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A review of life cycle assessment studies on bio-based materials

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Abstract

Concerns over climate change and the security of industrial feedstock supply have been opening a growing market for bio-based materials. However, this development confronts scientists, policy-makers, and industry with a challenge because the production of bio-based materials requires land and is typically associated with the application of agrochemicals. This article addresses the environmental impacts of bio-based materials in a meta-analysis of 44 Life Cycle Assessment (LCA) studies. We find that one metric ton (t) of bio-based materials saves relative to conventional materials 55 ± 34 GJ primary energy and 3 ± 1 t CO_2-equivalents of greenhouse gases. However, one metric ton of bio-based materials may increase eutrophication by 5 ± 7 kg phosphate-equivalents and stratospheric ozone depletion by 1.9 ± 1.8 kg nitrous oxide-equivalents. Our results are inconclusive with regard to acidification (savings of 2 ± 20 kg sulphur dioxide-equivalents/t of bio-bases materials) and photochemical ozone formation (savings of 0.3 ± 2.4 kg ethene-equivalents/t of bio-based materials). The large variability in the results of individual life cycle assessment studies highlights the difficulties to draw general conclusions about the environmental impacts of bio-based materials. Still, characteristic of most bio-based materials are impacts caused by the application of fertilizers and pesticides during industrial biomass cultivation. Additional land use impacts, such as the potential loss of biodiversity, soil carbon depletion, soil erosion, deforestation, as well as greenhouse-gas emissions from indirect land use change are not quantified in this review. Clearly, these impacts should be considered in a comprehensive environmental evaluation of bio-based materials.

Key words: bio-based materials, Life Cycle Assessment (LCA), environmental impacts, biomass

1 Introduction

Bio-based wood, paper, and textile materials have been produced for centuries. Together, these materials account for 14% of the global bulk materials production, while synthetic materials, predominantly produced from fossil-based feedstock, only account for a share of 7% (own estimates based on Deimling et al. 2007, Lasserre 2008, OGS 2007, UN 2008, Saygın and Patel 2010, IAI 2010)[i]. Concerns about greenhouse gas (GHG) emissions and the security of fossil-based feedstock supply, however, have been triggering relatively recent interest in using biomass for the production of synthetic materials (Patel et al. 2006, Deimling et al. 2007, Shen et al. 2009a,b). As of 2008, biomass provided 10% of the feedstock of the European chemical industry (Rothermel 2008). The production of bio-based synthetic materials such as polymers, lubricants, and fibers has been growing continuously in the past decade. Bio-based polymers such as alkyd resins or polylactic acid accounted for 7% of the total polymer production (PlasticsEurope 2007) while bio-based plastics (comprising polymers with a molecular mass higher than 20,000 unified atomic mass units) are still in their infancy. By the end of 2007 they account for only 0.3% (0.36 Mt) of the worldwide plastics production (Shen et al. 2009a,b).

Technological innovation will likely continue to open a wide range of new applications for bio-based materials, including the use of bio-based plastics for consumer goods and engineering purposes, of composites in the automotive industry, or of novel insulation and packaging materials (Hermann et al. 2010a, Shen et al. 2008, 2009a). Breakthroughs can be expected in the coming years for integrated biorefineries, which may optimize the use of biomass by providing a whole range of materials and energy products from bio-based feedstock.

However, the prospects for novel bio-based materials present scientists, policy-makers, and industry with an environmental challenge: the benefits of replacing fossil-based feedstock and reducing GHG emissions may come at the cost of additional land use and related environmental impacts. Strategic decision-making thus requires a thorough analysis of the environmental impacts of bio-based materials in comparison to their conventional fossil-based or mineral-based counterparts. To this end, Life Cycle Assessment (LCA) has been applied to a large range of bio-based materials, including starch-based polymers (e.g., Dinkel et al. 1996, Würdinger et al. 2002, Patel et al. 2006), fiber-composites (e.g., Wötzel et al. 1999, Müller-Sämann et al. 2002, Zah et al. 2007), or hydraulic oils and lubricants (e.g., Reinhardt et al. 2001). Detailed reviews of the LCA literature have focused initially on non-renewable energy use and GHG emissions only (e.g., Dornburg et al. 2004, Kaenzig et al. 2004), whereas more recent reviews also include additional environmental impact categories such as eutrophication and acidification (e.g., Deimling et al. 2007, Oertel 2007, Weiss et al. 2007). A more comprehensive quantification of the environmental impacts associated with a large range of bio-based materials is, however, still missing. Here, we address this problem by presenting a meta-analysis that summarizes the results of the existing LCA literature on bio-based materials. We do not claim absolute completeness with respect to all published LCA studies. Instead, we seek to: (i) identify general patterns in the environmental impacts of a wide range of bio-based materials and (ii) discuss potentials for making the production, consumption, and disposal of bio-based materials more environmentally friendly. This article excludes technical, economic, and social aspects of bio-based materials (e.g., production costs or the impact of non-food biomass farming on food prices and the livelihood of smallholders in the tropics). However, these aspects should be considered in a comprehensive evaluation of bio-based materials. The article continues by presenting background information and our methodology for reviewing the LCA literature on bio-based materials. We then present results, discuss uncertainties and critical aspects, and identify options for reducing the environmental impacts of bio-based materials.

2 Background information and methodology

Bio-based materials comprise materials that are produced partially or entirely from biomass, i.e., from terrestrial and marine plants, parts thereof, as well as biogenic residues and waste. Bio-based materials include traditional wood, paper, and textile materials as well as novel bio-based plastics, resins, lubricants, composites, pharmaceuticals, and cosmetics. The manufacturing processes of bio-based materials range from extraction and simple mechanical processing of natural fibers to fermentation and advanced enzymatic or catalytic conversions.

The environmental impacts of bio-based as well as conventional fossil-based or mineral-based materials are typically quantified through the internationally standardized LCA methodology (ISO 20006a,b). Here, we review the LCA literature on bio-based materials by applying: (i) a standard internet search for peer-reviewed articles contained in the online databases 'Web of Science' and 'Scopus' as well as (ii) a Google-based search for scientific and governmental reports, workshop documents, and working papers. We include LCA studies in our meta-analysis if they provide a minimum of methodological background information, quantify the environmental impacts of bio-based materials in physical units for at least one impact category, and are published in the English and German languages before December 2011. LCA results presented in flyers or oral presentations are excluded from this review. Likewise, we exclude LCA studies that report environmental impacts in percentages or indices only (e.g., Gironi and Piemonte 2011, Guo et al. 2011). This approach does not allow a complete coverage of all relevant LCA studies published to date; still, it is suitable for identifying the general pattern in the environmental impacts of bio-based materials.

We include in our review a total of 44 LCA studies that cover around 60 individual bio-based materials and 350 different life cycle scenarios (see Tables A1 and A3 in the Appendix). Preliminary scanning through the literature reveals that most studies focus on bio-based materials of European origin being manufactured by both small pilot installations and large-scale industrial plants. The reviewed LCA studies generally differ from each other in many, if not all, assumptions and choices made regarding, e.g., system boundaries, functional units, life cycle scenarios, or allocation procedures as well as in the detail of explanations on methodology and results. We refrain from correcting for differences in choices and assumptions. This approach is justified given the scope of this meta-analysis and the generally limited availability of necessary background information and inventory data.

