2019

LIFE15 ENV/SE/000315

# LCA for Biodolomer®
# within EU LIFE15 ENV/SE/000315

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# Executive Summary

GAIA specializes in developing and adapting biomaterials based on fiber for applications in existing production facilities for plastic products. According to GAIA, fiber based biomaterials can replace up to 80% of volume plastics currently manufactured from traditional, fossil based raw materials.

The material Biodolomer® consists of a bio-based biodegradable ester that is mixed with fiber, calcium carbonate and vegetable oils. The material is manufactured and sold by GAIA, both in the form of granulates as well as in the form of products such as trays for meat and fish, aprons (for single-use purposes in the healthcare industry), waste bags and carrier bags.

On commission by the ongoing project "Biodolomer® For Life" (LIFE15 ENV/SE/000315), which is part of the European Commission LIFE program, Profu has performed a consequential LCA of the Biodolomer® material, both as a granulate and in the form of carrier bags. These products were also compared with other materials (for granulates: bio-based and fossil based polyethylene; for carrier bags: bags made out of bio-based and fossil based polyethylene respectively and paper bags) in order to draw conclusions on the strengths and areas of improvements for the Biodolomer® material from an environmental impact perspective.

In order to keep the scope of the LCA-study manageable, the three impact categories deemed most relevant were selected. These were:

- Global warming potential (GWP)
- Cumulative energy demand (CED) (both renewable and non-renewable) and
- Water consumption (WC)

The study has taken place during 2019. The time horizon of the impacts in this study was 100 years, and the temporal scope was 2019. The geographical scope differs with the different material (which is further explained in sections 2.3 and 3), since they are produced in different locations (including extraction and processing of various raw materials). For all materials, however, the use phase and end-of-life phase were set to occur in Sweden.

The project did budget for extensive data collection regarding the life cycle of the Biodolomer® material. For the comparisons with other material, however, less resources were available, which meant that we relied heavily on data available in the Ecoinvent database for inventories for the alternative materials. Data on energy and resource consumption for certain processes were gathered from literature sources (for more details on the data requirements and the data quality, see sections 2.7 and 2.8).

Figure 1 shows an overall summary of the results from the LCA of the Biodolomer® carrier bag and the comparison to the other bags studied.

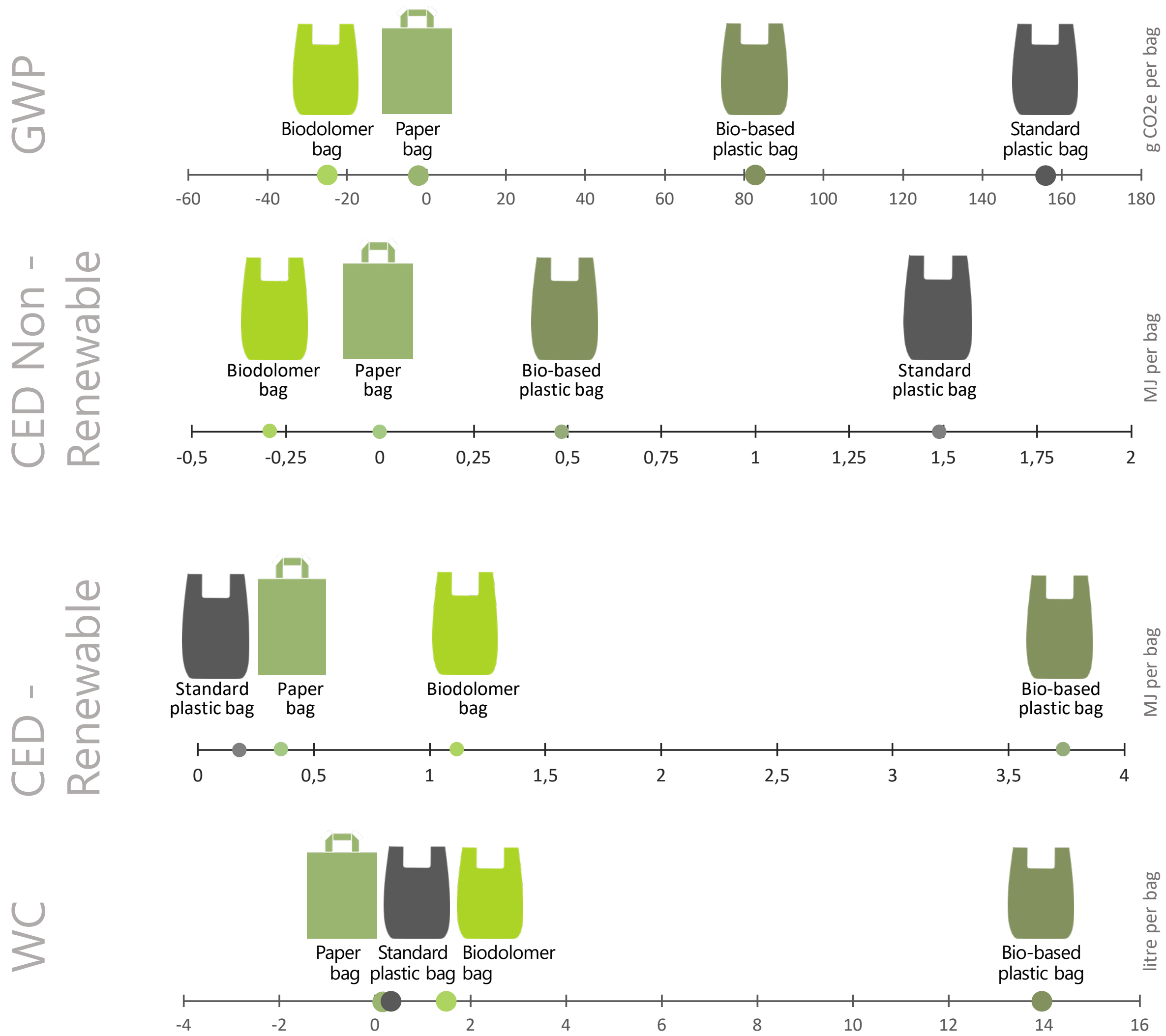


Figure 1 An overall summary of the results from the LCA of the Biodolomer carrier bag and the comparison to the other bags studied. GWP = Global Warming Potential, CED = Cumulative Energy Demand and WC = Water Consumption. When looking at the results, it should be noted that the project did budget for extensive data collection regarding the life cycle of the Biodolomer® material. For the comparisons with other materials, however, less resources were available, which meant that we relied heavily on data available in the Ecoinvent database for inventories for the other materials. The data quality is thus quite different and significantly higher for the Biodolomer life cycle than for the other materials.

This LCA study has shown that the Biodolomer® had the lowest impact in the impact categories GWP and non-renewable CED, both when studied in a cradle-to-gate perspective (as granulate, compared to bio PE and fossil PE alternatives) and in a cradle-to-grave perspective (in the form of a carrier bag, compared to bio PE, fossil PE and paper alternatives). In the categories renewable CED and WC, the fossil PE and paper alternatives performed slightly better.

The material production phase and secondary use phase were identified as those with the largest contribution to the overall life cycle impact of the Biodolomer® carrier bag. PLA and PBAT were the material components which contributed the most to the material production phase of Biodolomer® where PBAT had the largest impact per unit mass. Out of the likely secondary use activities identified, the reuse as carrier bag proved to have the most important impact by displacing other products, thus saving resources and reducing emissions.

The study has also shown that most of the environmental impacts studied potentially could be reduced for the Biodolomer® material by:

- Increasing the share of PLA over PBAT
- Increasing the biogenic share of PBAT
- Reducing electricity consumption, both for raw material production and for Biodolomer® production

Another option for improving the environmental performance of Biodolomer is to consider increasing the share of calcium carbonate. Increasing the calcium carbonate content in Biodolomer has several environmental advantages:

- It lowers all studied environmental impacts in the material production phase (since it is the raw material with the lowest GWP, CED (both Renewable and Non-renewable) and WC per kg material)

- It provides more “free” $CaCO_3$ to the waste-to-energy plants in the end-of-life stage, thus reducing the need for added limestone in the flue gas treatment.

- It lowers the energy content of the Biodolomer bag, thus reducing the displacement of imported waste at the Swedish waste-to-energy plants.

It must be stressed, however, that these measures are only acceptable if they do not risk the functionality of the product.

Because of the material properties of Biodolomer® and the fact that it is made up of mostly biogenic and inert materials, it is theoretically well suited for a number of different end-of-life disposal options, like material recycling, biological treatment (anaerobic digestion with bio-methane recovery) and energy recovery. The physical properties make the material easy to re-process. The mostly biogenic components mean that carbon dioxide emissions from combustion, either in a waste to energy plant or in cement kilns, can be considered to have a low global warming impact.

Sensitivity analyses of critical assumptions in the study, showed that the assumptions had significant impact on the results. However, those individual impacts would not have altered the main conclusions of the study.

# Contents





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# List of abbreviations

| | |
|---|---|
| LCA | Life cycle assessment |
| LCIA | Life cycle impact assessment |
| LCI | Life cycle inventory |
| GWP | Global Warming Potential |
| CED | Cumulative Energy Demand |
| WC | Water Consumption |
| $CaCO_3$ | Calcium carbonate |
| PP | Polypropylene |
| PE | Polyethylene |
| Bio PE | Polyethylene made of biomaterials |
| Fossil PE | Polyethylene made of crude oil |
| PLA | Polylactic acid |
| PBAT | Biodegradable aliphatic-aromatic copolyester |
| PBS | Polybutylene succinate |
| Biodolomer | Biodolomer® |

# 1 Introduction and objectives

This study was commissioned by the ongoing project "Biodolomer For Life" (LIFE15 ENV/SE/000315), which is part of the European Commission LIFE program to assess the life cycle environmental impacts of the production, use and disposal of the Biodolomer material, both as granulates and in the form of carrier bags. The study serves as a tool to evaluate strengths and areas of improvements for the Biodolomer material from an environmental impact perspective. This Section provides the background on the Biodolomer material and the aim of the study.

## 1.1 Background

GAIA specializes in developing and adapting biomaterials for applications in existing production facilities for plastic products. According to GAIA, biomaterials can replace up to 80% of volume plastics currently manufactured from traditional, fossil based raw materials.

The material Biodolomer consists of a bio-based polyester mixed with a mineral substance and vegetable oils. The material is manufactured and sold by GAIA, both in the form of granulates as well as in products such as aprons (for single-use purposes in the healthcare industry), waste bags and carrier bags.

This report presents an LCA study of Biodolomer within the framework of the reporting of the ongoing project "Biodolomer For Life", which is part of the European Commission LIFE program.

## 1.2 Aim of the study

The aim of this study is to evaluate the environmental performance of the Biodolomer material, both as a granulate and in the form of carrier bags. For this aim, the study assesses the environmental impacts associated with the raw material production, the material/bag production, use and end-of-life management options for a selected number of environmental impacts.

Furthermore, the environmental performance of the Biodolomer material is compared to other materials (for granulates: bio-based and fossil based polyethylene; for carrier bags: bags made out of bio-based and fossil based polyethylene respectively and paper bags) in order to draw conclusions on the strengths and areas of improvements for the Biodolomer material from an environmental impact perspective.

The environmental assessment of the granulate and the carrier bag alternatives is carried out with Life Cycle Assessment (LCA). LCA is a standardized methodology for quantifying environmental impacts of providing, using and disposing of a product or providing a service throughout its life cycle (ISO 2006a).

In an LCA, the potential environmental impacts associated with resources necessary to produce (both raw materials and the product itself), use and dispose the product are taken into account. When material and energy resources are recovered through reuse and waste management options (e.g. as material in a recycling process or as energy in the form of heat and electricity when incinerated), the system is credited with the avoided potential emissions that would have occurred in order to produce these resources from primary materials.

The LCA is mainly carried out with the SimaPro LCA software. SimaPro was developed by Pré Consultants and is one of the world's leading and most widely used LCA software tools. The goal definition of the LCA and the LCA methodology are provided in a section 2.

