LCA of vegetarian burger packed in biobased polybutylene succinate

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ABSTRACT

Packaging preserves food quality and safety, but can determine a relevant part of the environmental impact associated with food consumption. A vegetarian burger has been selected as case study to evaluate, through LCA, the environmental performance of a food product packed with novel biobased polybutylene succinate (PBS), in comparison with traditional fossil based packaging (mainly polypropylene). The use of PBS instead of conventional plastics in primary packaging would still increase the environmental impact of the vegetarian burger. These results should, however, be considered in perspective: biobased PBS is in an early stage of development, and far from full industrial scale. Moreover, some first results from conservation and shelf life studies indicate that PBS packaging could extend the shelf life of some food products and thus presumably contribute to a reduction of food waste and associated environmental impacts.

Keywords: LCA, biobased PBS, bioplastics, shelf life, vegetarian burger

1. Introduction

Packaging plays a fundamental role in the food industry, allowing to preserve food quality and safety (Williams and Wikström, 2011). On the other hand, packaging production and disposal, in some cases, can determine a relevant share of the environmental impact associated with food consumption, and contributes to generation of waste and depletion of non renewable resources (Marsh and Bugusu, 2007). Many companies and organizations are currently developing and testing different kinds of bioplastics, in order to provide a more environmental friendly solution for packaging (Davis and Song, 2006). The SUCCIPACK project, promoted by the EU through the 7th framework programme, aims to support European industry efforts to introduce biobased polybutylene succinate (PBS) in the food packaging market (www.succipack.eu).

PBS is a semi-crystalline polyester bioplastic with 35-40% crystallinity, melting temperature of 114-115°C, glass transition temperature of -32°C, and similar properties to PET (Song et al., 2011). PBS is synthesized through polycondensation of succinic acid and 1,4-butanediol (BDO) (Rudnik, 2010) and its building blocks can be fossil based or biobased. Most of the PBS currently available on the market are fossil based or only partially biobased (Storz and Vorlop, 2013). Regarding its barrier properties, PBS is more similar to PLA than to polyolefins and can be considered as a middle oxygen barrier, and a middle/poor water barrier. Introducing PBS as a new biobased material in food packaging requires various innovations, such as optimization of its thermomechanical and gas barrier properties. In this context, the SUCCIPACK project aims at formulating entirely biobased PBS that can be flexibly applied in the food packaging sector, developing a bioplastic that is both biobased and biodegradable.

Using biomass resources as raw materials does not automatically guarantee a better environmental performance than fossil resources (Miller et al., 2007), due to, for example, environmental impacts of the agricultural phase or high energy consumption for processing, especially for new developed materials produced in small scale facilities. For this reason, life cycle assessment is applied to assess biobased PBS and PBS packaging solutions in a cradle to grave perspective, in order to avoid environmental trade-offs and contribute to the development of the bioplastic, providing ecodesign feedback through screening LCAs. LCA has allowed to identify the most critical aspects in the synthesis of biobased PBS, and to identify possible improvement options, some of which have been already implemented in the production process.

The focus of the SUCCIPACK project, along with the development of the material, is the introduction of new packaging solutions in the food packaging market; screening LCAs of existing food products have been conducted, in order to evaluate the environmental performance of new packaging solutions in comparison with existing traditional packaging. The study presented here reports the LCA results obtained for a vegetarian organic burger and its packaging; this case study is the first one selected for a more in dept evaluation of the environmental performance of the potential application of PBS packaging materials in the food sector.

2. Methods

2.1. Goal and scope, functional unit and product description

The goal of this study is to quantify the environmental impacts associated with one package of vegetarian burger, comparing its traditional fossil based packaging (baseline solution) with biobased PBS packaging (biobased solution). The attributional modeling approach has been adopted, since the main objectives of the analysis are identification of environmental hotspots and optimization of the product (ecodesign). PBS can be considered a niche product, and therefore is not expected to bring major changes in the market.

The functional unit is 1 package of vegetarian organic burger including its primary (tray, sealing film and cardboard sleeve), secondary (cardboard box) and tertiary (pallet and plastic film) packaging.