Individual LCA studies may also differ from each other with in the method chosen for aggregating inventory data into individual environmental impact categories. The commonly used methods have been described by Heijungs et al. (1992), UBA (1995), and Guinée (2001). Our review covers the environmental impacts of bio-based materials in six categories, which we characterize and quantify as follows (Guinée 2001):

(i) non-renewable energy use (NREU), quantified in gigajoules [GJ]
(ii) climate change, quantified in metric tons of carbon dioxide equivalents [t CO_2-equ.] by considering the global warming potential of GHG emissions over a time horizon of 100 years
(iii) eutrophication, quantified in kilograms of phosphate equivalents [kg PO_4-equ.]
(iv) acidification, quantified in kilograms of sulfate equivalents [kg SO_2-equ.]
(v) stratospheric ozone depletion, quantified in kilograms of dinitrogen oxide equivalents [kg N_2O-equ.]
(vi) photochemical ozone formation, quantified in kilograms of ethane equivalents [kg ethene-equ.]

We express the relative environmental impacts of bio-based materials in comparison to the environmental impacts of conventional materials as:

$$D_{ij} = EI_{bio-based,ij} - EI_{fossil-based,ij}$$

where: D_{ij} = the difference in the environmental impact of the bio-based

and conventional material

$EI_{bio\text{-}based,ij}$ = the environmental impact of the bio-based material

$EI_{fossil\text{-}based,ij}$ = the environmental impact of the conventional material

i = the specific material

j = the specific environmental impact category

This approach follows the methodology applied in most of the reviewed LCA studies and results in negative values if bio-based materials exert lower impacts on the environment than their conventional counterparts. We quantify the relative environmental impacts of bio-based materials per metric ton of product [t^{-1}] and per hectare of agricultural land and year [$(ha*a)^{-1}$]. Several LCA studies report their results in terms of alternative functional units (e.g., Madival et al. 2009, Hermann et al. 2010a). We include these studies in our meta-analysis and recalculate the environmental impacts based on the background information provided in each respective study. If the information in the respective LCA studies is insufficient for estimating the relative environmental impacts of bio-based materials, we use information from additional literature sources in the following manner (see also Table A1 in the Appendix):

(i) A few LCA studies on plastics present the environmental impacts of the bio-based materials but refrain from comparing these with the impacts of fossil-based counterparts (e.g., Vink et al. 2007). In these cases, we calculate the difference in the impacts of bio-based and fossil-based materials based on data provided for fossil-based plastics by Boustead (2005a-d).

(ii) The reviewed LCA studies typically express the environmental impacts of bio-based and conventional materials by using product-based functional units (e.g., one metric ton or a square meter of material). To express the findings of part of these studies also in terms of a land use-based functional unit (i.e., per hectare and year), we include in our meta-analysis the results of two earlier recalculations conducted by the authors (Weiss and Patel 2007; Haufe 2010).

This method does not allow identifying the land use-specific impacts of all material cases investigated in the reviewed LCA studies. Still, our approach is justified by the research objective because it allows a more complete insight into the relative environmental impacts of bio-based materials than the sole comparison of the results presented in the LCA studies.

We estimate stratospheric ozone depletion based on nitrous oxide (N_2O) emissions only and exclude chlorofluorocarbons that are of minor importance since their banning by the Montreal Protocol in 1994 (Würdinger et al 2002; Müller-Sämann et al. 2002). We present the results in each impact category disaggregated for nine individual groups of bio-based materials and as total over all materials. We report the arithmetic mean and the standard deviation of the environmental impacts as identified in the reviewed LCA studies for each group of bio-based materials. The standard deviation can be regarded as indicative of the uncertainty interval in our results and reflects, to some extent, the diversity of life-cycle scenarios and methodological choices made in the reviewed LCA studies. We calculate the overall average impact of bio-based materials in each impact category based on the mean environmental impacts of the individual groups of bio-based materials (see Table A1 in the Appendix). This way, we ensure an equal representation of all nine groups of materials in the overall average.

We put our results in perspective by normalizing the overall average environmental impacts of bio-based materials based on the worldwide average inhabitant-equivalent values for the year 2000 with regards to primary energy consumption (EIA 2011) and the five environmental impact categories (Sleeswijk et al. 2008) covered here. This approach allows comparing our results with the worldwide average environmental impacts of one person in the year 2000. We discuss additional environmental impacts and secondary effects of bio-based materials alongside the uncertainties of our review in semi-quantitative terms after presenting the results.

3 Results

Non-renewable energy use and climate change

We find that bio-based materials save, on average, 55 ± 34 GJ/t and 127 ± 79 GJ/(ha*a) of non-renewable energy. These savings exceed the worldwide average per capita primary energy consumption in the year 2000 by a factor 8 ± 5 and 18 ± 11, respectively, of. Furthermore, bio-based materials save, on average, 3 ± 1 t CO_2-eq./t and 8 ± 5 t CO_2-eq./(ha*a) of GHG emissions relative to conventional product alternatives (Figure 1 and Table A2 in the Appendix), being equivalent to 37 ± 21% and 111 ± 79%, respectively of the worldwide average per capita GHG emissions in the year 2000. The results vary, however, within large ranges. This makes it infeasible to identify individual groups of bio-based materials which are environmentally superior with respect to non-renewable energy use and climate change.

Special attention has been paid in recent years to the production of bio-based chemicals. Patel et al. (2006) conducted an extensive *cradle-to-factory gate* (C-FG) analysis on the non-renewable primary energy use and the GHG emissions of a wide range of bio-based chemicals (Figure 2 and Table A3 in the Appendix). The findings of Patel et al. (2006) are in line with our results for a larger range of bio-based materials, indicating that the production of bio-based chemicals saves, on average, 43 ± 27 GJ/t and reduces the GHG emissions by 3 ± 2 t CO_2-eq./t in comparison to conventional fossil-based chemicals. The variability in the results for individual bio-based chemicals partially stems from differing assumptions regarding the type of biomass feedstock (i.e., corn starch, lignocellulosic biomass, or sucrose from sugar cane) and the applied production technology (e.g., current versus future technologies; aerobic versus anaerobic processes, or continuous versus batch processes).