# 2 LCA Methodology

This LCA study was carried out in line with the requirements detailed in the International Standards 14040 and 14044 (ISO 2006a and ISO 2006b). This section provides a detailed description of the LCA methodology used for the study; the goal of the LCA, the functional unit chosen, the system boundaries drawn, the modelling tools used, data requirements, impact assessment methods used, assumptions made, and limitations identified.

The final receiver of this study is the ongoing project "Biodolomer For Life", which is part of the European Commission LIFE program. The study serves as tool to evaluate strengths and areas of improvement for the Biodolomer material in different phases of its life cycle from an environmental perspective.

It should be noted that even if the report could be disclosed to third parties, the report does not strictly comply with the standard. The reason for this lack of compliance is that the report has not undergone the necessary external peer review by a panel of experts throughout the development of the project as required by the ISO standard.

The project did budget for extensive data collection regarding the life cycle of the Biodolomer material. For the comparisons with other material, however, less resources were available, which meant that we relied heavily on data available in the Ecoinvent database for inventories for the alternative materials. Data on energy and resource consumption for certain processes were gathered from literature sources (for more details on the data requirements and the data quality, see sections 2.7 and 2.8).

## 2.1 LCA goal definition

The goal of this study was to provide the ongoing project "Biodolomer For Life" (LIFE15 ENV/SE/000315) with information about the potential life cycle environmental impacts associated with the material Biodolomer, both as granulate and in the form of a carrier bag.

The aim of this study was to evaluate the environmental performance of the Biodolomer material, both as a granulate and in the form of carrier bags. For this aim, the study assesses the environmental impacts associated with the raw material production, the material/bag production, use and end-of-life management options for a selected number of environmental impacts.

Furthermore, the environmental performance of the Biodolomer material is compared to other materials (for granulates: bio-based and fossil based polyethylene; for carrier bags: bags made out of bio-based and fossil based polyethylene respectively and paper bags) in order to draw conclusions on the strengths and areas of improvements for the Biodolomer material from an environmental perspective.

The target audience of the LCA is the partners of the ongoing project "Biodolomer For Life", which is part of the European Commission LIFE program.

## 2.2 Functional unit

In the process of an LCA, the functional unit definition ensures that the assessment of products/services is based on fulfilling the same function. A simple, yet well defined, functional unit makes comparing assessment results for different products or services more robust.

For the comparison of the granulate products, the assessment is limited to a cradle-to-gate-analysis. For this analysis, Biodolomer is compared with biobased and fossil-based PE based on the following functional unit:

**"1 kg produced granulate, ready to use for production of products such as carrier bags".**

For the comparison of the carrier bags, we use the following functional unit:

**"A bag to be used to carry home up to 12 kg groceries from Swedish supermarkets to households in 2019"**

Due to material properties, the weight of a product in paper or plastic is not the same. For the analysis, we have used the weights of bags as shown in Table 1. Data for plastic bags are assumed based on information from GAIA. Data for paper bags is estimated based on Bisinella et al (2018).

Table 1 Weight of bags to fulfil the functional unit

| Bag type | Weight to fulfil the functional unit (g/bag) |
|---|---|
| Biodolomer bag | 27,5 |
| Bio-based PE bag | 27,5 |
| Fossil based PE bag | 27,5 |
| Paper bag | 42,0 |

## 2.3 System boundaries

The time horizon of the impacts in this study was 100 years, and the temporal scope was 2019. The geographical scope differs with the different material (which is further explained below and in section 3), since they are produced in different locations (including extraction and processing of various raw materials). For all materials, however, the use phase and end-of-life phase are set to occur in Sweden.

The LCA for the granulates was performed as a "cradle-to-gate" LCA, which means an assessment of a partial product life cycle of Biodolomer from resource extraction (cradle) to the factory gate. Neither the transport to the customers nor use phase and end-of-life phase were included.

The LCA for the carrier bags was performed as a "cradle-to-grave" LCA, meaning that all life-cycle stages of the carrier bags (including the use phase and the end-of-life phase) were included.

Production of energy and material resources necessary to produce the carrier bags were included within the system boundaries. Necessary resources were e.g. production of electricity and heat, production of raw materials, production of the main carrier bag material (such as Biodolomer), chemicals and ancillary materials (e.g. ink).

In accordance with the project partners, the production of the carrier bags was set in different locations:

- **Biodolomer bags**: Production of raw materials in Thailand, Germany, Norway and Sweden. The raw materials were then transported to GAIA's plant in Helsingborg, where the granulates and carrier bags were produced. The bags were then transported by truck to supermarkets in Sweden, assuming an average distance of 500 km.

- **Fossil based PE bags:** Production is assumed to take place in Europe, using raw materials from the world market. The bags were then distributed to supermarkets in Sweden using the following route: by freight train from Germany to southern Sweden (2 000 km) and by truck to customers (500 km).

- **Bio-based PE bags:** Production of granulates is assumed to take place in Brazil, using raw materials extracted in Brazil (mainly sugarcane). The granulates were then assumed to be shipped for production of bags in Europe, with the same conditions as for fossil PE. The bags were then distributed to supermarkets in Sweden using the same route as the fossil PE bags.

- **Paper bags:** Production is assumed to take place in Europe, using raw materials from Europe. The bags were then distributed to supermarkets in Sweden using the same route as the fossil PE bags.

Production of transportation fuel was included in the assessment.

Furthermore, the assessment assumed zero emissions arising from the first use (as bag to carry home groceries). All bags were then to some extent reused to replace other products (this is further described in section 3), which avoided potential emissions that would have occurred in order to produce these products.

The LCA included the production of energy and material resources required to collect, treat and manage the carrier bag once it was collected by the Swedish waste management system. The assessment included both direct emissions occurring during the waste management phase and the impact of avoided processes (i.e. avoided production of primary materials when bags are recycled and energy substituted when residues from sorting facilities where used to replace coal in cement production). The waste management processes mainly occurred in Sweden (collection, transport, sorting facilities, energy recovery in waste to energy plants and cement ovens). Recycling and use of recycled material (to replace virgin material) were assumed to take place in Europe.

The LCA did not include capital goods (e.g. the construction of facilities and production of machineries).

## 2.4 Modelling approach and allocation of multi-functionality

There are two commonly used modelling approaches for LCA, **consequential LCA** and **attributional LCA**. This LCA study of Biodolomer (both granulates and carrier bags) was made using **a consequential LCA approach**. By using a consequential LCA approach, the study explores the actual consequences of introducing the Biodolomer bag on the market. All relevant consequences have to be included in order to show the full environmental impacts caused by the introduction. When the consequences are evaluated it is often necessary to use data on marginal suppliers and substitution of displaced activities.

The other approach, called attributional LCA, is often less time consuming to perform. Instead of tracing all consequences, the attributional LCA is made using different predefined standards. With this approach, it is common to use data for market average suppliers, and to partition them according to different allocation rules. The use of allocation rules restricts the system boundaries. Many of the consequences included in the study had a distinct impact on the final results, for example the marginal electricity production and the alternative secondary use of bags. It was thus clear that a consequential LCA was required to capture the full impact.

Multi-functionality in the model was addressed by system expansion. Co-products/services generated along the life cycle of each material were assumed to substitute products in the market that were likely to react to changes in demand/supply induced by the investigated scenarios. One example is the secondary use of the carrier bags as waste bags, which was assumed to displace fossil based waste bin bag production. Another example is the recovered material from recycling of bio-based and fossil based PE, which was assumed to displace virgin fossil based granulate production.

## 2.5 Modelling tools

The main modelling work and calculations for this study were carried out with the SimaPro LCA software. SimaPro was developed by Pré Consultants and is one of the world's leading and most widely used LCA software tools.

Minor complementary modelling and calculations were carried out in Microsoft Excel. Regarding the impact from increased energy use (especially electricity), we used input from our extensive energy systems models TIMES-Nordic (Profu 2019a) and EPOD (Profu 2019b). Regarding waste management of bags in Sweden (the end-of-life stage in the life cycle) and its implications, we used input from our extensive waste management systems model ORWARE (Profu 2019c).

## 2.6 LCIA methodology and impact categories

In order to keep the scope of the study more manageable, the three impact categories deemed most relevant were selected. These were:

- Global warming potential (GWP),
- Cumulative energy demand (CED) (both renewable and non-renewable) and
- Water consumption (WC)

Final results are presented as characterized impacts calculated using the characterization methods in the table below.

Table 2 Characterization (midpoint) references utilized in the project

| Impact category | Acronym | LCIA method | Unit |
|---|---|---|---|
| Global warming potential | GWP | IPCC 2013 GWP100 | kg CO2e |
| Cumulative energy demand | CED | Cumulative Energy Demand V1.11 | MJ |
| Water consumption | WC | ReCiPe 2016 Midpoint (H) V1.03 | m3 |

- IPCC 2013 GWP100
  This characterization method is based on the IPCC report "CLIMATE CHANGE 2013 The Physical Science Basis" (IPCC 2013). Based on the report, the characterization factors for fossil methane and nitrous oxide in a 100-year perspective have been set to 34 and 298 respectively.

- CED
  Method to calculate Cumulative Energy Demand, based on the method first published in Ecoinvent version 2.0 and expanded by PRé Consultants for raw materials available in the SimaPro 7 database. This version is based on higher heating values (HHV). This version (1.11) was published in November of 2018. The Cumulative Energy Demand of a product or service represents the direct and indirect energy use throughout the life cycle, including the energy consumed during the extraction and processing of raw materials, manufacturing, use and disposal/end-of-life.

- ReCiPe 2016 Midpoint (H)
  Since the environmental and socio-economic impacts of a given water consumption is highly dependent on the geographical location of the extraction, we decided to use the ReCiPe midpoint method which contains a simple aggregate of the water consumption and hence do not attempt to give an indication of water scarcity. The hierarchist version of the model was chosen as this is considered the most balanced version and the default.

## 2.7 Data requirements

In order to carry out the LCA of Biodolomer granulate, detailed information and data on the materials composition and the entire value chain of the Biodolomer product was required. Within the project ample information was collected about the production process and the raw materials. This consists of e.g. data on energy consumption at GAIAs production facilities, emissions to air and water from GAIAs production facilities, freight technologies used and distances from suppliers etc[1]. Through contact with GAIAs suppliers we were able to collect LCI datasets for many of the components used in Biodolomer. Where this was not possible, either because such datasets did not exist or the supplier was not able to share, we relied on specific information about the suppliers' production in combination scientific literature and datasets available in the Ecoinvent 3 database. In order to be consistent with the modelling approach of the study, we used the consequential version of the data sets in the database.

For the comparative part of the LCA, we required data on material and energy consumption for the manufacturing of the alternative carrier bags, as well as material needed for packaging and distribution. Data on waste management technologies for the end-of-life of the carrier bags were also needed. For this part of the study it was not possible to achieve the same level of detail and specificity with regards to data collection as for the Biodolomer granulate and for the Biodolomer bags. Here we relied heavily on data available in the Ecoinvent database for inventories for all materials. Data on energy and resource consumption for certain processes were gathered from literature sources.

For the consumption of electricity and its effect on emissions and resource use, Profu has access to data and models that we consider describe the environmental impact from a consequential perspective in a more accurate way and which is more up to date than the datasets available in the Ecoinvent database. We used our experience in energy systems analysis and data from modelling in TIMES-Nordic and EPOD (Profu 2019a and Profu 2019b) to construct our own datasets of marginal electricity production mixes for the relevant electricity grids (see Appendix A).

For the modelling of waste management, we used a combination of LCI datasets from the Ecoinvent database and our own knowledge of the specific conditions in Sweden (including our national waste

[1] Important transport routes, transport distances and mode of transport are shown in Appendix A.

management systems model ORWARE) to model the effects of various waste management scenarios from a consequential perspective.