One unit of vegetarian burger contains 180 g of food product; its ingredients, in descending order of quantity are: seitan, spinach, potato, onion, sunflower oil, wheat flour, potato flakes and formulation for vegetable broth. Primary packaging is composed by a plastic tray sealed with plastic film and wrapped in a color printed white-lined chipboard sleeve. Secondary packaging is a corrugated (single wall) printed cardboard box and contains three units of primary packaging. Tertiary packaging is composed by a europallet wrapped in polyethylene film; each pallet carries 1584 units of primary packaging. The composition and weight of packaging for the two scenarios (baseline and biobased) are reported in Table 1. In the baseline solution the tray is thermoformed while in the biobased solution the tray is produced through injection molding.

Table 1. Packaging composition for one package of vegetarian burger

Packaging element		**Baseline solution**		**Biobased solution**	
		Material	**Weight (g)** [a]	**Material**	**Weight (g)** [a]
Primary	Tray	PP-EVOH-PP	15.2	80% biobased PBS + 20% talc	22.6
	Sealing film	PET-LDPE-EVOH-LDPE	1.7	Biobased PBS	2.1
	Cardboard sleeve	Coated white lined chipboard	17.5	Coated white lined chipboard	17.5
Secondary	Cardboard box	Corrugated board, single wall	17.0	Corrugated board, single wall	17.0
Tertiary	Europallet	Wood	15.8	Wood	15.8
	Film	LDPE	0.3	LDPE	0.3
Total			67.5		75.3

[a] Weight of each packaging element per functional unit.

The weights of biobased PBS packaging elements (tray and film) are calculated supposing that the volume of material employed is the same as in traditional packaging; the total weight is therefore higher for PBS packaging elements, due to a higher density of the materials.

Biobased PBS is synthesized from glucose in three main steps:

1. Fermentation of glucose to succinic acid
2. Hydrogenation of succinic acid to BDO
3. Polymerization (in molten and solid state) of succinic acid and BDO to PBS

PBS production process has been optimized taking into account technical and LCA feedbacks; further improvement of the technology is still possible, since data refer to the pilot scale. The technology currently implemented involves succinic acid production through yeast fermentation; during fermentation, succinic acid is neutralized with a ammonia and recovered through exchange over ionic resins. Sulfuric acid is used for the regeneration of the ion exchange column and ammonium sulfate is produced as co-product. Biobased BDO derives from succinic acid through catalytic hydrogenation and, finally, polymerization of succinic acid and BDO delivers biobased PBS. High molecular weight PBS is needed for most packaging applications; both melt and solid state polymerization are being applied, along with compounding of the material with additives (e.g. talc, PLA, PBSA, etc.), in order to obtain high molecular weight PBS and PBS grades suitable for target applications.

2.2. System boundaries

Vegetarian burger is produced in Italy, while packaging materials are supposed to be produced in Europe; the Italian and UCTE electricity mixes have been used accordingly. The burger has been supposed to be distributed within Italy, therefore packaging disposal reflects the Italian scenario (ISPRA, 2012). Primary data refer to 2011 and 2012.

System boundaries include production of food ingredients and packaging, raw materials, related transports, manufacturing process of food, distribution to retailers and end of life of packaging. Use phase (retail, storage and cooking) and disposal of food waste are excluded from the analysis. Furthermore, the role of packaging in preserving food quality and safety and its influence on food spoilage and loss have been, for the moment, excluded from the analysis, due to lack of data from specific conservation tests. Infrastructures have been excluded as well, except in case of database processes already containing infrastructures. A synthetic overview of system boundaries is reported in Figure 1.