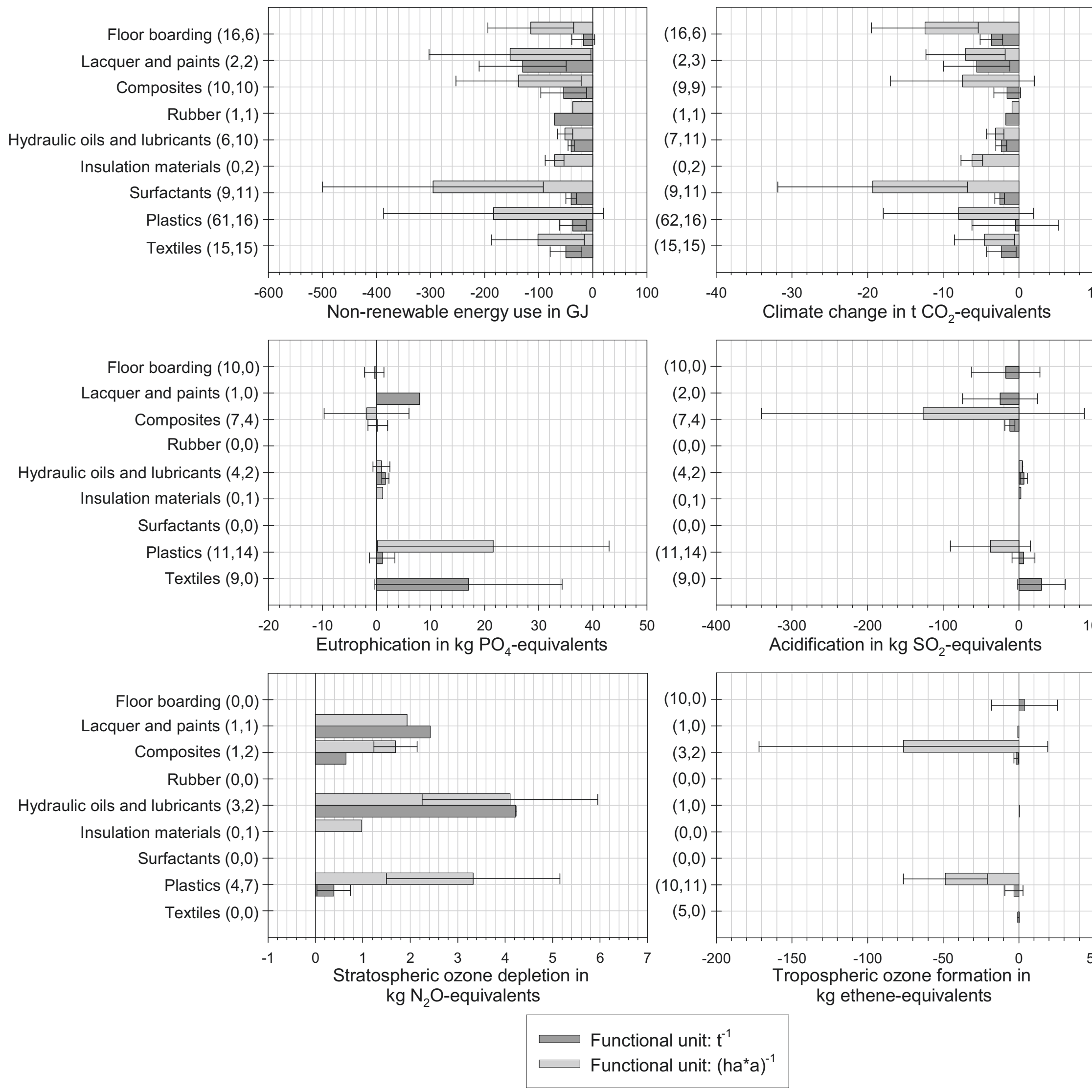

Figure 1: Product-specific environmental impacts of bio-based materials in comparison to conventional product alternatives (D_{ij}); uncertainty intervals represent the standard deviation of data; numbers in parentheses indicate the sample size for the functional units of per metric ton and per hectare and year, respectively

Further support of these findings is provided by Ren and Patel (2009), who estimate that using biomass feedstock for the production of basic chemicals such as ethylene, propylene, and aromatics saves 6 ± 5 t CO_2/t and 11 ± 6 t CO_2/t compared to the use of methane and coal feedstock, respectively. The GHG emission savings identified so far disregard, however, the potentially substantial effects of indirect land use change (see Discussion section).

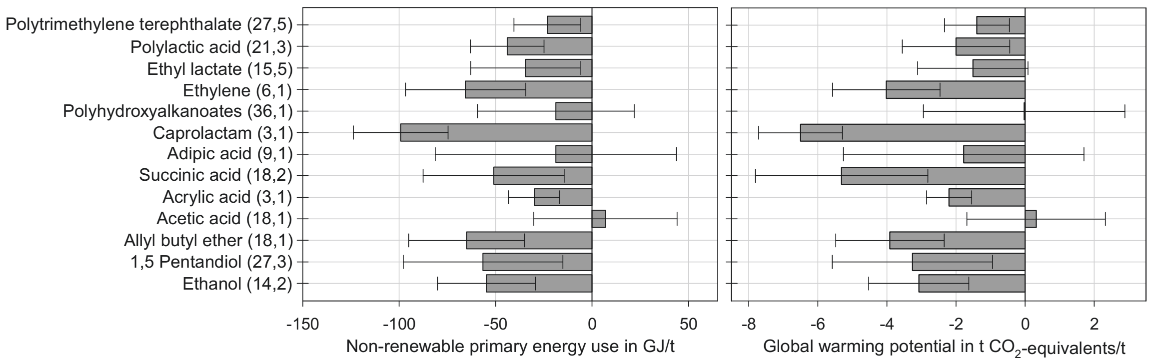

Figure 2: Non-renewable primary energy use and GHG emissions of bio-based chemicals in comparison to conventional product alternatives (D_{ij}); uncertainty intervals represent the standard deviation of data; numbers in parentheses indicate the sample size for the bio-based and the conventional material, respectively (Data source: Patel et al. 2006)

Eutrophication and acidification

The environmental benefits of bio-based materials in the categories of non-renewable primary energy use and GHG emissions are likely associated with environmental burdens regarding environmental eutrophication (Figure 1). Bio-based materials may induce, on average, 5 ± 7 kg PO_4-eq./t and 6 ± 11 kg PO_4-eq./(ha*a) higher emissions on the environment than their conventional counterparts. The additional impacts thereby account for 66 ± 98% and 79 ± 157%, respectively of the worldwide average per capita fresh water eutrophication in the year 2000. Our results can be explained with the high eutrophication potential of biomass production with industrial farming practices, and more specifically, with the nitrate and phosphate leaching from the applied nitrogen fertilizers as well as with the ammonia emissions from manure applications (e.g., Würdinger et al. 2002, Deimling et al. 2007, Cherubini and Jungmeier 2010).

Our findings are inconclusive with respect to acidification, indicating average savings of bio-based materials relative to conventional materials of 2 ± 20 kg sulfate SO_2-eq./t and 39 ± 61 kg SO_2-eq./(ha*a). This result translates into a factor of 0.3 ± 2.9 and 5.7 ± 8.9, respectively of the worldwide average per capita acidification in the year 2000. The relatively large uncertainty intervals indicate that acidification is largely case specific. Bio-based plastics and composites, for example, seem to decrease acidification, whereas bio-based lubricants are likely to increase acidification relative to their conventional counterparts (e.g., Reinhardt et al. 2001, Müller-Sämann et al. 2002). Acidification is mainly caused by emissions from the application of manure and mineral fertilizers in agriculture, as well as from combustion processes. The first source is relevant for biomass production in general, the second one predominantly for lubricants. Even if bio-based materials are incinerated at the end of their life cycle, the resulting emissions may constitute only a minor portion of the total acidifying emissions along the relatively long product life cycle.

Stratospheric ozone depletion and photochemical ozone formation

A relatively limited number of seven LCA studies indicates that bio-based materials may increase stratospheric ozone depletion by, on average, 1.9 ± 1.8 kg N_2O-eq./t and 2.4 ± 1.3 kg N_2O-eq./(ha*a) relative to their conventional counterparts (Figure 1). The additional impacts thereby account for 28 ± 26% and 35 ± 18%, respectively of the worldwide average per capita ozone depletion potential in the year 2000. The impacts in this category largely result from the N_2O emissions that originate from fertilizer application in agriculture (Müller-Sämann et al. 2002, Würdinger et al. 2002). Since fertilizer application is characteristic for industrial farming practices that are typically used for growing biomass feedstock, high stratospheric ozone depletion potentials may be found for a wide range of bio-based materials.

Our findings are largely inconclusive with respect to photochemical ozone formation, indicating that bio-based materials may save, on average, 0.3 ± 2.4 kg ethene-eq./t and 62 ± 20 kg ethene-eq./(ha*a) as compared with conventional materials (Figure 1). These savings account for 5 ± 35% and a factor of 9 ± 3, respectively of the worldwide average ozone formation potential in the year 2000. The large deviation between the product-based and land use-based results as well as the relatively large uncertainty intervals warrant caution and suggest that impacts in this category are case specific. The substantial deviations in the relative magnitude of the uncertainty intervals results here because different LCA studies compose the two data samples that are used to calculate the product-specific and land use-specific ozone formation potential. More specifically, the land use-based analysis does not contain LCA studies on floor boarding, a group of materials that shows a high variability in its impacts on photochemical ozone formation. Typically, floor boarding shows a high ozone formation potential in comparison to other bio-based materials. This observation stems from volatile organic compounds that are emitted from solvents contained in the glues and surface finishing of parquet floors. Gluing and surface finishing together account for 95% of the ozone formation potentials of parquet (Nebel et al. 2006). However, solid floor boards that are fixed mechanically without the application of glues show substantially lower solvent emissions than the over floor boarding scenarios (Nebel et al. 2006). Both parquet floors and solid floor boarding are included in the analysis, thus causing a large variability in the product-specific photochemical ozone formation potentials of floor boarding.