## 2.8 Data quality assessment

Data quality can be measured by a number of parameters, some common data quality parameters used in an LCA context are:

- Reliability
  How reliable is the source of the data?
- Completeness
  The proportion of available data compared to the potential perfect coverage
- Consistency
  The degree to which the data is consistent with other sources covering the same activity
- Timeliness
  The degree to which data represents reality at the required point in time
- Spatial correlation
  How well the available data represents environmental- and societal conditions at the required location
- Technical correlation
  How well the available data matches the technical specifications of the studied process

In order to present our data quality assessment in a legible way, all sources were divided into five main types (ranking from highest to lowest quality according to the quality parameters described above):

1. Measured values
2. LCI datasets
3. Peer-reviewed literature
4. Unverified third-party source
5. Assumptions

Data used to model each life cycle phase for the materials/products was then categorized as one of the five source types and the share of each type was approximated. This overview of the data quality is presented in Table 3.

As was previously noted, the data quality is quite different and significantly higher for the Biodolomer life cycle in the cradle-to-gate perspective. This is to be expected as Biodolomer is the main subject of the study. In the material production phase, approximately half of the data is sourced from measured values and a large part from LCI datasets connecting to raw material extraction processes. For bag production, however, almost all of the data is based on specific measurements.

For the use- and end-of-life phases, a large part of the data has been categorized as assumptions. This reflects that there are general uncertainties regarding how carrier bags are used and then disposed of, after their first use in Sweden. The method put forward in this study to model these phases of the life cycle is innovative in the sense that we are trying to model the actual consequences, instead of simply assuming one type of secondary use/waste treatment for all bags. Therefore, it was not possible to rely on previous work to any larger extent.

Table 3 Overview of data quality assessment.

| Bag type | Source type | Material production | Bag production | Use phase | End of life |
|---|---|---|---|---|---|
| Biodolomer | Measured values | 50% | 90% | 0% | 5% |
| | LCI dataset | 30% | 5% | 40% | 50% |
| | Peer-reviewed literature source | 5% | 0% | 10% | 15% |
| | Unverified third-party source | 10% | 0% | 0% | 0% |
| | Assumptions | 5% | 5% | 50% | 30% |
| Bio-PE | Measured values | 0% | 0% | 0% | 5% |
| | LCI dataset | 70% | 25% | 40% | 50% |
| | Peer-reviewed literature source | 20% | 70% | 10% | 15% |
| | Unverified third-party source | 0% | 0% | 0% | 0% |
| | Assumptions | 10% | 5% | 50% | 30% |
| Fossil-PE | Measured values | 0% | 0% | 0% | 5% |
| | LCI dataset | 70% | 25% | 40% | 50% |
| | Peer-reviewed literature source | 20% | 70% | 10% | 15% |
| | Unverified third-party source | 0% | 0% | 0% | 0% |
| | Assumptions | 10% | 5% | 50% | 30% |
| Paper | Measured values | 0% | 0% | 0% | 5% |
| | LCI dataset | 90% | 25% | 40% | 50% |
| | Peer-reviewed literature source | 0% | 70% | 10% | 15% |
| | Unverified third-party source | 0% | 0% | 0% | 0% |
| | Assumptions | 10% | 5% | 50% | 30% |

### 2.8.1 Critical assumptions

Overall, this LCA study involved different assumptions. The assumptions listed below were evaluated as critical for the results.

- **Bio-based component of PBAT**
  PBAT is one of the components of Biodolomer. PBAT is a biodegradable copolymer, consisting of three different monomers. PBAT is commonly based on fossil raw materials but each of the monomers that make up PBAT could in theory be produced from bio-based materials. According to GAIA and their supplier, the PBAT product used in the production of Biodolomer is based on two fossil based monomers and one bio-based monomer. The substitution of a fossil based component with a bio-based alternative has certain obvious and direct implications for a product life cycle but there are also effects that cannot be discerned without deeper analysis. For example, the bio-based component will not release fossil $CO_2$ when combusted for energy recovery in a waste-to-energy plant.

  The supplier of PBAT to GAIA did not disclose to us which component of their PBAT product that is bio-based or any other detailed LCI data for the product. Lacking better data, we used general LCI datasets for the three monomer components (1,4 butanediol, adipic acid and terephthalate acid) of PBAT available in the Ecoinvent database to model the production of PBAT in SimaPro. After showing these results to the PBAT supplier, we then made some modifications to our model with guidance from the PBAT supplier. This resulted in the GWP impact being lowered by roughly 50 %. We were not able to get sufficient information to make modifications relating to the other impact categories CED and WC. This likely means that the balance of non-renewable and renewable energy demand is slightly skewed towards the non-renewable and that the water consumption is underestimated to some extent.

- Sequestration of biogenic carbon considered net neutral
  Carbon sequestration is the process by which carbon dioxide is captured from the atmosphere and stored long term, which mitigates the effects of global warming. Carbon sequestration occurs naturally through biological, chemical and physical processes. One common such process is photosynthesis, which absorbs atmospheric carbon dioxide and binds the carbon atoms in biomass. Materials produced from biomass therefore contains carbon that once was atmospheric carbon dioxide.

  When accounting for sequestration of biogenic carbon in bio-based materials, two principal approaches are commonly used:

  1. Biogenic carbon is accounted for as carbon storage, thus considering that $CO_2$ is captured from the atmosphere during through photosynthesis and retained within the bio-based material (this approach is common in cradle-to-gate LCAs)

  2. Biogenic carbon is considered to be $CO_2$ neutral and excluded from the inventory analysis at the end-of-life phase (common in cradle-to-grave LCAs). In this case, carbon sequestration cannot be included to prevent double counting.

  Because the scope of this study covers the entire life cycle, from cradle-to-grave, we found that the most relevant approach was to consider biogenic carbon to be $CO_2$ neutral. Consequently, no carbon sequestration effect is included for the biogenic materials, neither as granulates nor as carrier bags.

- Indirect land-use change effects were excluded
  Indirect land-use change (ILUC) occurs, for example, when there is a limited amount of suitable arable land available for a certain type of production. ILUC is a follow-on effect of some kind of direct land-use change (DLUC). For example, when a piece of land used to grow food crops is bought up and the new owner instead starts growing crops for production of textiles or biofuels (DLUC), the demand for food does not disappear, it remains. This will likely lead to someone else producing more food somewhere else, which can result in indirect land-use change (ILUC), like changing forest into agricultural land, a process which causes substantial amounts of carbon dioxide emissions to the atmosphere (European Commission, 2019).

  The topic of Land-use change and especially ILUC effects rose to prominence in the early 2000s with the increase in production of biofuels for road transport, and is an area which has been heavily debated within the scientific community regarding environmental assessments. Some studies have shown that ILUC effects are significant for GWP-results when studying bio-based products (Nguyen & Hermansen, 2012). An important aspect of land-use change is that only DLUC effects can be empirically observed and assessed. ILUC effects on the other hand can only be quantified through complex modelling which links together data on trade flows, agricultural production etc.  The issue with including ILUC effects is that there is still a lack of consensus on how they should be handled and that there are large uncertainties in the models available to quantify their impact.

Some of these critical assumptions were considered for sensitivity analysis, as shown in section 4.3.

## 2.9 Cut-offs

The LCA did not include capital goods (e.g. the construction of facilities and production of machineries). Neither was construction and decommissioning of infrastructure and buildings included.

## 2.10 Life Cycle Interpretation

The Life Cycle Interpretation part of this study includes the analysis of the results (provided as characterized impacts) and the discussion of the results. The analysis of the results was carried out both for the granulates and the carrier bags. The comparison of results was executed per impact category and no weighting was applied.

The results were then discussed considering the goal and scope of the study, as well considering the data quality. The discussion of the results was supported by sensitivity analyses.

## 2.11 Format of the report

The format of the report is:

- Short executive summary in English (3 pages);
- Technical LCA report.

# 3 Scenarios

## 3.1 Biodolomer and comparisons to other materials

In the study, the Biodolomer materials (granulates and bags) are evaluated from a life cycle perspective and compared to other alternative materials.

Figure 2 illustrate the life cycle for the Biodolomer material in the application as a carrier bag. The life cycle is divided in to four main steps:

- **Material production (including raw material production):** These steps include all the environmental impacts in a "cradle-to-gate" perspective. The product from these steps are the granulates, i.e. these steps give the result for the Biodolomer granulate in a "cradle-to-gate" perspective.

- **Bag production:** The granulates are heated and pressed into a thin film which is then printed with ink according to the customers' needs. The bag parts are then cut out of the film and the seams are heat-sealed together to create the final product. The bags are rolled up for transport. The production of carrier bags is carried out at GAIA's factory in Helsingborg.

- **Use of bag:** The Biodolomer bag is first used to carry home groceries, fulfilling the functional unit. Different scenarios are then used to describe the secondary use of the bag (reuse as a carrier bag one more time, reuse a waste bag for collecting residual waste for energy recovery and reuse for collecting waste for material recycling). These scenarios are further described in section 3.2.

- **End-of-life:** The distribution between different end-of-life options depends on the scenarios for the secondary use. There are, however, two final end-of-life options for the Biodolomer material:

    - <u>Incineration in a waste to energy plant in Sweden</u>: In all scenarios, the major part of the Biodolomer bag end up in Swedish waste to energy plants with a high level of energy recovery. As explained in section 3.2.1, however, the energy production from the waste to energy plants are unaffected and instead, the import of waste to Sweden is affected from a consequential perspective when the Biodolomer bag is sent to energy recovery.

    - <u>Combustion as fuel in cement kilns in Sweden:</u> In all scenarios, a minor fraction of the Biodolomer bags is collected for material recycling, and then separated as a reject at sorting plants[2]. This reject is sent to cement kilns, where is its assumed to replace coal.

The same phases are studied for the materials that are compared to the Biodolomer material (for granulates: bio-based and fossil based polyethylene; for carrier bags: bags made from bio-based and fossil based polyethylene respectively and paper bags). In the case of bags, the use phase and/or the

[2] Recycling of Biodolomer is also an option, which is further discussed in section 5.

end-of-life options differ for the other bags due to their material characteristics and the current setup of material recycling and energy recovery in Sweden.

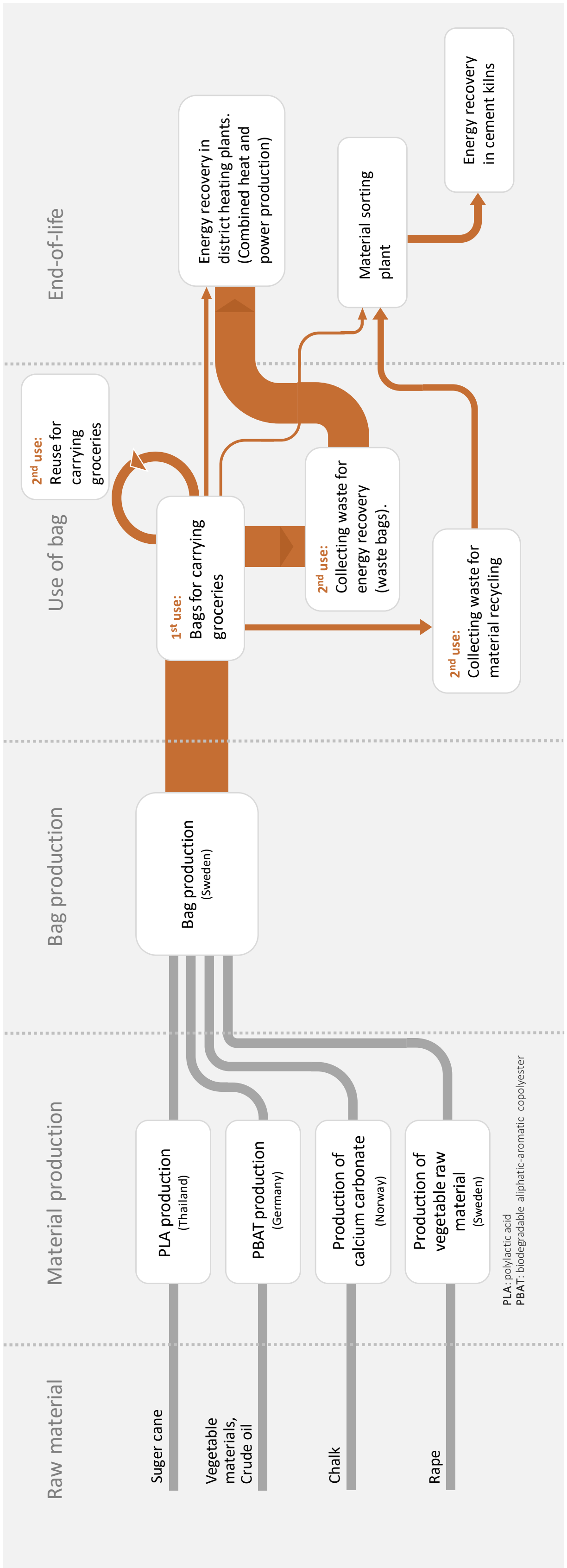


Figure 2 Life cycle for the Biodolomer material in the application as carrier bag

## 3.2 Scenarios for the use and end-of-life phases

For the use and end-of-life phases, there are general uncertainties in Sweden regarding how carrier bags are used and then disposed of, after their first use. The method put forward in this study to model these phases of the life cycle is innovative in the sense that we are trying to model the actual consequences, instead of simply assuming one type of secondary use/waste treatment for all bags.