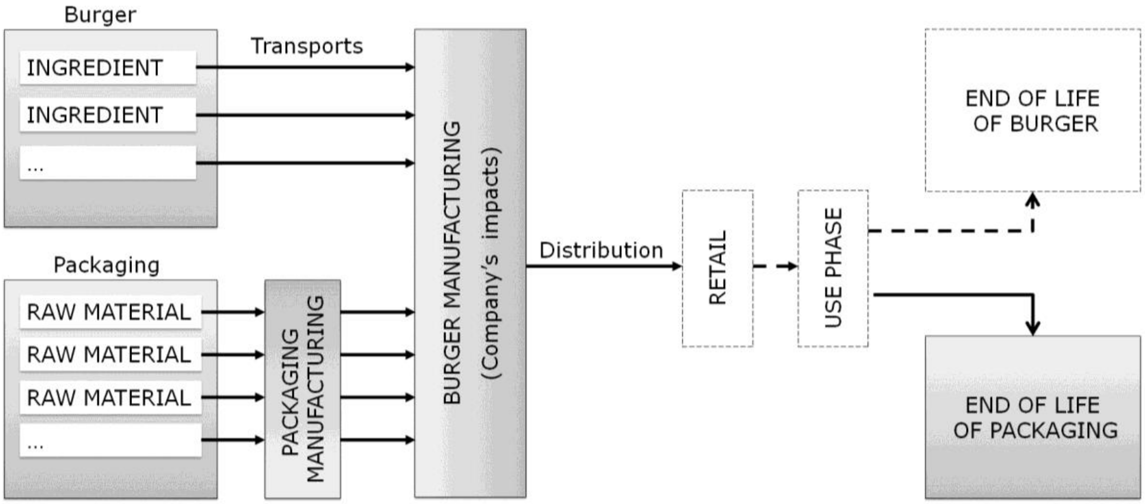

Figure 1.System boundaries. Solid lines: processes included in the system boundaries, dotted lines: processes excluded from the system boundaries.

Concerning biobased PBS granulate, inputs and outputs included in the system boundaries for each processing step are reported in Figure 2. In order to guarantee transparency, atmospheric CO_2 stored in biobased materials has been assessed neutrally, thus no CO_2 credits have been assigned to biobased PBS.

Outputs subject to recycling in the end of life phase (post-consumer), PBS not available for further processing and starch produced during burger's manufacturing, are addressed according to the cut-off approach. Therefore, the environmental impacts of the recycling process are excluded from the system boundaries. Other substances (e.g. water, H_2, N_2) are supposed to be recycled within the PBS granulate manufacturing process.

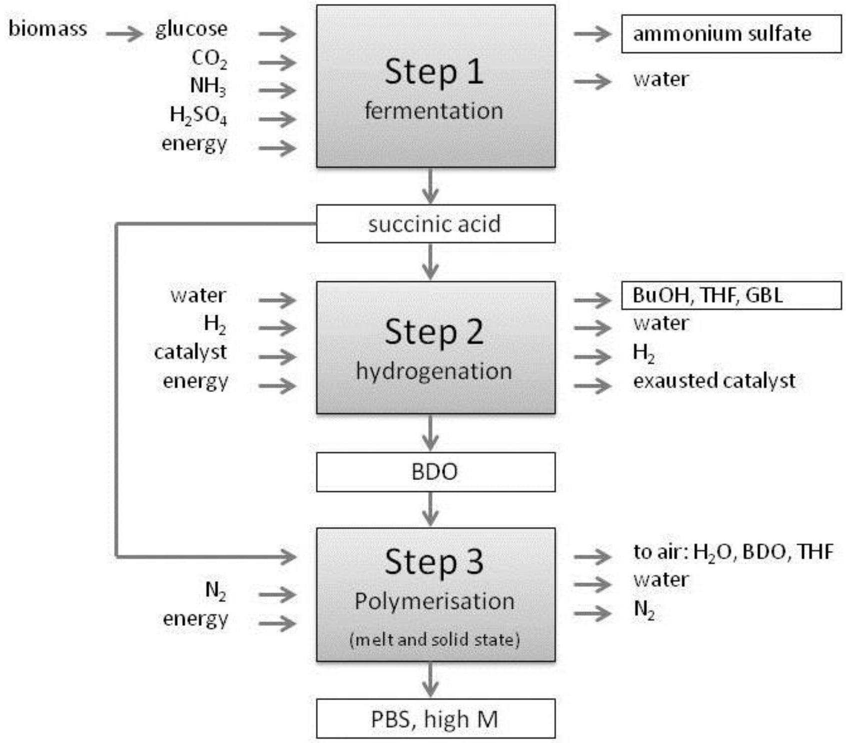

Figure 2. System boundaries: inputs and outputs for biobased PBS production; white boxes: products and co-products

2.3. Data sources and key assumptions

Data on vegetarian burger manufacturing and traditional packaging composition and weight have been provided by the burger's manufacturing company. The main focus of the study is biobased PBS, therefore, while foreground data have been collected from biobased PBS manufacturer, database processes have been used for traditional packaging materials. For the agricultural phase of both food and packaging and for glucose production (from sugar beet), database or literature data have been used (for vegetables: Stoessel et al., 2012). Database processes have been also used for packaging manufacturing (e.g. thermoforming, injection molding, etc.). All database processes derive from the ecoinvent v2.2 database (ecoinvent Centre, 2010). Data not available as foreground data or database information have been approximated; the main assumptions adopted in this study are reported below.