Additional environmental impacts

In addition to these results, bio-based materials exert a large variety of environmental impacts that are not quantified by most LCA studies and thus by this review. Several LCA studies suggest that bio-based materials may:

(i) exert lower human and terrestrial ecotoxicity as well as carcinogenic potentials than conventional materials (e.g., Wötzel et al. 1999, Corbière-Nicollier et al. 2001; Würdinger et al. 2002; Harding et al. 2007, Shen and Patel 2010)

(ii) exert higher aquatic ecotoxicity than conventional materials (Shen and Patel 2010)

Additional land use-related impacts, such as water consumption for biomass cultivation, soil erosion, soil carbon losses, and changes in biodiversity, have received recent attention (see, e.g., Geyer et al. 2010a,b). These impacts are particularly relevant at the local and regional scales, but are difficult to quantify and are therefore excluded from both the majority of LCA studies and this review.

4 Discussion

Our review indicates that bio-based materials on average save non-renewable energy and can help to mitigate climate change (if indirect land use change is disregarded, see discussion below). These findings confirm the results of previous LCA reviews that are, however, based on smaller data samples (Deimling et al. 2007, Oertel 2007, Patel et al. 2003, Dornburg et al. 2004, Kaenzig et al. 2004, Weiss et al. 2007). The LCA literature suggests that bio-based materials, on average, are associated with higher eutrophication and stratospheric ozone depletion than conventional materials. Our findings are inconclusive with regard to acidification and photochemical ozone formation. A similar tendency in the environmental impacts has also been identified by the LCA literature on bioenergy and biofuels (e.g., Reinhardt et al. 2000, Quirin et al. 2004, Larson 2006, von Blottnitz and Curran 2007, WBGU 2008, Schmitz et al. 2009). The relative environmental impacts of bio-based materials scatter over a wide range, spanning over both negative and positive values for several impact categories (Figures 1 and Table A1 in the Appendix). Decision making should account for this variability by considering individual cases, potentially weighing global environmental concerns (e.g., climate change, stratospheric ozone depletion) against local and regional concerns (e.g., eutrophication, photochemical ozone formation, land use change).

4.1 Discussion of uncertainties

The results of our review are subject to uncertainties and limitations that arise from (i) the method used for analyzing the LCA studies and (ii) the uncertainty in the inventory data as well as the diversity of methodological choices applied in the individual LCA studies.

Addressing the first source of uncertainty, our review only quantifies the environmental impact of bio-based materials in six categories. These categories are typically the most prominent ones addressed in the LCA literature. Still, they enable only a partial evaluation of bio-based materials because of insufficient accounting for: (i) other relevant land use-related impacts as well as (ii) the potential risks resulting from the use of genetically-modified crops and microorganisms.

Our approach to refrain from harmonizing the reviewed LCA studies with respect to differences in methodological choices and inventory data may limit the reliability and accuracy of our results. Methodological differences are likely to result in a random error for impact categories of sufficiently large data samples (e.g., non-renewable energy use or GHG emissions). However, more caution is required when interpreting the results for impact categories in which only a few data points are available (e.g., acidification, photochemical ozone formation) because methodological inconsistencies may lead here to systematic errors. In the latter cases, the data samples are often highly skewed, making the mean a less reliable estimator of the general tendency of the sample. To analyze whether the skewness of data samples affects the interpretation of our results, we calculate also the median environmental impacts (see Table A3 in the Appendix). The deviations between the arithmetic mean and median are typically negligible for the totals of all bio-based materials as well as for impact categories and groups of materials for which large data samples are analyzed (e.g., as is the case for non-renewable energy use and GHG emissions). The deviations become, however, larger for cases in which small data samples span large value ranges. Such a case appears for, e.g., the acidification potential of floor boarding where the mean and median may lead to different conclusions (see Table A3). Caution is therefore necessary before drawing conclusions solely based on one indicator for the central tendency of data samples.

Addressing the second source of uncertainty in all rigidity is beyond the scope of this article, given both the vast diversity of plausible methodological choices and the level of detailed information provided by the reviewed LCA studies. Instead, we provide some indication about the uncertainty associated with the results of individual LCA studies.

The data used for the inventory analysis are typically subject to substantial uncertainties. Dinkel et al. (1996) quantify error ranges of inventory data of 40% and deviations resulting from differences in the applied allocation method of up to 90% of the final result. Miller et al. (2007) emphasize the considerable variability and uncertainty in the emission profiles of agricultural systems due to differences in geography, climate, and agricultural practices. The aggregate volatile organic compound and N_2O emissions, for example, vary in their study of soybean-based lubricants by over 300% due to variability in agricultural processes, cropland characteristics, and soybean oil extraction. Furthermore, the reviewed LCA studies often vary from each other in the number of pollutants included in their inventory analysis as well as in their method used for aggregating inventory data into individual environmental impact categories (compare, e.g., Wötzel et al. 1995, Corbière-Nicollier et al. 2001, Müller-Sämann et al. 2003, Turunen and van der Werf 2006). The latter inconsistency might be negligible for our analysis (see, e.g., Corbière-Nicollier et al. 2001, Dreyer et al. 2003). However, the former source of uncertainty leads to a systematic underestimation of environmental impacts. The former sources of uncertainty, however, may present a random error in our review of environmental impact categories and groups of materials for which a large amount of LCA studies is available (e.g., NREU and GHG emissions of plastics or textiles). However, systematic uncertainties may result for the other four, less frequently analyzed, environmental impact categories. Again, one should be cautious when interpreting the results for these categories.

4.2 Discussion of critical aspects in the life cycle assessment of bio-based materials

The large range of results for individual groups of bio-based materials stems from the diversity of product systems, methodological choices, and plausible assumptions made in the reviewed LCAs (see, e.g., Patel et al. 2006). Usually, it is a combination of choices that potentially leads to substantial differences in the outcome of individual LCA studies, even if similar product scenarios are analyzed. Among these choices, the following are particularly critical: (i) the choice of functional unit, (ii) the selection of crops, (iii) the treatment of secondary effects such as impacts of indirect land use change, (iv) the treatment of agricultural residues, (v) the consideration of alternative agricultural practices, (vi) the treatment of temporary carbon storage, and (vii) choices regarding end-of-life waste treatment.

Choice of functional unit

The land use in the production of biomass feedstock can be accounted for by expressing the environmental impacts of bio-based materials per area of cultivated or harvested land [$(ha*a)^{-1}$] instead of per unit of product, e.g., [t^{-1}]. This so-called land use-based approach provides an indication for the *land use efficiency* of bio-based materials. The choice of either a land use-based or a product-based approach does not change the sign of the results but affects their magnitude. In particular, materials with a very low share of a bio-based component can potentially achieve very high land use efficiency if the chosen material is environmentally favorable because the specific land requirements are low. Bringezu et al. (2009) therefore recommend that assessments of biomass use should take two perspectives, namely a land use-based and a product-based perspective, and discuss the outcomes in an integrated manner. Further analysis may supplement the discussed approaches by quantifying the *environmental intensity* of bio-based materials, expressed as environmental impact per monetary unit, i.e., the specific price or production costs of bio-based materials. Such an analysis could provide new insights into the environmental cost efficiency of bio-based materials.

