. These were the Mediterranean forests of the Iberian mountain group and the pastures of the north-western Cantabrian region.

There are several methodologies available to assess the impact of land use [21]. Two different methods have been selected in our case: Weidema & Lindeijer's [14] and Eco-indicator 99 [22]. In the first method, for the sake of simplicity, the geographical data considered were an altitude ranging from 1000 to 3000 metres for the Iberian mountains and below 1000 metres for the Cantabrian area. Richness of vascular plant species was estimated [23] at 0.125 and 0.175 species per square kilometre respectively. Making use of data provided by the authors, the impact was expressed in person-equivalents. These results are shown in Table 2.

Table 2. Impact on land occupation of a one-hectare potato field (Weidema & Lindeijer's method [14])

Occupation impact on	**Person-equivalents**	
	Cantabrian region	**Iberian mountain group**
Productivity	23	-17
Biodiversity	24	68

The results in terms of productivity reflect that soils occupied by potato fields are more productive than forests, as predicted by the authors in cases where human intervention raises net primary productivity (NPP) value. This increase in productivity is attributable to the use of fertilizers, irrigation, etc. However, when a pasture is replaced by a potato field there is a negative impact on productivity. These results are inverted regarding biodiversity, with greater impact on the Iberian mountains than on the Cantabrian region. Nevertheless, these results could significantly vary depending on the source for data. Considering the NPP values given by Romano [24], opposite results are obtained.

Table 3. Impact on land occupation (productivity) of a one-hectare potato field, by NPP data source

Source of data	**Person-equivalents**	
	Cantabrian region	**Iberian mountain group**
Weidema & Lindeijer [14]	23	-17
Romano[a] [24]	38	66
Romano[b] [24]	-33	-26

[a] NPP data (potential and actual) as extracted from Vitousek *et al.* [25].
[b] NPP data as extracted from Vitousek *et al.* [25] (potential) and Margalef [26] (actual).

The second method [22] was applied to obtain a value for Ecosystem Quality (EQ). The Cantabrian region was considered as "less intensive meadow", whereas the Iberian mountain group was considered as "broad-leaved forest". The restoration time for occupation and conversion was 50 and 30 years respectively. Table 4 shows the resulting impact on land occupation and conversion, both locally and on a regional level. The impact on the Iberian mountain group area is clearly higher.

Table 4. Impact on land occupation and conversion of a one-hectare potato field (Goedkoop & Spriensma's method [22])

	Cantabrian region	**Iberian mountain group**
PDF_{occ}	1,15	
EQ_{occ} ($m^2 \cdot yr$)	5,75E+05	
PDF_{conv}	0,10	1,03
EQ_{conv} ($m^2 \cdot yr$)	3,00E+04	3,09E+05

3.2 Landscape aesthetic impact

A spread use of biopolymers would entail the expansion of land areas dedicated to crops (*e.g.* potato fields). The visual impact involved by these large fields cannot be neglected. But, how could it be compared to the visual impact of a relatively compact petroleum or plastic processing plant? In order to assess visual impact due to this circumstance, it must be taken into account that the relevance of visual impact depends on the qualities of previously existing landscape, as well as psychological and cultural factors associated to observers. These latter factors display enormous diversity. However, several authors [27-29] have found that natural character and variety contribute positively to scenic value. Planting potato fields could either have a positive or negative effect on landscape natural character or 'naturalness' depending on the type of terrain being substituted.

Values can be assigned to the different terrain types as a measure of their perceived naturalness (for instance, grasslands would have greater value than an intensive crop field, but lower than a forest's edge [27]) to create an aesthetic indicator of naturalness that would allow to compare different alternatives in landscape planning scenarios. Another positive aesthetic impact would be achieved with the reduction of petrochemical facilities thereby reducing their visual impact.

As for landscape variety, the expected impact of planting large extensions of intensive crops would be negative as it would produce locally monotonous landscapes. However, an appropriate landscape planning could help buffer this effect by means of introducing punctual (trees, barns) or linear (hedgerows, pathways) landscape elements.