Concerning vegetarian organic burger's ingredients, data referring to organic agriculture have been preferred, while data on Integrated Production (IP) have been used when data on organic farming were not available. LCI data for the production of wheat, potato and sunflower derive from the ecoinvent v2.2 database, while data on vegetables (i.e. spinach, onion) derive from Stoessel et al. (2012). An additional energy consumption has been calculated for frozen ingredients and refrigerated transports, based on Masanet et al. (2008) and Stoessel et al. (2012). It has been assumed that no organic waste, except starch obtained from the manufacturing of seitan, is produced. A transport of 500 km has been assumed for burger distribution.

Data provided by biobased PBS manufacturer are mass balance of main inputs and outputs for the three steps and energy required for the production of succinic acid and melt polymerization. Missing material and energy inputs have been approximated in different ways. Mass of hydrogen and nitrogen required has been calculated based on patent EP 0881203 (Pedersen et al., 2001) and the application of the ideal gas law. Energy required for the hydrogenation step has been supposed to be the same as in the ecoinvent v2.2 process "cyclohexanol, at plant" while cooling energy employed during the polymerization step refers to PET polymerization, as reported by Van Uytvanck et al. (2014). Energy used for solid state polymerization (SSP) refers to an industrial equipment used for the SSP of PET.

In the end of life phase, direct CO_2 and CH_4 emissions deriving from the degradation of plastic materials have been assumed to be of fossil origin for conventional packaging and biogenic for biobased PBS packaging. Waste treatment processes for PBS (e.g. landfilling and incineration) have been created using an ecoinvent tool for the calculation of specific waste datasets (Doka, 2007). According to the carbon neutrality approach, biogenic CO_2 emissions do not contribute to global warming potential.

2.4. Allocation

The recovery of succinic acid from fermentation broth delivers ammonium sulfate as co-product, while the hydrogenation of succinic acid to BDO produces small amounts of n-butanol (4.6% w/w), gamma-butyrolactone (1.6% w/w) and tetrahydofuran (0.3% w/w). In case of BDO, allocation of environmental impacts among co-product has been based on physical relationship (mass), whereas for succinic acid and ammonium sulfate, due to the relatively great amount of ammonium sulfate produced (0.56 kg of ammonium sulfate for each kg of succinic acid), and the remarkable difference in price between the two substances, economic allocation has been applied, assigning 98.6 % of the environmental burden to succinic acid and 1.4% to ammonium sulfate.

For vegetable burger production, being impossible to retrieve data for specific production lines (various food products are produced in the same facility), total energy and water consumption, and waste production of the company (company's impacts) have been allocated to vegetable burger based on its economic value with respect to the overall turnover.

2.5. Life Cycle Impact assessment methods

The methods employed to carry out LCIA are CML baseline v3.01 (Guinée et al., 2002) integrated with the impact category "Land competition" (Guinée et al., 2002) and the method ReCiPe Endpoint H/A v1.10 (Goedkoop et al., 2012). Both methods comprise a set of indicators potentially useful when considering agricultural processes (e.g. euthrophication, human toxicity, ecotoxicity, land use) and allow the normalization of the results. It has been decided to apply one midpoint and one endpoint method, in order to gain a broader overview of the environmental impacts related to the product under study. ReCiPe endpoint, in particular, is applied because it provides a single score indicator, that gives an overall synthetic estimation of the environmental performance of the product. All calculations have been performed with the software SimaPro 8.0.3.

3. Results

The results obtained for the vegetarian burger for the baseline and biobased scenarios are reported in Table 2 and Figure 3 (method CML, characterization). Each impact category has been split into different aspects of the life cycle, in order to identify which processes give the most relevant contribution to the overall environmental impact. The parts of the life cycle selected are: burger ingredients, including transport to burger's production facility; company's impacts, allocated as previously explained; refrigerated distribution; packaging manufacturing, further subdivided into 1^{ry}, 2^{ry} and 3^{ry} packaging and, finally, packaging disposal.

Table 2. Impact assessment of one package of vegetable burger, for 180 grams of food including its packaging. Method CML, characterization.