Figure 3 illustrate the use and end-of-life phases for the Biodolomer bag. After its first use, the majority of the bags are reused as waste bags for collecting waste for energy recovery (displacing fossil based PE waste bags). A smaller fraction of the bags is reused for carrying groceries one more time (displacing fossil based PE carrier bags). An even smaller fraction is used to collect waste for material recycling (displacing 50 % fossil based PE waste bags and 50 % reusable fossil based PP bags). Small fractions of the Biodolomer bags are sent directly to energy recovery (i.e. thrown directly in the waste bin for residual waste) and material recycling (i.e. directly sorted as waste for recycling).

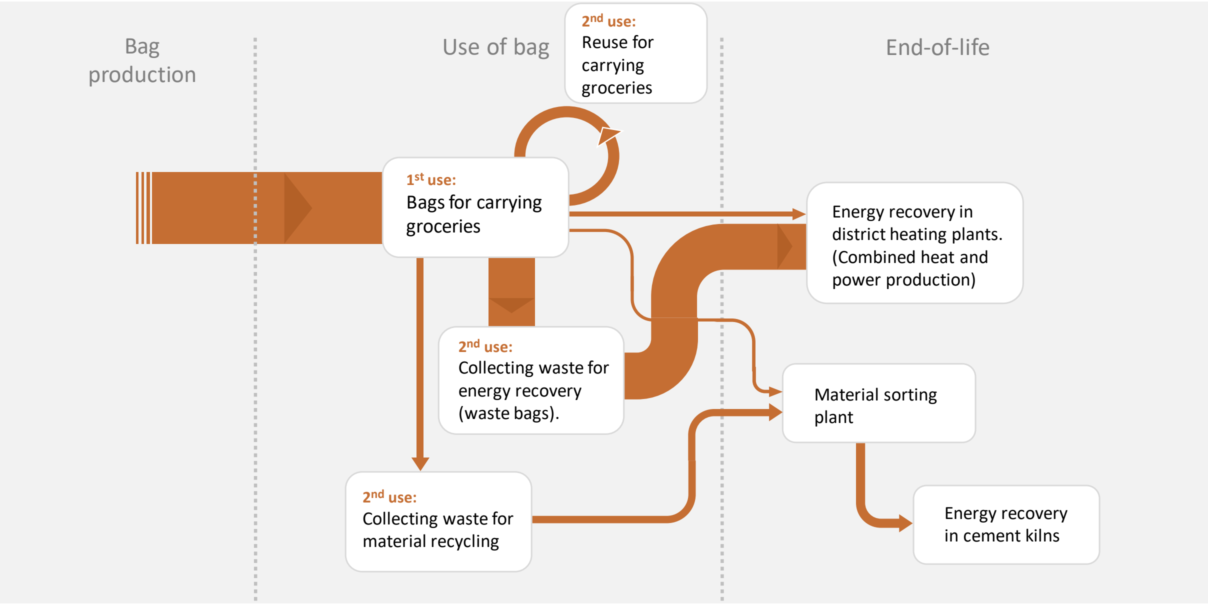


Figure 3 Illustration of the use and end-of-life phases for Biodolomer carrier bag

In the analysis, we have used "Low" and "High" scenarios regarding the environmental impacts from reuse and end-of-life for the carrier bags. The "Low" scenario reflects combinations of reuse activities with large displacing effects, while the "High" scenario includes a lesser degree of reuse and instead a larger share of bags sent directly to energy recovery and material recycling. These assumptions are assumed to be the same for the granulate based bags (Biodolomer bag, the bio-based PE bag and the fossil based PE bag, c.f. Table 4).

Table 4 Distribution of different options in the "Low" and "High" environmental impacts scenarios for reuse and end-of-life of Biodolomer, bio PE and fossil PE carrier bags

| Use of bag after 1st use | Description | Share in the Low Environmental Impact Scenario | Share in the High Environmental Impact Scenario |
|---|---|---|---|
| Reuse as carrier bag | The bags are reused as a carrier bags for groceries and thus replacing new fossil based PE carrier bags. | 25 % | 5 % |
| Reuse as bag for collecting materials for material recycling | The bags are reused for collecting materials (plastic, paper, metals etc.) for material recycling. The reused bags replace new fossil based PE waste bags (50 %) and reusable fossil based PP bags (50 %). The reused bags are thrown in the bin for plastic recycling after reuse. | 15 % | 5 % |
| Reuse as bag for residual waste | The bags are reused as bags for collecting residual waste and thus replacing new fossil based PE waste bags. The bags are thus sent for energy recovery together with the residual waste. | 55 % | 75 % |
| Sent directly to material recycling | The bags are thrown with plastic collected for material recycling. | 2 % | 5 % |
| Sent directly to energy recovery | The bags are thrown with residual waste collected for energy recovery. | 3 % | 10 % |

For the paper bag, the use and end-of-life phases are different and illustrated in Figure 4. The paper bag is not assumed to be reused as waste bag for collecting waste for energy recovery as it is not water resistant in the same way as the plastic bags and is therefore not well suited for the containment of a sometimes quite wet mixture of residual household waste. A higher share of the paper bags is instead assumed be used to collect waste for material recycling and consequently, a higher share is then assumed to be recycled (material recycling of paper and paper containers is an established and well-functioning market in Sweden). The "Low" and "High" scenarios for paper bags are shown in Table 5.

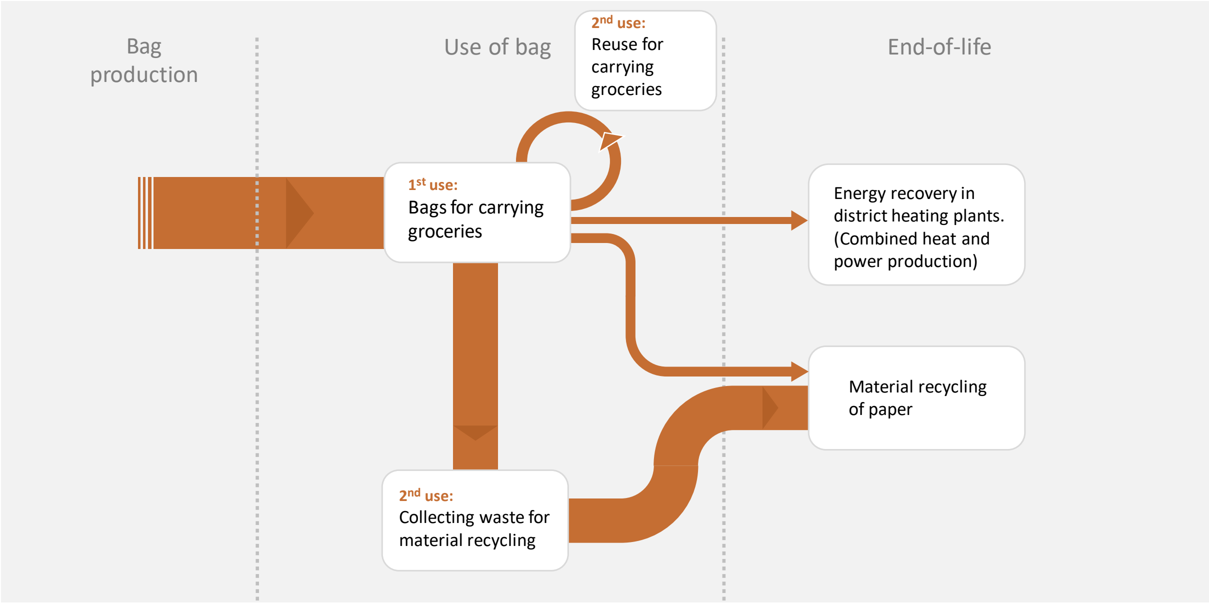


Figure 4 Illustration of the use and end-of-life phases for paper carrier bag

Table 5 Distribution of different options in the "Low" and "High" environmental impacts scenarios for reuse and end-of-life of paper carrier bags

| Use of bag after 1st use | Description | Share in the Low Environmental Impact Scenario | Share in the High Environmental Impact Scenario |
|---|---|---|---|
| Reuse as carrier bag | The bags are reused as a carrier bags for groceries and thus replacing new paper bags | 25 % | 5 % |
| Reuse as bag for collecting materials for material recycling | The bags are reused for collecting materials (plastic, paper, metals etc.) for material recycling. The reused bags replace new fossil based PE waste bags (50 %) and reusable fossil based PP bags (50 %). The reused bags are thrown in the bin for paper recycling after reuse. | 70 % | 55 % |
| Sent directly to material recycling | The bags are thrown with paper collected for material recycling | 3 % | 15 % |
| Sent directly to energy recovery | The bags are thrown with residual waste collected for energy recovery | 2 % | 25 % |

In the results (see section 4), we primarily use an average of the "Low" and "High" scenarios in Table 4 and Table 5. But we also illustrate the outcome with the "Low" and "High" scenarios.

### 3.2.1 End-of-life options

As described in Figure 3, the major part of the Biodolomer bag end up in Swedish waste to energy plants with a high level of energy recovery. Swedish waste to energy plants today import roughly 25 % of the waste incinerated (Profu 2019d). The marginal importing country is UK, where the export to Sweden is used as one method to decrease the amount of landfilling. The Swedish waste to energy plants are thermally limited, i.e. they are used to their maximum capacity based on the energy content of the waste (Profu 2018).

When more carrier bags (Biodolomer, bio PE, fossil PE or paper bags) are used in Sweden and eventually end up at waste to energy plants, the consequence is therefore that less other waste can be incinerated due to the thermal constraints. The displaced waste is the imported waste, currently coming from UK, which is consequently landfilled instead, leading to increased emissions from landfilling. The larger the energy content of the carrier bag (bio PE and fossil PE bags has much higher energy content than Biodolomer and paper bags), the larger this effect. The effects of reduced import and increased landfilling in UK (due to the displaced imports to energy recovery) is calculated with the ORWARE model (Profu 2019c).

Carrier bags that are collected for material recycling first end up at sorting plants. In these plants, the outcome for the Biodolomer bags differ compared to the other bags. The main part of Bio PE, fossil PE and paper bags are assumed to be separated and sent to recycling, thus replacing virgin production of PE and paper respectively. A minor part of these materials ends up in the reject fraction from the sorting plants, which is sent to cement kilns to displace the use of coal. For Biodolomer bags, however, the whole fraction sent to the sorting plants is assumed to end up in the reject fraction, and thus in the end assumed to displace the use of coal in cement kilns. The reason for this assumption is that the study reflects the current (2019) conditions where there currently are no pathways available to go from waste Biodolomer to a recycled material product. This issue lies mainly with the sorting facilities and value chains for recycled polymers.

# 4 Life Cycle Impact Assessment

## 4.1 Results for granulates

### 4.1.1 Biodolomer granulates

The first set of results presented are for the Biodolomer material in granulate form. Here the study covers the cradle-to-gate perspective, i.e. from extraction of raw materials to the finished product at the factory gate. The results are displayed in Table 6 below.