Selection of crops

The environmental impacts of bio-based materials depend on the chosen feedstock. Differences result here from crop-specific farming practices, climatic conditions, agricultural yields, transport distances, use of residues for co-products, as well plant-specific yields characterized by, e.g., starch and fiber content. The environmental impacts of bio-based materials typically decrease if crop-specific feedstock yields are high, environmental impacts of agricultural practices are low, and for cases in which agricultural crops yield substantial amounts of useful co-products (e.g., bagasse in the case of sugar cane). In comparison to fossil-based chemicals, using lignocellulosic biomass or sugar cane as a feedstock for the production of bio-based chemicals saves, on average, 60% and 120% more GHG emissions per metric ton, respectively than using corn starch (Patel et al. 2006).

Secondary effects – the case of indirect land use change

The demand of biomass feedstock for producing bio-based materials may expand the agricultural land use and thus accelerate the direct and indirect land use change on a global scale. Indirect land use change, that is, the unintended expansion of farmland elsewhere due to the rededication of existing farmland, may add substantially to the overall environmental impacts of bio-based materials. The effects of indirect land use change are excluded from the reviewed LCA studies but have been studied in the context of biofuels. Plevin et al. (2010) found that the GHG emissions from indirect land use change of corn ethanol production in the US span between 10 and 340 kg CO_2-eq./GJ ethanol, thereby ranging from small to several times greater than the life cycle emissions of gasoline. Substantial indirect land use change effects for the biofuels production in the USA and in Brazil have been identified by Searchinger et al. (2010), Lapola et al. (2010), and Arima et al. (2011).

On a related note, the effects of direct land use have been analyzed by Piemonte and Gironi (2010), who find that land use emissions have a substantial and largely negative impact on the GHG emission savings of bioplastics unless waste biomass or biomass grown on degraded or abandoned land is used as feedstock. Wicke et al.

(2008) find that direct land use change is the most decisive factor in the GHG emissions of palm oil energy chains. Hoefnagels et al. (2010) show that the GHG emissions directly associated with the production of biodiesel from palm oil quadruple if plantations are located on former peat lands and rainforests instead of on degraded land or logged-over forests. Based on these considerations it is reasonable to assume that indirect land use change will reduce the GHG emission savings of bio-based materials; the extent to which this will happen is, however, uncertain and subject of ongoing research. In general, the impacts of land use change can be reduced by:

(i) producing non-food biomass on degraded land that will need to be restored,

(ii) achieving yield and productivity increases in regions with lagging yield developments, such as Sub-Sahara Africa (Bruinsma 2009, Nellemann et al. 2009, Hubert et al. 2010),

(iii) more intensive use of farmland by planting so-called *agricultural intercrops* between main cropping periods, which serve energy or material purposes (Karpenstein-Machan 2001),

(iii) introducing comprehensive land use management guidelines,

(iv) establishing programs and policies of sustainable resource management, which also consider and limit the consumption of global resources, including global land use (Bringezu and Bleischwitz 2009).

Treatment of agricultural residues

Often, only parts of crops are used in the production of bio-based materials, leaving residues available for other purposes. The LCAs generally assume that residues either remain on the field as a substitute for mineral fertilizers (e.g., Würdinger et al. 2002) or are simply excluded from the product system (e.g., Corbiére-Nicollier et al. 2001). The environmental impacts of bio-based materials may, however, substantially decline if residues are used for materials or other useful purposes. Dornburg et al. (2004) identified reductions in the non-renewable energy use and GHG emissions of bio-based polymers of up to 190 GJ and 15 t CO_2 per hectare and year, respectively, if agricultural residues are used for energy. Similar effects can be expected if agricultural and forestry residues or biogenic wastes are utilized for the production of bio-based materials and second-generation biofuels in integrated biorefineries (Williams et al. 2009; Cherubini and Jungmeier 2010). Such integrated biorefineries present a promising technological solution to make use of the whole crop and subsequently reduce the environmental impacts associated with the production of bio-based materials, energy, and fuels.

Agricultural practices

The relatively high environmental impacts of bio-based materials in the categories of eutrophication and stratospheric ozone depletion (but also a substantial share of their non-energy use and GHG emissions) arise from biomass production with conventional industrial farming practices. Kim and Dale (2008) found that no-tillage farming and the cultivation of winter crops can decrease the environmental impacts of corn production by up to 70%. Würdinger et al. (2002) have demonstrated that extensive farming practices, which differs from conventional farming in that they apply no synthetic pesticides and nitrogen fertilizers, substantially reduce the eutrophication, acidification, and stratospheric ozone depletion potential of bio-based starch-based loose-fill packaging materials. In particular, the product-related N_2O emissions can be decreased by 95% if wheat for the production of loose-fills is extensively grown (Figure 3; Würdinger et al. 2002).

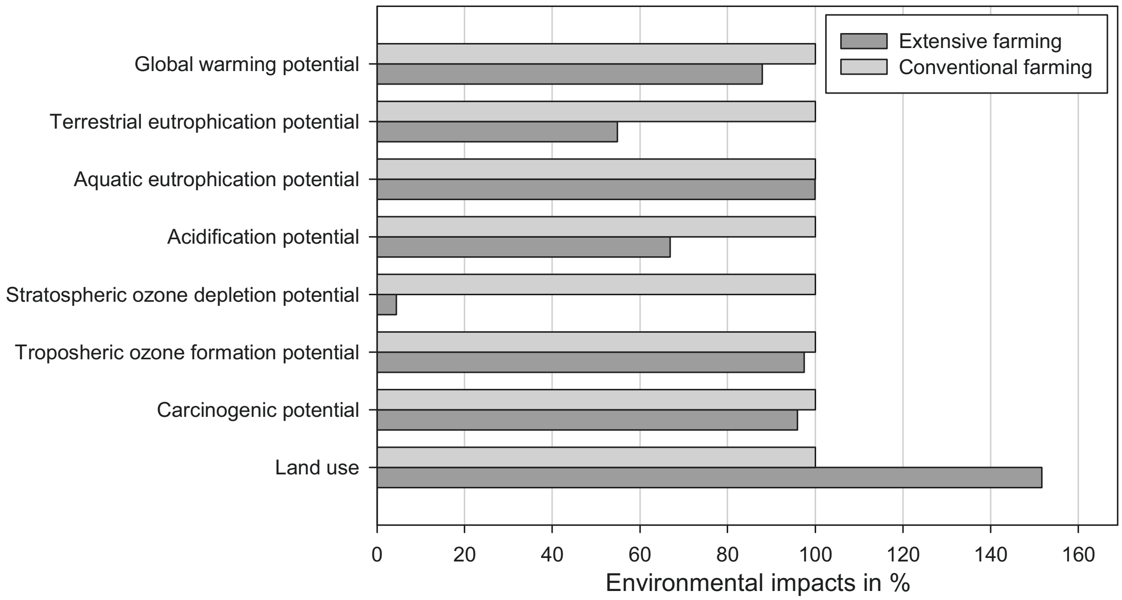

Figure 3: The relative environmental impacts of a defined volume of loose-fill packaging materials produced from conventional and extensively grown wheat-starch (Data source: Würdinger et al. 2002)

Since the restriction of ozone-depleting substances under the Montreal Protocol (UNEP 2000), fertilizer induced N_2O emissions have been constituting the single most important driver of stratospheric ozone depletion on a global scale (Ravishankara et al. 2009). Nitrous oxide is furthermore a potent greenhouse gas that might not always be accounted for appropriately in the assessment of GHG emissions from farming (Bringezu et al. 2009). Smeets et al. (2009) suggest that N_2O emissions might contribute 10-80% to the total GHG emissions of biofuels, depending on crop type, climate conditions, and reference land use scenario. Results for biofuels indicate that altogether 3-5% of the provided nitrogen might be converted to N_2O (Crutzen et al. 2007). Although contested (see, e.g., Ogle et al. 2008, Smeets et al. 2009), this finding suggests that the commonly used average emission factor of 1% (IPCC 2006) may substantially underestimate the actual N_2O emissions. Optimized farming practices and crop management, which includes avoiding stagnant anaerobic soil conditions, have to be adopted to substantially reduce N_2O emissions. However, as changes are generally constrained by prevailing economic and social factors, it remains doubtful as to whether substantial reductions in the environmental impacts of biomass production are achievable on a large scale. The findings of Würdinger et al. (2002) furthermore indicate that extensive farming practices may come at the cost of decreasing yields and thus higher land requirements for biomass production. The expansion of extensive farming might thus increase the environmental impacts of direct and indirect land use change. This complexity requires a thorough evaluation of bio-based materials on regional, national, and global scales.