Impact category	Unit	Biobased solution	Baseline solution
Abiotic depletion	mg Sb eq	0.829	0.676
Abiotic depletion (fossil fuels)	MJ	10.3	8.73
Global warming (GWP100a)	kg CO_2 eq	0.794	0.672
Ozone layer depletion (ODP)	mg CFC-11 eq	0.094	0.061
Human toxicity	kg 1,4-DB eq	0.172	0.111
Fresh water aquatic ecotox.	kg 1,4-DB eq	0.171	0.124
Marine aquatic ecotoxicity	kg 1,4-DB eq	402	262
Terrestrial ecotoxicity	g 1,4-DB eq	1.49	1.22
Photochemical oxidation	g C_2H_4 eq	0.131	0.105
Acidification	g SO_2 eq	5.93	5.24
Eutrophication	g PO^{3-}eq	4.58	4.02
Land competition	m^2a	0.591	0.561

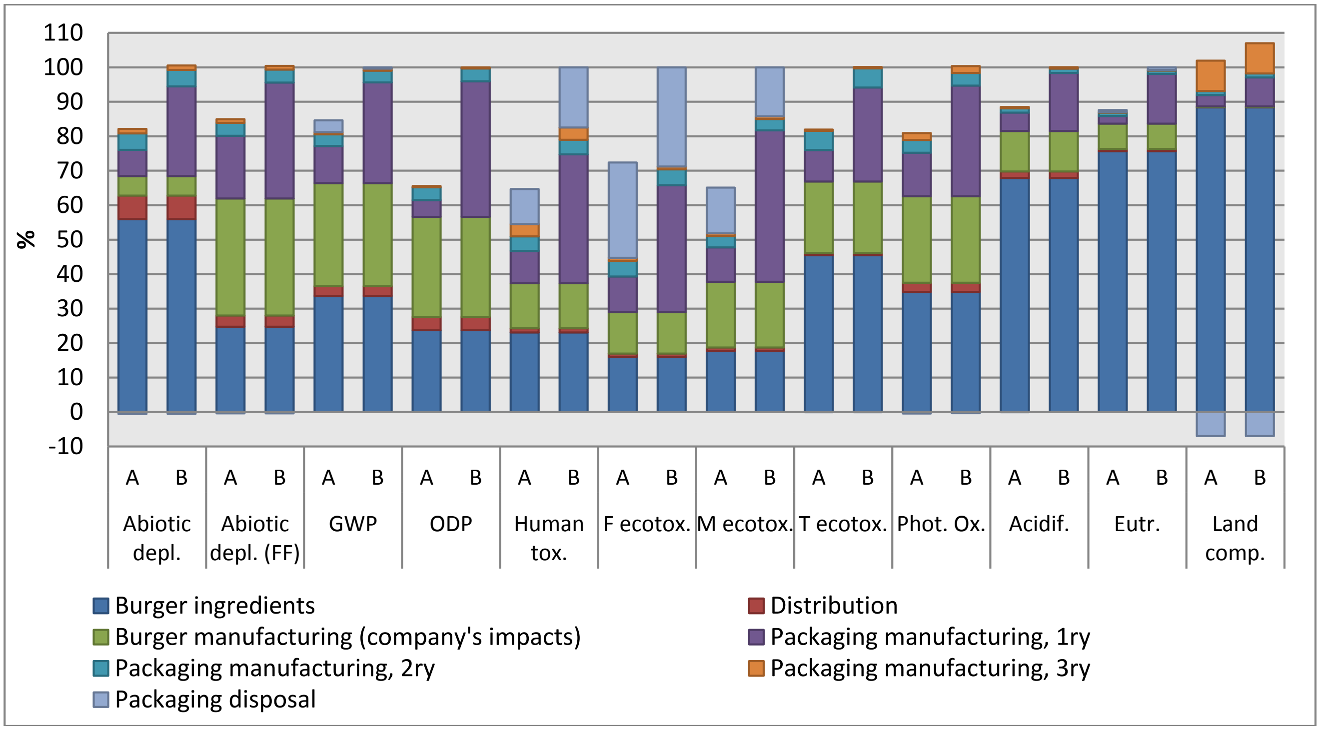

Figure 3. Impact assessment of vegetable burger. A = baseline scenario; B = biobased scenario; method CML, characterization. (FF= Fossil Fuels; ODP = Ozone Layer Depletion; F = Freshwater; M = Marine; T = Terrestrial).