Table 6 LCIA results for Biodolomer granulate from cradle-to-gate. All impacts are calculated for the production of 1 kg granulate.

| Impact category | Value | Unit |
|---|---|---|
| GWP | 2,4 | kg $CO_2$e/kg |
| CED (Non-renewable) | 39,6 | MJ/kg |
| CED (Renewable) | 37,9 | MJ/kg |
| WC | 0,07 | $m^3$/kg |

For the GWP result, it is important to stress that we have not included any effect of biogenic uptake of $CO_2$ in these figures (as explained in section 2.8.1).

### 4.1.2 Biodolomer granulates in comparison to bio-based and fossil based polyethylene granulates

The second set of results are for the comparison of Biodolomer and two alternative products, also in the cradle-to-gate perspective. The paper alternative is excluded from this comparison as the product kraft paper is not considered comparable in function to the other products.

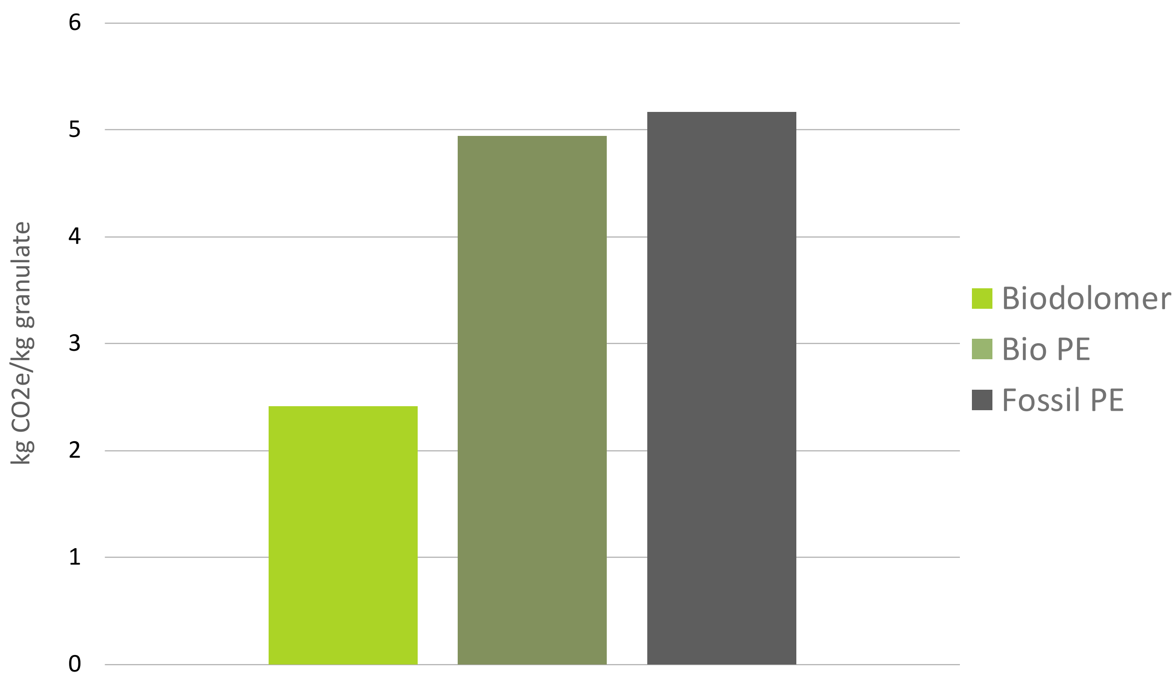


Figure 5 GWP results for granulate products.

The first figure (see above) shows the results of global warming potential for the three granulate products. This shows that the impact from producing 1 kg of Biodolomer granulate is less than half that of Bio PE and Fossil PE, which have a roughly similar impact. For both PE-products the energy consumption for polymerization gives rise to a major part of the total GWP impact. One advantage of the Biodolomer is that it can be blended and processed at lower temperatures, thus requiring less energy for heating, which contributes to the lower impact seen here.

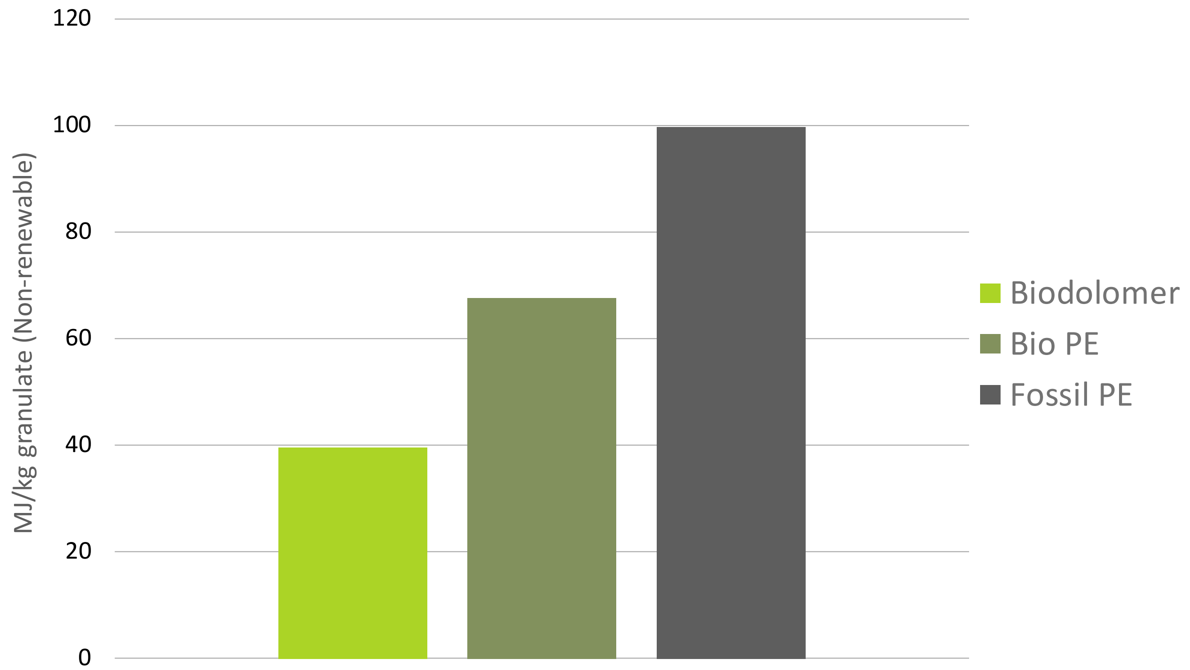


Figure 6 Results for non-renewable CED for granulate products.

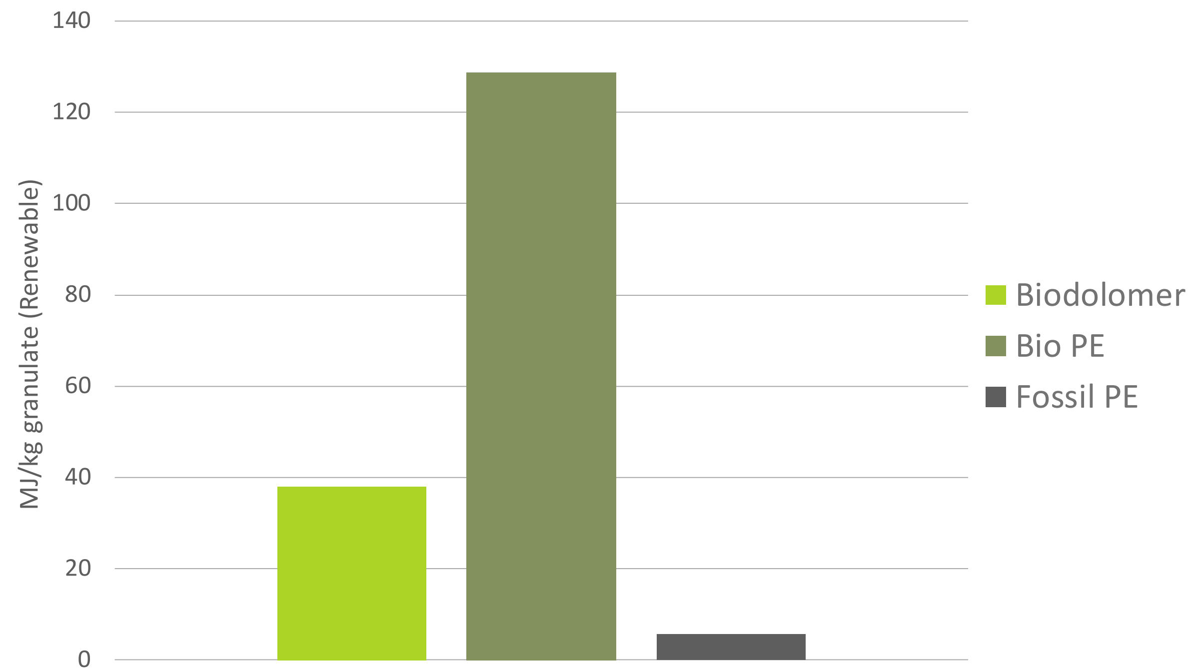


Figure 7 Results for renewable CED for granulate products

Figure 6 and Figure 7 (see above) displays the results for cumulative energy demand[3], for non-renewable energy and renewable energy respectively. As can be expected there is a large difference here between renewable and non-renewable energy demand. Fossil PE requires the most non-renewable energy but almost no renewable energy. Bio PE requires substantially less non-renewable energy but far more renewable energy, this is in part because of the renewable energy sequestered in the material itself. Production of Biodolomer requires the smallest input of non-renewable energy and only about a third the amount of renewable energy that Bio PE requires. Comparing Figure 5 and Figure 6, it is clear that global warming potential is connected to non-renewable energy demand but that it is not the only driver for this impact.

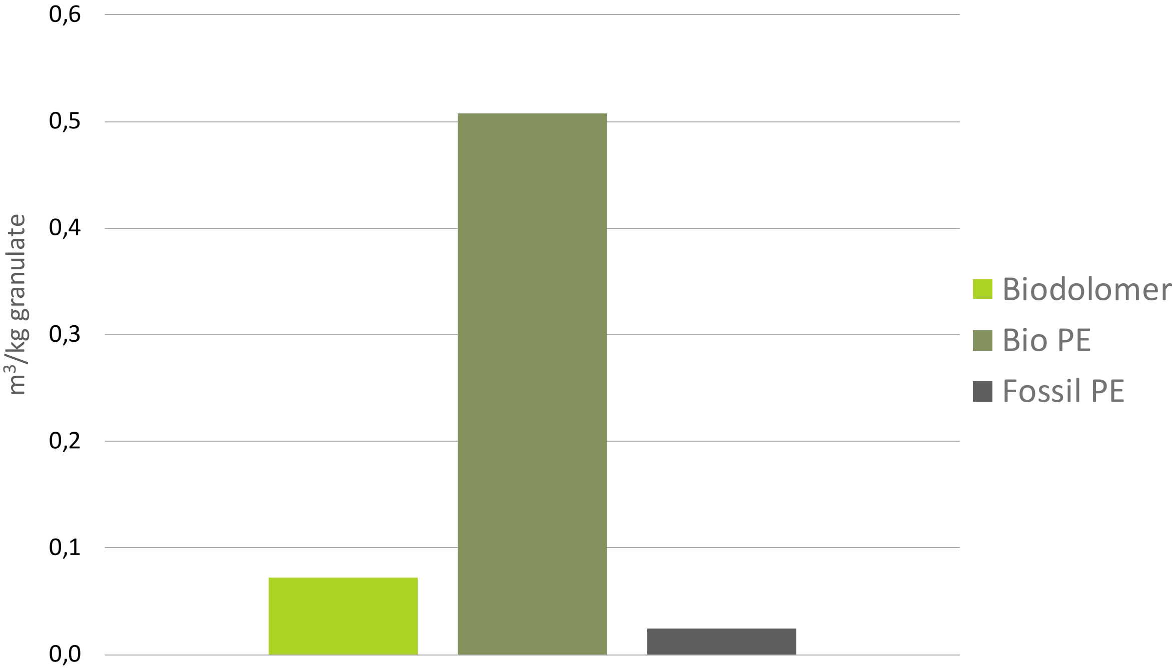


Figure 8 Water consumption results for the granulate products.