Treatment of temporary carbon storage

When assessing the GHG emissions of bio-based materials, there are three ways of addressing bio-based carbon:

(i) ignoring it by considering bio-based carbon as neutral because it has been withdrawn from the atmosphere and will be returned to the atmosphere within a limited period of time; this approach implies that any allocation issue that may arise is implicitly treated through the relative carbon content of co-products (Guinée et al. 2009);

(ii) considering it by regarding bio-based carbon to be neutral but, as opposed to the previous option, allocation of bio-based carbon can be treated consistently with the allocation of other environmental burdens,

(iii) crediting it by considering bio-based carbon to be sequestered in bio-based materials; this approach is more relevant for consequential LCAs, where the consideration of reference land uses is critical (Brandão and Levasseur, 2011).

Crediting additional carbon storage implies that both the uptake of carbon from the atmosphere (that is temporarily contained in bio-based materials), as well as its release during use or waste treatment, must be accounted for as positive or negative GHG emissions. This approach regards the time period in which the carbon is stored outside of the atmosphere as beneficial for the climate due to the temporarily foregone radiative forcing. As a consequence, it may lead to systematically lower

GHG emissions for a cradle-to-factory gate analysis than for a cradle-to-grave analysis.

End-of-life waste treatment

Covering the end-of-live waste treatment phase allows for analyzing the impacts of a variety of waste treatment scenarios that may be associated with a wide range of GHG emissions. By including the end-of-life waste treatment, an LCA can, in particular, investigate whether biodegradability is indeed an environmentally favorable property of bio-based materials (Würdinger et al. 2002, Groot and Borén 2010, Hermann et al. 2010b). Hermann et al. (2010b) show for polylactic acid that the product-specific GHG emissions might vary by approximately 20% depending on whether or not energy is recovered during waste incineration. In the LCA study of loose-fills, Würdinger et al. (2002) suggest that the differences in GHG emissions between various waste treatment scenarios are similar to the differences between bio-based and fossil-based loose-fill packaging materials. These findings call for a detailed assessment of all major waste management options including landfilling, composting, waste-to-energy facilities, municipal waste incineration, digestion, and recycling (Edelmann and Schleiss 2001, Amlinger et al. 2008). Carbon cascading by using biomass first for material purposes and then recovering energy through incineration at the end of the product life cycle can maximize the GHG emission savings of bio-based materials (Dornburg et al. 2009; Oertel 2007, Bringezu et al. 2009). However, recent LCA studies have shown that composting can be more attractive than incineration (thus carbon cascading) if compost is used to replenish carbon stocks in agricultural soils (Hermann et al. 2010b, Khoo and Tan 2010). The results of LCA studies remain ambiguous and suggest that the GHG emission savings achievable for bio-based materials via carbon cascading, i.e., incineration with energy recovery and biodegradation, i.e., composting are case specific.

5 Conclusions and outlook

The findings of this meta-analysis allow us to draw the following conclusions:

- Bio-based materials save non-renewable energy resources, thus enable the manufacturing industry to substitute renewable resources for part of its fossil-based or mineral-based feedstock.
- Bio-based materials generally exert lower environmental impacts than their conventional counterparts in the categories of climate change (if GHG emissions from indirect land use change are neglected).
- Bio-based materials may generally exert higher environmental impacts than their conventional counterparts in the categories of eutrophication and stratospheric ozone depletion; the results are inconclusive with regard to acidification and photochemical ozone formation.
- Normalizing our results based on worldwide average inhabitant-equivalent values suggests that bio-based materials may contribute more substantially to non-renewable energy savings than they might decrease or increase impacts in the other environmental impact categories covered here.
- The environmental impacts of bio-based materials span a large range. This finding is partially attributable to the diversity of plausible methodological choices and assumptions and asks for caution when interpreting the outcome of this meta-analysis.
- Our analysis only quantifies part of the environmental impacts of bio-based materials. More comprehensive quantitative analyses should address, in particular, land use-related impacts (such as effects on biodiversity and soil organic matter, soil erosion) as well as the risks related to eco-toxicity and the use of genetically modified crops and microorganisms.
- Biomass cultivation with conventional farming practices, characterized by the application of mineral fertilizers, is the key contributor to the high eutrophication and stratospheric ozone depletion potentials of bio-based materials. These impacts can be reduced by improving fertilizer management and employing extensive farming practices. It should, however, be

considered that agricultural extensification, e.g., by decreasing the application of agrochemicals may result in lower crop yields, thus increasing land requirements for biomass production.

- The GHG emission savings identified here are subject to uncertainties because the reviewed LCA studies (i) may only insufficiently account for N_2O emissions from biomass cultivation and (ii) exclude the effects of indirect land use change. Depending on product scenarios and time horizons, especially the latter factor may lower substantially the established GHG emission savings. Further research in warranted.

The entire life cycle of bio-based materials offers potentials for decreasing environmental impacts. Most critical might be the reduction of land use and its impacts on GHG emissions, eutrophication, and stratospheric ozone depletion. Three strategies could be pursued: (i) expanding the feedstock base by utilizing organic waste as well as forest and agricultural residues, (ii) deploying integrated biorefineries that allow a more complete use of the biomass, including lignocellulosic non-food crops and residues for producing bio-based materials, energy, fuels, and heat, and (iii) carbon cascading by using biomass first for material purposes and at the end of their life cycle for energy. In developing countries, increasing yields and optimizing agricultural production are of paramount importance. Existing potentials could be realized by applying innovative investment solutions (Herrero et al. 2010) that may also generate positive spill-over effects on food production. Together these measures may contribute to mitigate both land use pressure on natural habitats and competition for land between food, feed, as well as biomass for other purposes. A comprehensive accounting of global land use for both food and non-food biomass consumption would allow assessing the overall effect on direct and indirect land use change as a basis for policy adjustments (Bringezu et al. 2012).

To date, bio-based materials are produced largely by small-scale pilot plants. Progress in biotechnology, technological learning, up-scaling of production facilities, and process integration will likely reduce both the environmental impacts and the costs of bio-based materials (Vink et al. 2010, Hermann et al., 2010a). To quantify existing possibilities, LCA results can be combined with assessments of the technical and economic potential of bio-based materials (e.g., Saygın et al. 2010). The extent to which bio-based materials can reduce industrial non-renewable energy use and GHG emissions will crucially depend on their market diffusion. In spite of current growth rates, bio-based materials will require at least a decade to reach substantial market shares, even at high fossil fuel prices (Shen et al. 2009b; Saygın and Patel 2010). In any case, the impact of bio-based materials on the economy-wide non-renewable energy use and GHG emissions will remain limited because non-energy use for synthetic materials production accounts for only 6% of the global fossil fuel supply. The vast majority of fossil fuels is thus consumed for energy elsewhere in the economy (IEA 2009).