Alternative B (biobased scenario) has higher impacts than alternative A (baseline scenario) for all impact categories considered. The difference between the two scenarios is among 5 % (land competition) and 35 % (human toxicity and marine ecotoxicity). As can be expected, the impact categories that vary most are those with a high contribution of packaging, namely, ozone layer depletion, human toxicity, freshwater ecotoxicity, and marine ecotoxicity. These variations are mainly due to substances emitted in relation to the manufacturing of biobased PBS, for instance, ozone depletion is connected, in particular, to the production of heat, electricity, ammonia and glucose; human toxicity to electricity and liquid carbon dioxide; freshwater and marine ecotoxicity to electricity.

It should be noticed that, since the carbon neutrality approach has been adopted, the LCI model does not account for absorption of atmospheric CO_2 in biobased materials. According to the stoichiometry of the monomer, the CO_2 embedded in biobased PBS is around 2 kg/kg of PBS. Therefore, for each package of spinach burger, approximately 40 g of CO_2 are absorbed from the atmosphere and embedded in biobased plastics (cradle to gate). Some of the carbon absorbed is released in the end of life of packaging; according to the assumptions and waste scenario adopted, biobased packaging disposal releases around 23,1 g of biogenic CO_2 and 16 mg of biogenic CH_4, with a net carbon sequestration of approximately 16.5 g CO_2 per package.

The contribution of food (including distribution) to each impact category varies among 29% (freshwater ecotoxicity, biobased scenario) and 95% (eutrophication, baseline scenario). Concerning the food product, the phases of the life cycle with the highest contributions are burger's ingredients and company's impacts, while distribution is less relevant. Burger's ingredients are particularly important for the impact categories land competition, acidification, eutrophication and terrestrial ecotoxicity, mainly due to the agricultural phase of the life cycle; in case of abiotic depletion, transports give the most relevant contribution.

Concerning packaging, its manufacturing, and in particular the manufacturing of 1^{ry} packaging, has higher impacts than packaging disposal for most impact categories. The negative values in the graph (positive impacts) are due to the reuse of pallets.

The characterization results (not shown) obtained with the method ReCiPe endpoint H/A lead to similar considerations. The ReCiPe characterization results, normalized with respect to the European average, are reported in Figure 4. The impact categories with the highest values after normalization are fossil depletion (FD), agricultural land occupation (ALO), climate change (effects on human health CC/HH and on ecosystems CC/E) and particulate matter formation.

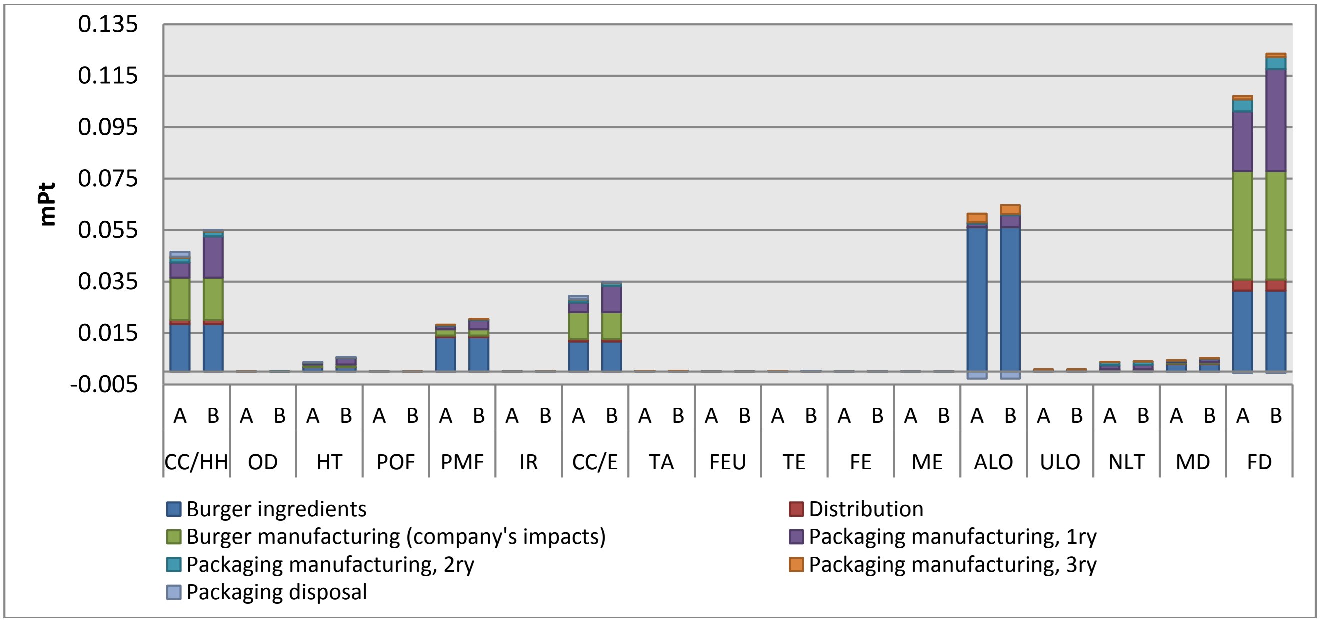

Figure 4. Impact assessment of vegetable burger. A = baseline scenario; B = biobased scenario; method ReCiPe endpoint H/A, normalization.