Figure 8 shows the results for the water consumption impact category. Water consumption is an important impact to analyze when studying bio-based products as agricultural activities have a tendency to require large quantities of water. The results show that the production of Bio PE causes the largest impact in this category by a large margin. The production of sugar cane in Brazil is the main point of origin for this impact because relatively large quantities of water is used for irrigation according to the data sources used. The Biodolomer granulate requires less than one seventh of the water needed to produce Bio PE granulate. The Fossil PE granulate requires the least amount of water, about one third of the water needed to produce the Biodolomer granulate.

[3] The Cumulative Energy Demand of a product or service represents the direct and indirect energy use throughout the life cycle, including the energy consumed during the extraction and pro-cessing of raw materials, manufacturing, use and disposal/end-of-life.

## 4.2 Results for carrier bags

### 4.2.1 Biodolomer bags

The full life cycle of the Biodolomer material is studied through the product of a carrier bag. In Table 7, the results for each impact category and life cycle phase is presented. As previously stated in section 3.2, we have studied two different scenarios for the use phase and end-of-life phase, here we use an average of these two scenarios.

Table 7 LCIA results for Biodolomer carrier bag from cradle-to-grave.

| Impact category | Material production | Bag production | Use of bag | End of life | Net effect | Unit |
|---|---|---|---|---|---|---|
| GWP | 66,47 | 5,83 | -89,98 | -7,45 | -25,13 | g $CO_2$e/bag |
| CED (Non-renewable) | 1,09 | 0,09 | -1,30 | -0,20 | -0,32 | MJ/bag |
| CED (Renewable) | 1,04 | 0,01 | 0,06 | 0,00 | 1,12 | MJ/bag |
| WC | 1,98 | 0,04 | -0,52 | 0,00 | 1,51 | litre/bag |

In terms of both GWP and CED (Non-renewable), the net life cycle effect of using a Biodolomer bag is a negative figure, which means that the production and use of the Biodolomer bag leads to reduced emissions of greenhouse gases and the reduced consumption of non-renewable energy. These reductions occur in the use phase and end-of-life phase where credit is given for the displacement of other products and resources.

In general, the most important parts for the results are the material production phase and the use phase. In the use phase, most of the displaced products are fossil based, which explains the large credits for GWP and CED (Non-renewable). The displaced fossil based products have relatively low consumption of renewable energy and water; thus, these credits are lower in comparison to the resources used in the material production stage of Biodolomer.

### 4.2.2 Biodolomer bags in comparison to other bag options

Moving on to the comparison in the cradle-to-grave perspective, the paper bag alternative is now included. Figure 9 displays the results for GWP for each alternative product and each life cycle phase. The red bars included are showing the two different scenarios ("Low" and "High" as explained in section 3.2) for the use phase and end-of-life phase.

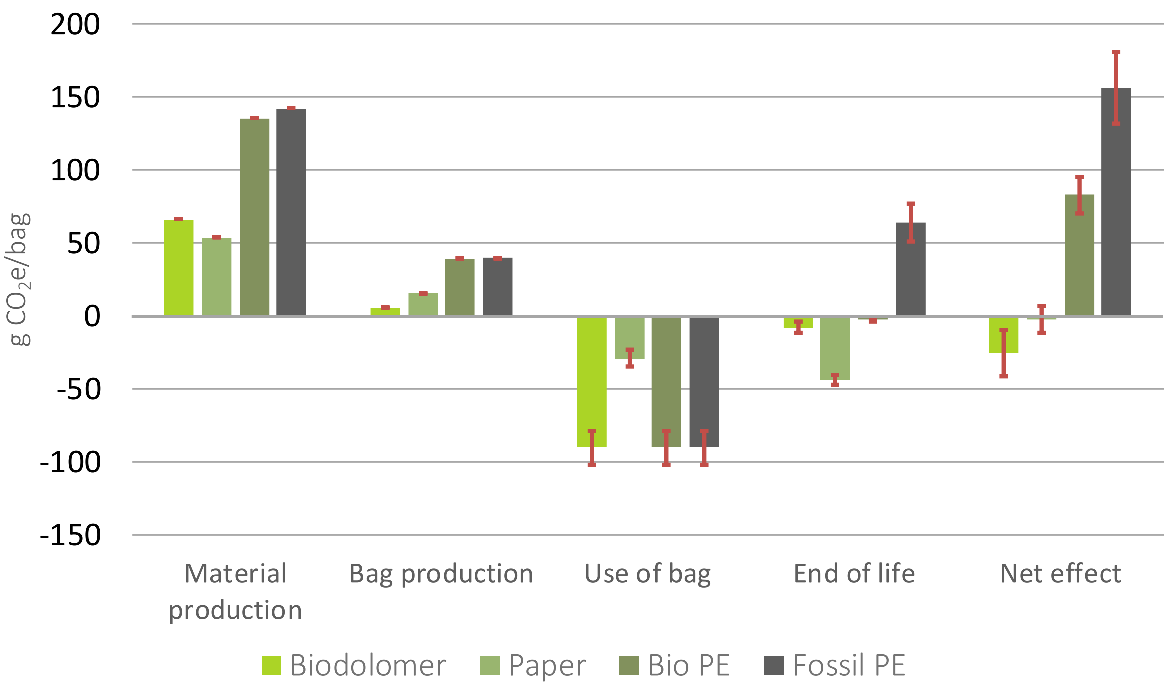


Figure 9 GWP results for bag products. The main results are shown by the green and black bars. The "red" ranges illustrate the outcomes for the Low and High Environmental Impact scenarios for the use and end-of-life stages as described in section 3.2. In the main result, an average between the Low and High Environmental Impact scenarios is used.

The results in Figure 9 show that the Biodolomer bag has the lowest impact over the entire life cycle. From the cradle-to-gate perspective (in this case material and bag production), Biodolomer and paper have very similar impacts, but the credit awarded to the Biodolomer bag in the use phase is larger than for the paper bag. The credit given to the paper bag in the end-of-life phase is larger than for the Biodolomer bag, but the difference here is smaller. Both Bio PE and Fossil PE also have very similar impacts in the first three phases of the life cycle but there is a large difference in the end-of-life phase to the advantage of the Bio PE bag. The reason for this is that the $CO_2$ released from combustion of Bio PE (in waste to energy plants and cement ovens) is biogenic and consequently not contributing to GWP. The range given by the scenarios in the use phase and end-of-life phase are not insignificant but do not change the order in which the alternative materials are ranked even in an extreme case.

Figure 10 and Figure 11 (see below) show the results for cumulative energy demand, for non-renewable and renewable energy respectively. The relationship between the alternative products is similar in Figure 10 and in Figure 9, i.e. the GWP impact and the CED (Non-renewable) impact from producing the paper bag is lower than from Biodolomer but the reverse is true when the entire life cycle of the product is considered. The range given by the different scenarios for the use phase and end-of-life phase are significant for the CED (Non-renewable) impact category with the largest range being shown for the two PE-bags. Fossil PE has the largest impact in this impact category by far.

When looking at renewable energy demand in Figure 11, there is little impact occurring after the material production phase, with the exception of the end-of-life phase for the paper bag. In this impact category, our results show that the Fossil PE bag has the lowest impact and that the paper bag has the lowest impact among the primarily bio-based materials.

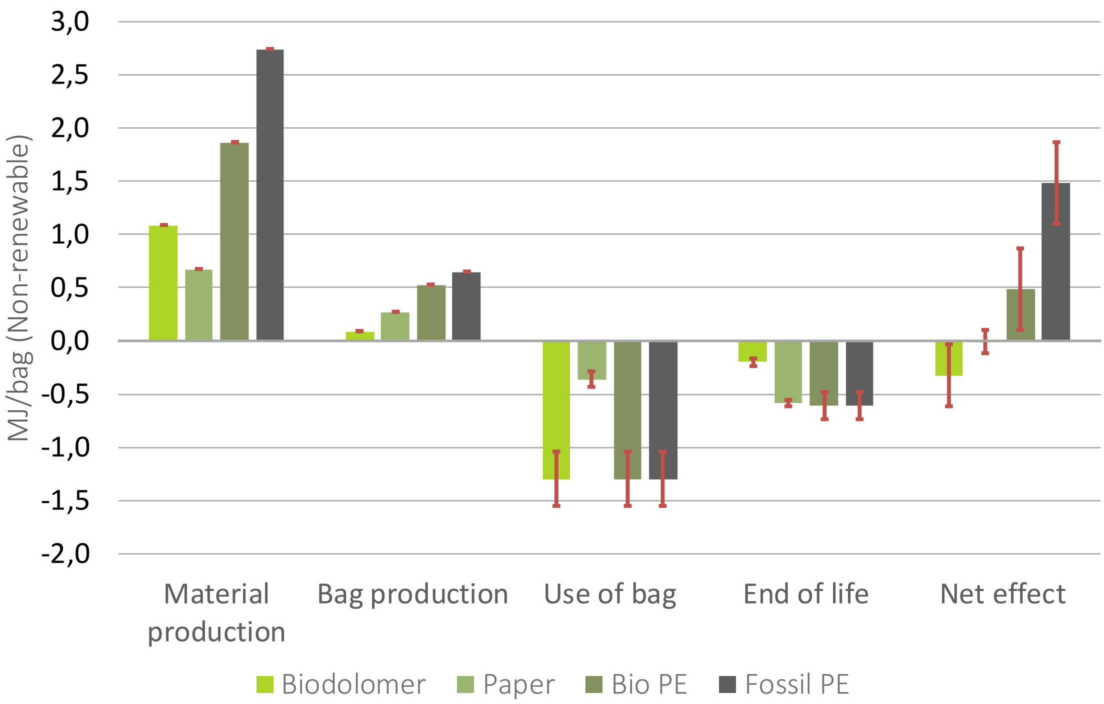


Figure 10 CED (Non-renewable) results for bag products. The main results are shown by the green and black bars. The “red” ranges illustrate the outcomes for the Low and High Environmental Impact scenarios for the use and end-of-life stages as described in section 3.2. In the main result, an average between the Low and High Environmental Impact scenarios is used.

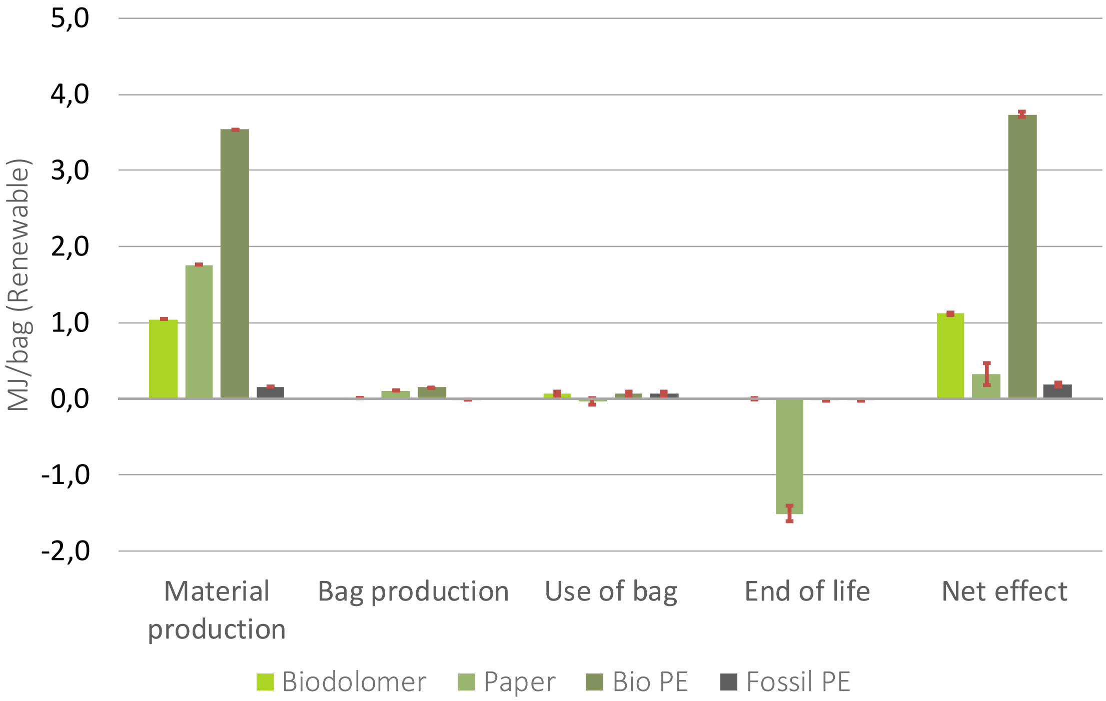


Figure 11 CED (Renewable) results for bag products. The main results are shown by the green and black bars. The “red” ranges illustrate the outcomes for the Low and High Environmental Impact scenarios for the use and end-of-life stages as described in section 3.2. In the main result, an average between the Low and High Environmental Impact scenarios is used.