In any case, the identification, prediction and assessment of aesthetic impact requires:

- Thorough knowledge of the project interfering with landscape and its alternatives.
- Relevant data about the environment.
- Development of aesthetic impact indicators referred to a specific set of places or areas and their associated cultural values [30].

So far, the poor methodological development of indicators that seek to measure the scenic value of landscapes makes it difficult to assess the aesthetic impacts associated to extensive potato fields. However, the conclusion that an adequate landscape planning can lead to positive impacts such as increased naturalness and landscape variety can be derived *ex ante*. In sharp contrast, the use of conventional plastics brings about nothing but negative visual impacts associated to oil extraction and processing facilities.

3.3 Land take of biodegradable and non-biodegradable waste

The environmental impact caused by the disposal of biodegradable multilayer material and conventional plastic waste is analysed next. Our work focuses on the global warming impact category because a significant amount of greenhouse effect gases (GHG) such as CO_2 (also N_2O and CH_4, to a lower extent) are emitted during disposal. The methodology developed by Smith *et al.* [31] was used. Three different scenarios were contemplated: incineration with no energy recovery, disposal in landfill without gas control, and composting in simple windrow systems.

During incineration, organic carbon compounds are oxidized to CO_2 and water vapour, which are then discharged to the atmosphere in the stack gas. Incineration of fossil carbon contained in plastics makes a net positive contribution to global warming, whereas incineration of biobased materials as short-cycle carbon compounds is neutral in global warming terms.

In landfill sites, plastic waste degrades 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. Estimates of the Degradable Organic Carbon content (DOC) have been derived from estimates of the total carbon content in waste, together with estimates of the proportion of this total carbon that is biogenic and thus degradable. The proportion of DOC which is dissimilable (DDOC) under landfill conditions is hardly known. To explore the sensitivity of the results to the assumed DDOC level, two alternatives have been considered, wherein 30% and 50% of DOC is thought to be dissimilable. The biogenic carbon locked up in landfills can be considered to have been removed from the natural carbon cycle, hence reducing the global carbon dioxide emissions.

Composting is the aerobic degradation of waste to produce compost which can be used as a soil improver. The plain-and-simple windrow has been chosen among the variety of centralised composting systems. This system is an open-air pile which is periodically turned by agricultural machinery. The required data and procedures for the obtaining of greenhouse gas emission flows can be found in Vidal *et al.* [20]. Table 5 lists the CO_2 equivalent emissions of a functional unit of one square metre of multilayer plastic material for all three disposal scenarios given: incineration, landfill, and composting. The superior performance at disposal from the biodegradable multilayer material is highlighted by these results. It is also evident that the environmental impact is lowest when composting is the disposal method of choice. In contrast, the environmental impact is highest when the multilayer material uses conventional petroleum plastics, especially when waste is incinerated.

Table 5. GHG flows of one square metre of plastics and biomaterials in different disposal scenarios

		Plastic	**Biomaterial (30% DDOC)**	**Biomaterial (50% DDOC)**
GHG emissions (kg CO_2 eq.)	Incineration	0,794	0,007	0,007
	Landfilling	0,002	0,292	0,918
	Composting	-	-0,074	-0,064

Assuming a composting disposal scenario for biopolymers and incineration for conventional plastics, -that is, an ecologically optimal disposal for biopolymers against a common disposal treatment for plastics- the multilayer biodegradable film's potential for reducing CO_2 emissions is dramatically underscored (Figure 3). Indeed, the impact of conventional multilayer film is in this case 90% higher than that of biopolymer film, thereby stressing the importance of including disposal -in all its possible scenarios- when assessing environmental impact.