(CC/HH = Climate Change Human Health; CC/E = Climate Change Ecosystems; OD = Ozone Depletion; TA = Terrestrial Acidification; FEU = Freshwater eutrophication; HT = Human toxicity; POF = Photochemical oxidant formation; PMF = Particulate matter formation; TE = Terrestrial ecotoxicity; FE = Freshwater ecotoxicity; ME = Marine ecotoxicity; IR = Ionising radiation; ALO = Agricultural land occupation; ULO = Urban land occupation; NLT = Natural land transformation; MD = Metal depletion; FD = Fossil depletion).

The ReCiPe single scores values are reported in Figure 5. The biobased solution has a higher single score than the baseline solution (14%), consistently with the results previously outlined for the CML method. The food product (including distribution), has a contribution of 82% in the baseline scenario and 72% in the biobased scenario. For both scenarios, burger's ingredients give the largest contribution to the total score, followed by company's impacts and manufacturing of primary packaging. The impact categories that give the most relevant contributions to the single score indicator in the case of traditional packaging are agricultural land occupation (27%), fossil depletion (24.5%) and climate change (21.4% human health; 13.6% ecosystems), while for the biobased solution the most relevant impact category is agricultural land occupation (25%; mainly due to the agricultural phases of burger and packaging), followed by fossil depletion (24.9%) and climate change (22.2% human health; 14.1% ecosystems).

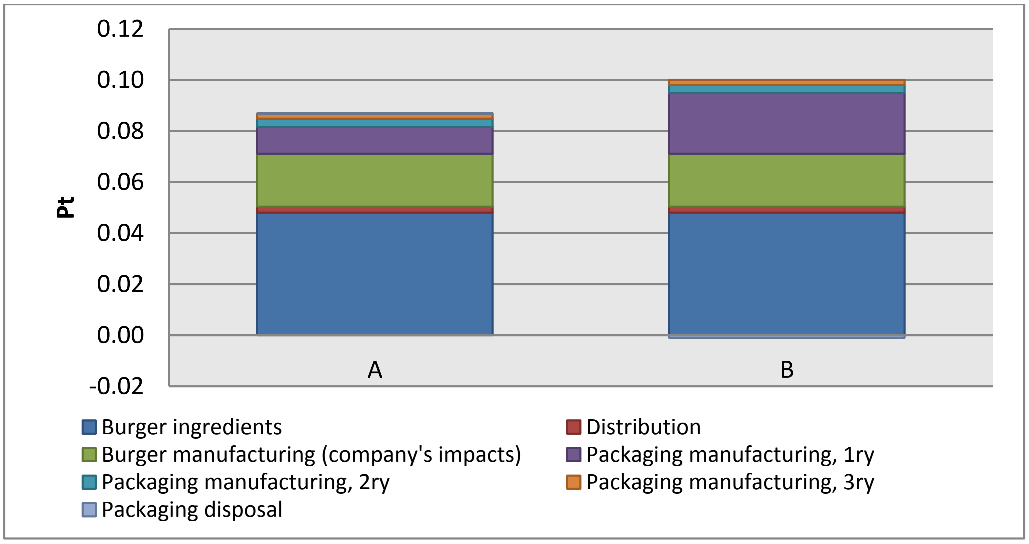

Figure 5. Impact assessment of vegetable burger. A = baseline scenario; B = biobased scenario; method ReCiPe endpoint H/A, single score.