This meta-analysis has highlighted the environmental potentials and challenges of bio-materials. Addressing these challenges may indeed enable bio-based materials to substantially decrease the environmental impacts resulting from the production, use, and disposal of industrially manufactured materials.

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Appendix

Table A1: Overview of LCA studies and environmental impact categories; impacts are reported per metric ton of bio-based material [t^{-1}] and per hectare of agricultural land and year [$(ha*a)^{-1}$] used to produce bio-based feedstock; system boundaries refer to cradle-to-factory gate (C-FG) or cradle-to-grave (C-G)

Reference	Product group	System boundary	Number of product scenarios	NREU		Climate change		Eutrophication		Acidification		Stratospheric ozone depletion		Photochemical ozone formation	
				t^{-1}	$(ha*a)^{-1}$	t^{-1}	$(ha*a)^{-1}$	t^{-1}	$(ha*a)^{-1}$	t^{-1}	$(ha*a)^{-1}$	t^{-1}	$(ha*a)^{-1}$	t^{-1}	$(ha*a)^{-1}$
Shen and Patel (2010)[g]	Textiles	C-FG	5	x	x[o]	x	x[o]	x	-	x	-	-	-	x	-
Althaus et al. (2007)[g]	Textiles	C-FG	4	x	x[o]	x	x[o]	-	-	-	-	-	-	-	-
Vink et al. (2007)[g]	Textiles	C-FG	1	x	x[o]	x	x[o]	-	-	-	-	-	-	-	-
Patel et al. (2006)[g]	Textiles	C-FG	1	x	x[o]	x	x[o]	-	-	-	-	-	-	-	-
Turunen and van der Werf (2006)[g]	Textiles	C-FG	4	x	x[o]	x	x[o]	x	-	x	-	-	-	-	-
Groot and Borén (2010)	Plastics	C-FG	1	x[a]	-	x[a]	-	x[a]	-	x[a]	-	-	-	x[a]	-
Hermann et al. (2010b)	Plastics	C-FG	42	x[q]	-	x[q]	-	-	-	-	-	-	-	-	-
Khoo et al. (2010)	Plastics	C-FG	1	-	-	x	-	-	-	-	-	-	-	-	-
Vink et al. (2010)	Plastics	C-FG	1	x[a]	-	x[a]	-	-	-	-	-	-	-	-	-
Madival et al. (2009)	Plastics	C-G	2	x	-	x	-	x[p]	-	x[p]	-	-	-	x	-
Kim and Dale (2008)	Plastics	C-FG	1	x[a]	-	x[a]	-	-	-	-	-	-	-	-	-
Macedo et al. (2008); Reis Neto (2007)[i]	Plastics	C-FG	1	x[a]	x[o]	x[a]	x[o]	-	-	-	-	-	-	-	-
Vidal et al. (2007)	Plastics	C-FG	1	x	x[o]	x	x[o]	x	-	x	-	-	-	-	-
Vink et al. (2007)[g]	Plastics	C-FG	1	x	x[o]	x	x[o]	-	-	-	-	-	-	-	-
Harding et al. (2007)[j]	Plastics	C-FG	3[b]	x	x[o]	x	x[o]	x	-	x	-	-	-	x	-
Patel et al. (2006)	Plastics	C-FG	3	x	x	x	x	-	-	-	-	-	-	-	-
Kim and Dale (2005)[i]	Plastics	C-FG	2	x	x[o]	x	x[o]	-	-	-	-	-	-	-	-
Akiyama et. al. (2003)[i]	Plastics	C-FG	2	x	x[o]	x	x[o]	-	-	-	-	-	-	-	-
Müller-Sämann et al. (2002)	Plastics	C-G	2	-	x	-	x	-	x	-	x	-	x	-	-
Würdinger et al. (2002)	Plastics	C-G	4[b]	x	x[o]	x	x[o]	x	x[e]	x	x[e]	x	x[f]	x	x[f]
Estermann et al. (2000)[h]	Plastics	C-G[c]	1	x	x[o]	x	x[o]	-	-	-	-	-	-	-	-
Dinkel et al. (1996)	Plastics	C-G[c,d]	4[b]	x	x[o]	x	x[o]	-	x[e]	-	x[e]	-	x[e]	-	x[e]
Reinhardt et al. (2007)	Surfactants	C-FG	2	-	x	-	x	-	-	-	-	-	-	-	-

Patel et al. (1999)	Surfactants	C-G[d]	9	x	x[o]	x	x[o]	-	-	-	-	-	-	-	-
Müller-Sämann et al. (2002)	Insulation materials	C-G	2	-	x	-	x	-	x	-	x	-	x	-	-
Miller et al. (2007)	Hybraulic oils and lubricants	C-G	1	x	x	x	x	-	-	-	-	-	-	-	-
McManus et al. (2004)	Hybraulic oils and lubricants	C-FG	1	x	x	x	x	x	-	x	-	-	-	x	-
Müller-Sämann et al. (2002)	Hybraulic oils and lubricants	C-G	4	-	x	-	x	-	x	-	x	-	x	-	-
Reinhardt et al. (2001)	Hybraulic oils and lubricants	C-G	3	x	x	x	x	x	-	x	-	x	-	-	-
Patel et al. (1999)	Hybraulic oils and lubricants	C-FG	1	x	x[k]	x	x[k]		-	-	-	-	-	-	-
Wightman et al. (1999)	Hybraulic oils and lubricants	C-G	1	-	-	x	x	-	-	-	-	-	-	-	-
Havinga (2003); EA (2001)[a]	Rubber	C-FG	1	x	x[o]	x	x[o]	-	-	-	-	-	-	-	-
Le Duigou et al. (2011)	Composites	C-FG	2	x	-	x	-	-	-	-	-	-	-	-	-
Vidal et al. (2009)	Composites	C-FG	3[b]	x	x[o]	x	x[o]	x	-	x	-	-	-	-	-
Zah et al. (2007)	Composites	C-FG	1	-	-	x	x[l]	x	-	x	-	-	-	x	-
Pervaiz and Sain (2003)	Composites	C-G	1	x	x[o]	x	x[o]	-	-	-	-	-	-	-	-
Müller-Sämann et al. (2002)	Composites	C-G	2	-	x	-	X	-	x	-	x	-	x	-	-
Corbière-Nicollier et al. (2001)	Composites	C-G	1	x	x[o]	x	x[o]	x	x[e]	x	x[e]	-	-	x	x[f]
Pless (2001)	Composites	C-FG	2	x	x[o]	x	x[o]	-	-	-	-	-	-	-	-
Flake et al. (2000)	Composites	C-FG	1	x	x[o]	-	-	-	-	-	-	-	-	-	-
Diener and Siehler (1999)	Composites	C-FG	1	x	x[m]	-	x[f]	x	x[e]	x	x[e]	-	-	-	-
Woetzel et al. (1999)	Composites	C-FG	1	x	x[o]	x	x[o]	x	x[e]	x	x[e]	x[a]	x[f]	x	x[f]
Tufvesson and Börjesson (2008)	Lacquer, paint, and waxes	C-FG	1	x	x	x	X	x	-	x	-	-	-	x	-
Bartmann et al. (2000)	Lacquer, paint, and waxes	C-FG	1	x	x[a]	x	x[o]	-	-	x	-	x	-	-	-
Albrecht et al. (2008); Egger (2008)	Floor boarding	C-G	2	x[a]	x[o]	x[a]	x[o]	-	-	-	-	-	-	-	-
Nebel et al. (2006); Egger (2008)	Floor boarding	C-G	12[m]	x[a]	x[o]	x[a]	x[o]	x[a]	-	x[a]	-	-	-	x[a]	-
Sharai-Rad and Welling (2002)	Floor boarding	C-G	2[n]	x[a]	x[o]	x[a]	x[o]	x[a]	-	x[a]	-	-	-	x[a]	-