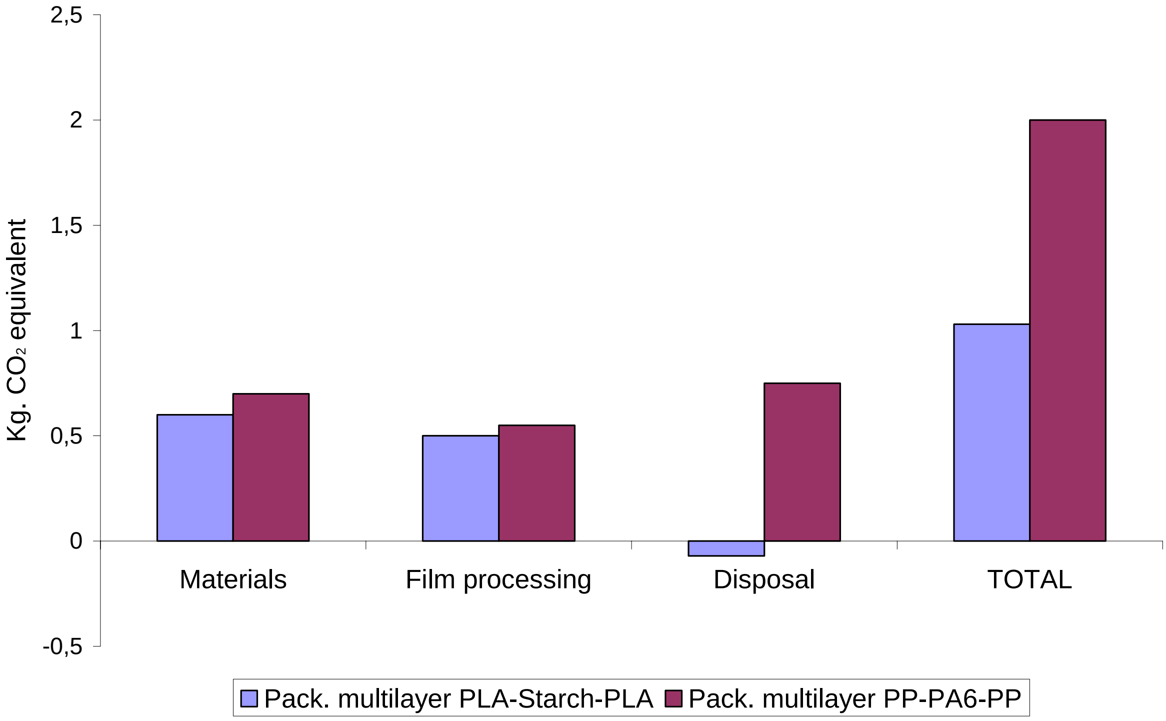

Figure 3. Global warming impact of 1 m^2 of multilayer sheet as assessed using LCA methodology

4 CONCLUSIONS

Extracting a definite conclusion about the environmental efficiency of biodegradable polymers compared to conventional products is no easy task, as can be seen from the literature reviewed and the results obtained in the projects we have taken into account. In these, the environmental impact caused by biopolymers is assessed in comparison with wood and conventional plastics. Bioproduct processing techniques -as opposed to production processes used for conventional products- often lack optimisation. This yields paradoxical results of biopolymers being "less green" than petroleum products. On the other hand, the assessment criteria employed often fail to effectively yield realistic results or even cover all the impact categories involved.

Further development of impact categories -such as land use by crop fields destined to the production of organic raw material for biopolymers- is needed in order to properly assess environmental impact.

No reliable methodologies have yet been developed to assess the impact category of land occupation and transformation, even though this is a crucial impact category given its long-term implications, as illustrated by the example given in section 3.1.

As for landscape aesthetic impact associated to biopolymers, we note that adequate landscape planning can lead to positive impacts such as increased naturalness and landscape variety. In contrast, the use of conventional plastics brings about nothing but negative visual impacts, related to oil extraction and processing facilities.

Waste disposal should not be neglected in the assessment of biopolymers, as results vary dramatically depending on the disposal method employed.

As a final remark, we note that the general recommendation of giving consideration to less frequently used impact categories (land use, aesthetic impact; also noise, odour, etc.) can be applied to the environmental assessment of any type of product, not just biopolymers.