4. Discussion

At the current scale of production (pilot scale) and state of development of the technology, the projected use of novel biobased PBS packaging in comparison to traditional fossil based packaging would increase the environmental impact of the packed vegetable burger. Currently, biobased PBS environmental impacts are higher than the ones of traditional packaging and according to the assumptions adopted a higher amount of biobased material is needed for the same amount of packed food. The environmental impacts of biobased PBS are mainly related to succinic acid production, since succinic acid is used to produce both BDO and biobased PBS. In particular, the technology currently applied for succinic acid synthesis through fermentation has a relatively high energy consumption (32 MJ/kg succinic acid). According to Cok et al. (2014), allocation of environmental burden among succinic acid and ammonium sulfate can be also relevant, economic allocation being the most conservative allocation choice, and therefore, the one with the highest overall environmental impact attributed to biobased PBS.

Another aspect that should not be underestimated in LCA, is the source of database information used; for instance, incomplete LCI (life cycle inventory) datasets could lead to lower environmental impacts than more complete datasets, due to lack of information and not to the actual environmental performance of the product (European Bioplastics, 2012). For example, the ecoinvent v2.2 record for polypropylene (PP is the main material in burger's traditional packaging), is based on inventory data from PlasticsEurope (Hischier R., 2007). These data are highly aggregated and not transparent, and this hampers the identification of possible inconsistencies between LCI and LCIA of PP and PBS.

Moreover, in the case study considered, the difference between the two packaging solutions is more evident than it would be in other applications, since the environmental impact of the vegetable burger (excluding packaging) is relatively low (i.e. GWP 2.9 kg CO_2 eq/kg) and, therefore, the packaging plays a more important role in determining the overall environmental impact.

Whereas traditional plastics are produced through well established and mature technology on industrial scale, entirely biobased PBS is in an early stage of development, and far from full industrial scale, and its environmental performance could improve moving from pilot scale to industrial scale. The main aspects to be considered in order to improve the environmental performance of biobased PBS are the energy required for the synthesis of succinic acid and the yield of the polymerization phase (e.g. reduction of the amount of PBS not available for further processing). In particular, concerning succinic acid production, alternative synthetic routes could be tested. For instance, in the analysis reported by Cok et al. (2014), succinic acid produced through low pH yeast-based fermentation followed by direct crystallization seems to have lower environmental impacts compared to the technology described in the present paper. Concerning polymerization, it seems that the application of a solid state polymerization phase in combination with melt oligomerization could reduce the environmental impact of biobased PBS in comparison to the application of melt polymerization. The applicability of this option is currently being evaluated in order to identify the most efficient solution.

Concerning the whole system (food product + packaging solution), the implementation of some improvement actions could reduce the overall environmental impact. The impact of primary packaging could be reduced by lowering its weight, especially in the case of biobased packaging. The cardboard sleeve, that is present for aesthetic reasons, could be eliminated and substituted, for instance, with a label, or its dimension could be reduced. Other aspects are the reduction of fossil energy employed by burger's manufacturing company and the use of fresh and local ingredients that would decrease the need for refrigerated long distance transports.

One of the main roles of packaging is to preserve food, reducing food spoilage and food waste. This aspect was not yet considered in the present study, but the effects of food loss on the overall environmental impact of the vegetarian burger will be the subject for further evaluations. In particular, some first results from conservation and shelf life studies indicate that PBS packaging could extend the shelf life of some food products and thus presumably contribute to a reduction of food waste and associated environmental impacts. LCA analyses of packaging solutions, therefore, should be focused not only on packaging reduction, but also on enhancing packaging's ability to preserve food and reduce food waste; in some cases, an increase of the environmental impact of packaging could be necessary in order to improve the overall environmental performance of the system, if food loss is included in the system boundaries (Williams and Wikström, 2011).

5. Conclusion

In this case study, LCA has been applied to an existing food product in order to evaluate its environmental impacts and to assess the potential outcomes of the introduction of new biobased PBS packaging materials in the food market. The application of LCA has allowed to identify the critical aspects and improvement options for the vegetarian burger and its packaging, and to provide ecodesign feedback for the development of biobased PBS.

At the current state of development of the technology, the use of biobased PBS instead of conventional fossil based plastics for primary packaging would increase the overall environmental impact of the food product under study. These results should, however, be considered in perspective: while traditional plastics are produced through well established and mature technology, biobased PBS is in an early stage of development, and far from full industrial scale. Moreover, the weight of analyzed PBS packaging is higher than the one of traditional packaging, due to higher density of PBS-based materials. In general, biobased PBS seems to be an interesting material for packaging applications but its environmental performance should be further improved. The increase of the environmental impact of packaging could be justified if this increase could result in a lower rate of food waste, reducing the overall environmental impact of the packaged food product.

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