- excluded from this review

[a] own calculations based on information provided in the respective LCA study

[b] only one product scenario considered in the impact categories NREU and climate change

[c] C-FG for the impact category NREU

[d] covering manufacturing and disposal only

[e] as recalculated by Weiss and Patel (2007)

[f] as recalculated by Weiss (2003)
[g] data source for conventional materials: Boustead (2005c)
[h] data source for conventional materials: Boustead (2005b)
[i] data source for conventional materials: Boustead (2005a)
[j] data source for conventional materials: Boustead (2005d)
[k] own calculations based on a combination of information provided by Patel et al. (1999) and Reinhardt et al. (2001)
[l] own calculations based on miscellaneous data sources
[m] number of considered scenarios varies between impact categories
[n] only one scenario considered in the impact categories of NREU and climate change
[o] as recalculated by Haufe (2010)
[p] only considering aquatic eutrophication and acidification
[q] calculated based on data communicated by the authors of the LCA study for various wrapping materials

Table A2: Arithmetic mean and median of the environmental impacts of the nine groups of bio-based materials as compared to conventional product alternatives; uncertainty ranges represent the standard deviation of the data sample; the totals represents the arithmetic mean and the median of values identified for the nine groups of materials

	Non-renewable energy use in GJ				Climate Change in t CO_2-equivalents			
	t^{-1} (mean)	t^{-1} (median)	$(ha*a)^{-1}$ (mean)	$(ha*a)^{-1}$ (median)	t^{-1} (mean)	t^{-1} (median)	$(ha*a)^{-1}$ (mean)	$(ha*a)^{-1}$ (median)
Textiles	-50 ± 29	-60	-101 ± 86	-91	-2 ± 2	-2	-5 ± 4	-3
Plastics	-37 ± 25	-37	-184 ± 203	-108	-0.5 ± 6	-1	-8 ± 10	-6
Surfactants	-40 ± 10	-40	-296 ± 204	-141	-3 ± 1	-3	-19 ± 13	-12
Insulation materials	-	-	-71 ± 17	-71	-	-	-6 ± 1	-6
Hydraulic oils and lubricants	-40 ± 6	-39	-51 ± 14	-51	-2 ± 1	-2	-3 ± 1	-3
Rubber	-71	-71	-37	-37	-2	-2	-1	-1
Composites	-54 ± 42	-37	-137 ± 116	-102	-2 ± 2	-2	-7 ± 10	-4
Lacquer and paints	-130 ± 81	-130	-153 ± 150	-153	-6 ± 4	-6	-7 ± 5	-8
Floor boarding	-18 ± 21	-14	-115 ± 79	-92	-4 ± 1	-3	-12 ± 7	-10
Total	*-55* ± 34	*-39*	*-127* ± 79	*-92*	*-3 ± 1*	-2	*-8 ± 5*	*-6*

- not quantified

Table A2 (cont.):

	Eutrophication in kg PO_4-equivalents				Acidification in kg SO_2-equivalents			
	t^{-1} (mean)	t^{-1} (median)	$(ha*a)^{-1}$ (mean)	$(ha*a)^{-1}$ (median)	t^{-1} (mean)	t^{-1} (median)	$(ha*a)^{-1}$ (mean)	$(ha*a)^{-1}$ (median)
Textiles	17 ± 17	21	-	-	30 ± 31	24	-	-
Plastics	1 ± 2	0	22 ± 21	19	6 ± 15	4	-37 ± 53	-37
Surfactants	-	-	-	-	-	-	-	-
Insulation materials	-	-	1	1	-	-	2	2
Hydraulic oils and lubricants	2 ± 1	2	1 ± 2	1	7 ± 5	9	4 ± 0.1	4
Rubber	-	-	-	-	-	-	-	-
Composites	0 ± 2	-1	-2 ± 8	-3	-12 ± 7	-15	-127 ± 213	-25
Lacquer and paints	8	8	-	-	-25 ± 50	-25	-	-
Floor boarding	0 ± 2	0	-	-	-17 ± 45	3	-	-
Total	*5 ± 7*	*1*	*6 ± 11*	*10*	*-2 ± 20*	*4*	*-39± 61*	*-4*

- not quantified

Table A2 (cont.):

	Stratospheric ozone depletion in kg N_2O-equivalents				Photochemical ozone formation in kg ethane-equivalents			
	t^{-1} (mean)	t^{-1} (median)	$(ha*a)^{-1}$ (mean)	$(ha*a)^{-1}$ (median)	t^{-1} (mean)	t^{-1} (median)	$(ha*a)^{-1}$ (mean)	$(ha*a)^{-1}$ (median)
Textiles	-	-	-	-	-0.2 ± 0.6	-0.4	-	-
Plastics	0.4 ± 0.4	0.4	3.3 ± 1.8	3.3	-3.2 ± 5.9	-0.9	-49 ± 28	-41
Surfactants	-	-	-	-	-	-	-	-
Insulation materials	-	-	1.0	1.0	-	-	-	-
Hydraulic oils and lubricants	4.2 ± 0.01	4.2	4.1 ± 1.9	4.1	0.5	0.5	-	-
Rubber	-	-	-		-	-	-	-
Composites	0.6	0.6	1.7 ± 0.5	1.7	-1.9 ± 1.5	-2.5	-76 ± 95	-76
Lacquer and paints	2.4	2.4	1.9	1.9	-0.9	-0.9	-	-
Floor boarding	-	-	-	-	3.7 ± 21.9	9.4	-	-
Total	*1.9 ± 1.8*	*1.5*	*2.4 ± 1.3*	*1.9*	*-0.3 ± 2.4*	*-0.6*	*-62 ± 20*	*-58*

- not quantified

Table A3: Non-renewable primary energy use and GHG emissions of bio-based chemicals in comparison to conventional product alternatives (Primary data source: Patel et al. 2006)

	Number of product scenarios (bio-based, fossil-based)	NREU in GJ/t	Climate change in t CO_2-equivalents/t
Ethanol	14,2	-55 ± 25	-3 ± 1
1,5 Pentandiol	27,3	-57 ± 41	-3 ± 2
Allyl butyl ether	18,1	-65 ± 30	-4 ± 2
Acetic acid	18,1	7 ± 37	0 ± 2
Acrylic acid	3,1	-30 ± 13	-2 ± 1
Succinic acid	18,2	-51 ± 37	-5 ± 2
Adipic acid	9,1	-19 ± 62	-2 ± 3
Caprolactam	3,1	-99 ± 25	-7 ± 1
Polyhydroxyalkanoates	36,1	-19 ± 41	0 ± 3
Ethylene	6,1	-66 ± 31	-4 ± 2
Ethyl lactate	15,5	-35 ± 28	-2 ± 2
Polylactic acid	21,3	-44 ± 19	-2 ± 2
Polytrimethylene terephthalate	27,5	-23 ± 17	-1 ± 1

Endnote

[i] The total global production of bulk materials reached approximately 6,500 Mt in 2009. This figure comprises the production of cement, iron and steel, bricks, glass, polymers and other petrochemicals, lubricants, bitumen, aluminum, textiles, wood, and paper (own estimates based on Deimling et al. 2007, Lasserre 2008, OGS 2007, UN 2008, Saygın and Patel 2010, IAI 2010)).