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- DOLFIN: Craft project of the 6th Framework Programme: contract n. COOP-CT-2003-508682. “Development of innovative plastic structures for aquiculture using a new composite with crop waste as reinforcing filler”.
- Project of the Technological Cooperation between Research & Technology Centres Programme (IMPIVA - Generalitat Valenciana - Spain): References IMCITA/2005/22 and IMCOCA/2006/14. “Estudio medioambiental de los productos plásticos y de sus procesos de fabricación mediante el análisis del ciclo de vida”.
- Project of the Environmental Science and Technology National Programme of the R&D National Programme 2004-2007 (Ministry of the Environment of Spain): References 2.4-320/2005/2-B and 566/2006/1-2.4. “Análisis del ciclo de vida de residuos de materiales biodegradables y biocompuestos, como alternativa a los polímeros convencionales”.

REFERENCES

[1] Weber C.J. Biobased Packaging Materials for the Food Industry – Status and Perspectives. *European commission – concerted action*, Denmark, 2000.

[2] Gärtner S.O., Reinhardt G.A. Biobased products and their environmental impacts with respect to conventional products. In *Proceedings of the 2nd World Conference on Biomass for Energy, Industry and Climate Protection*, Rome, 2004.

[3] Braschkat J., Gärtner S.O., Reinhardt G.A. Environmental impacts of bio-based products in comparison with conventional products. *Agroindustria, Ed. Ranalli, Bologna*, 2004, Vol.2, pp. 53-59.

[4] Patel M., Bastioli C., Marini L., Würdinger G.E. Life-Cycle Assessment of Bio-Based Polymers and Natural Fibres. *Encyclopedia “Biopolymers”*, 2003 Vol.10, pp. 409-452.

[5] Scott G. Green polymers. *Polymer degradation and stability*, 2000, 68, pp. 1-7.

[6] Känzig J., Anex R., Jolliet O. Conference report: International workshop on assessing the sustainability of bio-based products. *International Journal of Life-Cycle Assessment*, 2003, 8 (5), pp. 313-314.

[7] Dinkel F., Pohl C., Ros M., Waldeck B. Ökobilanz Stärkehaltiger Kunststoffe. *Bundesamt für Umwelt, Wald end Landschaft (BUWAL)*, 1996.

[8] Schwarzwälder B., Estermann R., Marini L. The Part of Life-Cycle-Assessment for Biodegradable Products: Bags and Loose Fills. *Chiellini E, Gil H, Braunegg G, editors. Biorelated Polymers: Sustainable Polymer Science and Technology, Plenum Pub Corp Published*, 2000, pp. 371-83.

[9] Müller-Sämann K.M., Reinhardt G.A., Vetter R., Gärtner S.O. Nachwachsende Rohstoffe in Baden-Württemberg: Identifizierung Vorteilhafter Produktlinien zur stofflichen Nutzung unter Besonderer Berücksichtigung Unweltgerechter Anbauverfahren. *Projektabschluss-bericht Forschungszentrum Karlsruhe IfUL Müllheim*, 2003.

[10] Kim S., Dale B.E. Cumulative Energy and Global Warming Impact from the Production of Biomass for Biobased Products. *Journal of Industrial Ecology*, 2003 (7) Vol. 3-4, pp. 147-162.

[11] Vink E.T.H., Rábago K.R., Glassner D.A., Gruber P.R. Applications of life cycle assessment to Nature Works polylactide (PLA) production. *Polymer Degradation and Stability*, 2003, 80, pp. 403-19.

[12] ExcelPlas Australia, Centre for Design (RMIT), and Nolan ITU. The impacts of degradable plastic bags in Australia. *Final Report to Department of the environment and Heritage, Department of the Environment and Heritage,* Commonwealth Government of Australia: Canberra, 2004.

[13] Bohlmann G.M. Biodegradable Packaging Life-Cycle Assessment. *Environmental Progress,* 2004, 23, (4): 342-346.

[14] Weidema B.P., Lindeijer E. Physical impacts of land use in product life cycle assessment. Final report of the EURENVIRON-LCAGAPS sub-project on land use. *Department of manufacturing engineering and management, Technical University of Denmark,* 2001.