Figure 12 (see below) shows the results for water consumption. The results are similar to those for renewable energy demand. Once again, the end-of-life phase for the paper bag makes a clear reduction to its total impact. The Fossil PE-bag and paper bag have similarly low net impacts. The Biodolomer bag causes a slightly larger impact. The Bio PE-bag shows the highest water consumption based on the data sources used.

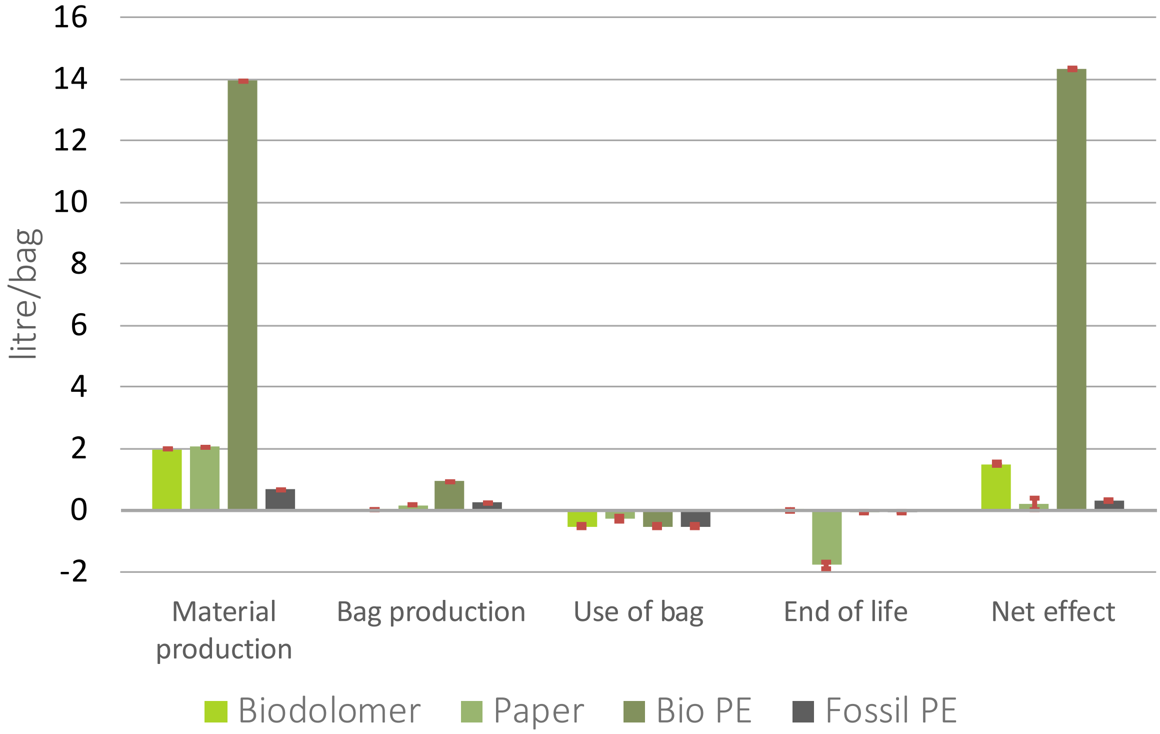


Figure 12 WC results for bag products. The main results are shown by the green and black bars. The "red" ranges illustrate the outcomes for the Low and High Environmental Impact scenarios for the use and end-of-life stages as described in section 3.2. In the main result, an average between the Low and High Environmental Impact scenarios is used.

## 4.3 Sensitivity analysis

In this section, we present results from additional modelling which aims to evaluate whether or to what extent a selection of the modelling choices and critical assumptions identified in the LCA methodology section influence the overall results of the study. Only the results for GWP were re-calculated according to the alternative modelling choices.

### 4.3.1 Equalized electricity consumption for plastic bag production

The data on electricity consumption for production of the Biodolomer bag comes from measurements at the actual production facility in Sweden. The data on electricity consumption for production of the PE bags was taken from scientific literature. The measured electricity consumption for production of the Biodolomer bag is less than half of that given by the literature source for production of a PE bag. There could be a number of reasons for this difference. One of them being the slightly different physical properties of Biodolomer and pure polyethylene which could have an effect on the energy required to process the materials. Another reason could be the fact that the literature data is based on average values from different production facilities where the machinery could be of varying age.

To study the impact of this, the electricity consumption for the production of the Biodolomer bag was increased to match that of the PE-bag. The results of the modified Biodolomer bag was then compared to the alternatives as previously.

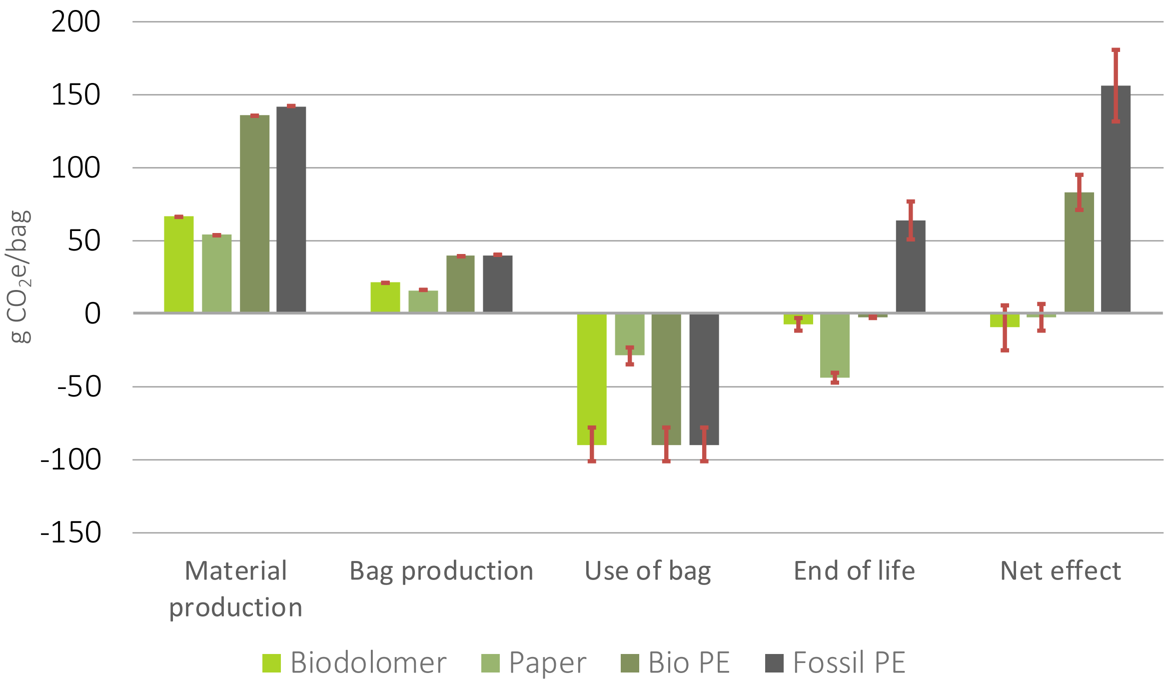


Figure 13 GWP results for bag products in the sensitivity analysis with equalized electricity consumption for plastic-type bags. The main results in the sensitivity analysis are shown by the green and black bars. The "red" ranges illustrate the outcomes for the Low and High Environmental Impact scenarios for the use and end-of-life stages as described in section 3.2. For the main results in the sensitivity analysis, an average between the Low and High Environmental Impact scenarios is used.

In Figure 13, we see the new comparison of GWP results for the entire life cycle of the bag products. Compared with the main results in Figure 9, we can see that the impact for the Biodolomer bag in the bag production phase has increased, as was expected.

Looking at the net effect, we can see that the result for the Biodolomer bag has shrunk (compared to Figure 9) but that it still has the lowest impact. There is, however, a larger overlap of the results for the Biodolomer and paper bags. This is illustrated by the "red" ranges for the net effect results in Figure 13. These "red" ranges illustrate the outcomes for the Low and High Environmental Impact scenarios for the use and end-of-life stages as described in section 3.2.

### 4.3.2 Neutralized positive effect from bio-based component of PBAT

One of the three monomer components that make up the PBAT product used in the production of Biodolomer is bio-based. Lacking detailed LCI data from the PBAT supplier on this production process and information about which specific component that is bio-based, we used general LCI datasets for fossil based monomers to model the production of PBAT. This model was later modified using some unverified information given by the PBAT supplier. These modifications decreased the GWP impact of the PBAT production by roughly 50 %.

To study the impact of this assumption, the results from our original model of the PBAT production process was used instead of the modified version. This case with all fossil based components of PBAT represents a worst-case scenario for this part of the Biodolomer life cycle.

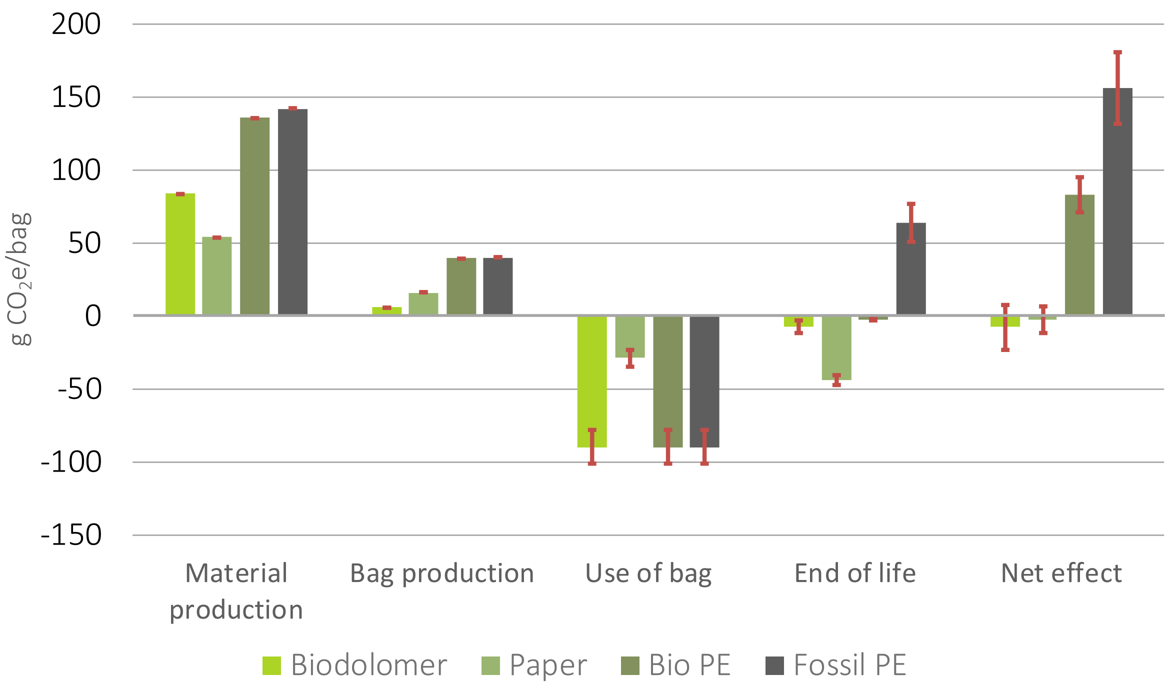


Figure 14 GWP results of bag products in the sensitivity analysis with modified Biodolomer using all fossil PBAT. The main results in the sensitivity analysis are shown by the green and black bars. The “red” ranges illustrate the outcomes for the Low and High Environmental Impact scenarios for the use and end-of-life stages as described in section 3.2. For the main results in the sensitivity analysis, an average between the Low and High Environmental Impact scenarios is used.