[15] Smith A., Brown K., Olgivie S., Rushtone K., Bates J. Waste Management Options and Climate Change. *AEA Technology,* Final Report ED21158R4.1, 2001.

[16] Geigrich J. Modern Times and Imperfect Cycles – Managing the waste from biobased products. *Journal of Industrial Ecology,* 2004, Vol. 7, Nr. 3-4, pp. 10-12.

[17] Goedkoop M. The Eco-Indicator 95. Final Report. *PRé Consultants*, Amersfoort, The Netherlands, 1995.
[18] Guinée J.B. Handbook of Life-Cycle Assessment – Operational Guide to the ISO Standards. *Dodrecht: Kluwer Academic Publishers*, 2002.
[19] Guinée J.B., Gorrée M., Heijungs R., Huppes G.R.K., de Koning A., Wegener A., Suh S., Udo de Haes H., Bruijn H., Duin R.v., Huijbregts M.A.J. Life-Cycle Assessment: An Operational Guide to the ISO Standards. *Ministry of Housing, Spacial Planning and Environment*, 2001.
[20] Vidal R., Mulet E., López-Mesa B., Bellés M.J., Vicent L., Martínez P., González R. LCA for Biodegradable Multilayer Packaging, Multibio Project. *GID Technical report for AIMPLAS*, 2005.
[21] Lindeijer E. Review of land use impact methodologies. *Journal of Cleaner Production* 8, 2000, pp. 273-281.
[22] Goedkoop M., Spriensma R. The Eco-Indicator 99. A damage oriented method for Life Cycle Impact Assessment. Methodology Report. *PRé Consultants B.V.,* Amersfoort, The Netherlands, 2001.
[23] Barthloot W., Lauer W., Placke A. Global distribution of species diversity in vascular plants: towards a world map of phytodiversity. *Erdkunde* 50, 1996, Vol.4, pp. 317-327. Available in: http://www.botanik.uni-bonn.de/phytodiv.htm.
[24] Romano D. Recursos basados en la fotosíntesis. *Curso Ecología y Globalización: Flujos monetarios, de energía y de materiales, Sustentabilidad y Globalización, J. Riechmann y J. Nieto, Ed. Germanía,* Alzira, Valencia, 2003.
[25] Vitousek P.M., Ehrlich P.R., Ehrlich A.H., Matson P.A. Human appropiation of the products of photosynthesis. *Bioscience*, Vol.36, n.6, 1986, pp. 368-373.
[26] Margalef R. *Ecología*, ISBN 84-282-0405-5, 1998 (Ediciones Omega).
[27] Schüpbach B. Methods for indicators to assess landscape aesthetic. *NIJOS rapport 7/2003, NIJOS/OECD Expert Meeting – Agricultural Landscape Indicators – Oslo*, 2002.
[28] Mattsson B., Cedeberg C., Blix L. Agricultural land use in LCA: case studies of three vegetable oil crops. *Journal of Cleaner Production*, 8, 2000, pp. 283-292.
[29] Pachaki C. Agricultural landscape indicators, a suggested approach for the scenic value. *NIJOS/OECD Expert Meeting – Agricultural Landscape Indicators – Oslo*, 2002.
[30] Haynes-Young R., Potschin M. Building landscape character indicators. European Landscape Character Areas Typologies, Cartography and Indicators for the Assessment of Sustainable Landscapes. *Final Project Report: FP5 EU Accompanying Measure Contract: ELCAI-EVK2-CT-2002-80021*, The Netherlands, 2005.
[31] Smith A., Brown K., Ogilvie S., Rushton K., Bates J. Waste management options and climate change. *European Commission, DG Environment*, ED21158R4.1, AEA Technology, Brussels, 2001.

Contact: Daniel Garraín
GID - Engineering Design Group
Dpt. EMC - Universitat Jaume I Castellón
Av. Sos Baynat s/n
12071 Castellón - Spain
Phone: +34 964 729 252
Fax: +34 964 728 106
garrain@uji.es
www.gid.uji.es