The results in Figure 14 show that this assumption has a significant impact on the GWP-impact of the Biodolomer bag, both from the cradle-to-gate and the cradle-to-grave perspectives. The impact in the material production phase has increased by roughly 25 %. Looking at net effect, we can see that the negative net effect for the Biodolomer bag has shrunk but that it still has the lowest impact. The change means that there is a larger overlap of the ranges (given by the scenarios for use and end-of-life in section 3.2) for the Biodolomer bag and the paper bag. The Biodolomer bag still has a much lower impact compared to the plastic-type alternatives though.

### 4.3.3 Including sequestration of biogenic carbon

The production of biomaterials causes the removal of carbon dioxide from the atmosphere through the process of photosynthesis and a share of the carbon atoms are bound in the biomaterial itself. In this study, we made the assumption that it is highly likely that the same amount of carbon dioxide that is removed will be released to the atmosphere again within the relevant timeframe for the GWP when the material is incinerated or decomposed at the end of its life cycle. Therefore, sequestration of biogenic carbon was excluded.

To study the impact of this assumption, the processes for the material production of all bio-based materials were modified to include removal of atmospheric carbon dioxide corresponding to their respective carbon contents. In practice this means that negative emissions were added for the production of Biodolomer, Bio-PE and paper.

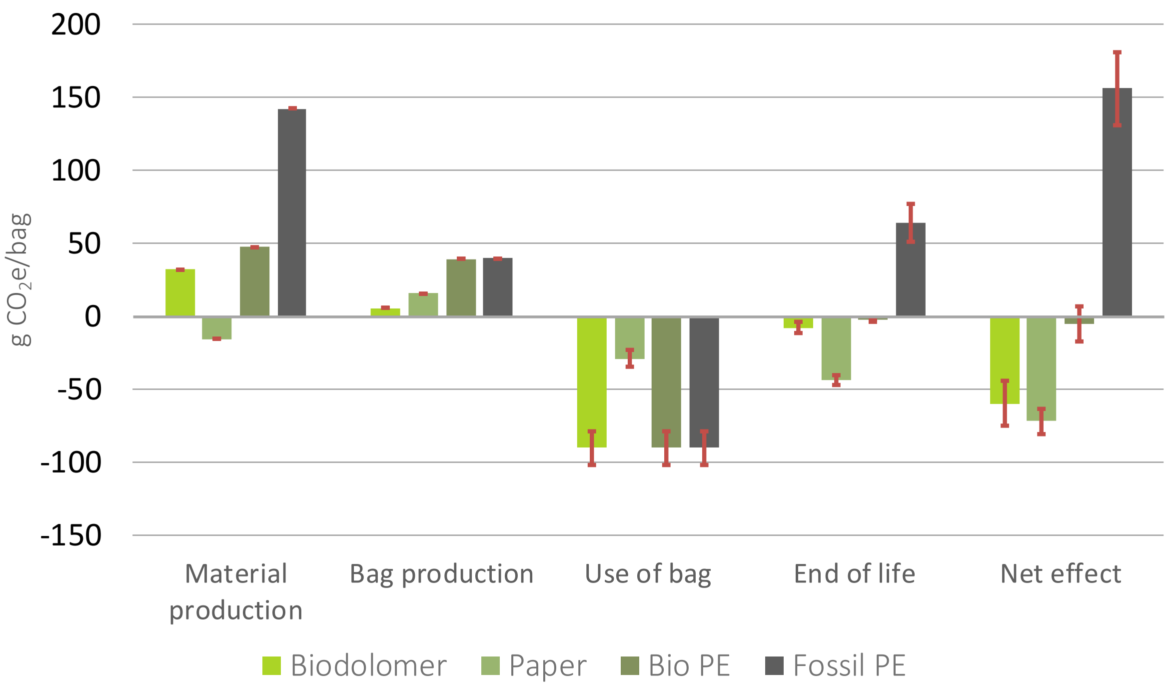


Figure 15 GWP results for bag products in the sensitivity analysis where sequestration of biogenic carbon was included. The main results in the sensitivity analysis are shown by the green and black bars. The "red" ranges illustrate the outcomes for the Low and High Environmental Impact scenarios for the use and end-of-life stages as described in section 3.2. For the main results in the sensitivity analysis, an average between the Low and High Environmental Impact scenarios is used.

The new results (displayed in Figure 15) show that the effects of this assumption are significant. With sequestration of biogenic carbon included, the GWP impact stemming from the material production phase has decreased by between 50-130 % for the three different bio-based materials. Bio PE saw the largest decrease in absolute terms. In terms of net effect for the entire product life cycle, this means that the paper bag now has the lowest impact. The change also means that there is a large overlap of the ranges (given by the scenarios for use and end-of-life in section 3.2) for the Biodolomer bag and the paper bag.

# 5 Discussion

The results in section 4 show the environmental performance of the Biodolomer throughout its life cycle as a carrier bag. The comparison with the other carrier bags gives insights into the strengths and areas of improvements for the Biodolomer material from an environmental perspective.

Looking at the life cycle of Biodolomer, it is clear that the largest impacts can be found in the material production phase (where material and energy is used, resulting in resource use and emissions) and the use of the bag (where secondary use is crucial for displacing other products, thus saving resources and reducing emissions).

When looking at the material production phase, the largest resource use and emissions occur from the raw materials PLA and PBAT. Looking at the impact categories per kg PLA and per kg PBAT respectively, it is clear that PBAT has a higher environmental impact for GWP, CED (Non-renewable) and WC, while the opposite is true regarding CED (Renewable). Looking at ways to further improve the material, e.g. if the aim would be to lower the GWP of Biodolomer, one option for improvement could thus be to evaluate if it is possible to shift to a higher share of PLA and a correspondingly lower share of PBAT in the Biodolomer, without risking the functionality of the product.

A similar effect could possibly also be achieved by encouraging the PBAT supplier to develop and supply a PBAT where all three monomer components are of biogenic origin. Another option could be to include PBS (Polybutylene succinate) of biogenic origin, as an alternative to PLA and/or PBAT. Profu has not studied the environmental impacts of biogenic PBS within this project, but that could be an interesting area for future work.

Another option for improving the environmental performance of Biodolomer is to consider increasing the share of calcium carbonate, if this is possible without risking the functionality of the product. Increasing the calcium carbonate content in Biodolomer has several environmental advantages:

- It lowers all studied environmental impacts in the material production phase (since it is the raw material with the lowest GWP, CED (both Renewable and Non-renewable) and WC per kg material)
- It provides more “free” $CaCO_3$ to the waste-to-energy plants, thus reducing the need for added limestone in the flue gas treatment.
- It lowers the energy content of the Biodolomer bag, thus reducing the displacement of imported waste at the Swedish waste-to-energy plants.

The large impact of the use phase and end-of-life phase that has been highlighted in this study (for all bags) shines a light on the importance of thought through product design which can drive and steer user behaviour. For GAIA it is relevant to consider how further development of the Biodolomer material and products can be directed towards increased reusability. For example:

- Could the reusability and the resistance to breakdown for the carrier bag be improved by changing the mix of components?
- What are the advantages and disadvantages of increasing the specific bag weight in order to increase it reusability? Higher material consumption means increased environmental impacts from the material production stage, but this might be well outweighed by the benefits of being able to reuse the bag not only once, but two or three times.

Another option to improve the environmental performance of the Biodolomer material is to consider how this material would be collected and separated for material recycling. The Biodolomer material works well to recycle into new products, once collected and delivered at the production plant. The current Swedish collection system for packaging, organized by FTI and the Swedish municipalities, is not designed for separating Biodolomer at the sorting facilities. One option could be to separate the Biodolomer material using its relatively high density. Other options to investigate could be to somehow physically or chemically "label" the Biodolomer material so it could be easily separated with some type of technology at the sorting plant.

It should also be noted that the University of Applied Sciences Hannover (Endres and de la Cruz 2013, Kitzler 2013) have tested the influence of PLA/PBAT blends as impurities in LDPE. The tested mixtures contained between 0.5 % and 10 % impurities. The researchers found that:

- Nearly all mixtures of LDPE with PLA/PBAT showed the same viscosity behaviour, elasticity and tensile strength as pure LDPE
- No optical changes (i.e. transparency or appearance) of LDPE could be observed in the contamination scenario with PLA/PBAT
- There was first slight decrease in the melt flow rate at 10 % impurity material.

The comparison with other carrier bags showed that it is of large importance for GAIA to make sure that their suppliers continuously work with improving their resource- and energy efficiency. The environmental impact of the Biodolomer bags and the other bags are very much dependent on the conditions for the raw material production. It is thus reasonable that GAIA receive transparent information from all suppliers regarding current conditions and future development for the raw material- and component production. The comparison and the sensitivity analysis regarding electricity consumption at bag production also highlights the large GWP and CED (non-renewable) benefits of working with measures to reduce electricity consumption. This conclusion becomes very clear in a consequential LCA, where the marginal electricity production technologies that are affected by increased/reduced electricity consumption are included.

Our sensitivity analysis showed that sequestration of biogenic carbon has a very large impact on the GWP results for bio-based materials. This is not new knowledge and the debate about how to account for biogenic carbon in bio-based materials has gone on in the LCA community for some time. Generally, the issue boils down to whether the expected retention time for the material in question is long enough for the sequestered carbon to have any significant effect on global warming. In the case with carrier bags, we can with a high degree of certainty say that this is not the case and therefore it was reasonable to exclude carbon sequestration effects.

When it comes to analyzing CED results, one can generally say that it is desirable to achieve a high degree of energy efficiency, i.e. a low CED. However, all forms and flows of energy are not created equal. For instance, non-renewable energy typically has a much stronger correlation with other impacts such as GWP and resource depletion, while various forms of renewable energy have a larger span of impact across multiple impact categories. For this reason, we believe that renewable and non-renewable energy should, as often as practically possible, be presented separately. Bio-based materials will generally have a larger renewable CED due to renewable energy being embodied in the material itself, which is evident from the results as almost the entire renewable CED is concentrated to the material production phase. Regarding the results, the PE bag alternatives stand out, fossil PE in terms of non-renewable CED and bio PE in terms of renewable CED. This is partly explained by the higher energy content of PE compared to Biodolomer and paper, but it does not account for the entire difference.

This LCA study was performed as an consequential LCA and many of the consequences included in the study had a significant impact on the end results, for example the marginal electricity production, the alternative secondary use of bags and the end-of-life options (especially the consequences for Swedish waste to energy practices and displacement of imported waste). It was thus clear that a consequential LCA (and not an attributional LCA) was required to capture the full impact of the product life cycles studied. It is impossible to say how large the deviation of results would be for an attributional LCA without performing such analysis and comparing the results. However, such a comparison was not part of the scope of this study.

# 6 Conclusions

This LCA study has shown that the Biodolomer had the lowest impact in the impact categories GWP and non-renewable CED, both in a cradle-to-gate perspective (as granulate, compared to bio PE and fossil PE alternatives) and in a cradle-to-grave perspective (in the form of a carrier bag, compared to bio PE, fossil PE and paper alternatives). In the categories renewable CED and WC, the fossil PE and paper alternatives performed slightly better[4].

The material production phase and secondary use phase were identified as those with the largest contribution to the overall life cycle impact of the Biodolomer carrier bag. PLA and PBAT were the material components which contributed the most to the material production phase of Biodolomer where PBAT had the largest impact per unit mass. Out of the likely secondary use activities identified, the re-use as carrier bag proved to have the most important impact by displacing other products, thus saving resources and reducing emissions.

The study has also shown that most of the environmental impacts studied potentially could be reduced for the Biodolomer material by:

- Increasing the share of PLA over PBAT
- Increasing the biogenic share of PBAT
- Increasing the share of calcium carbonate over all other raw materials
- Reducing electricity consumption, both for raw material production and for Biodolomer production

It must be stressed, however, that these measures are only acceptable if they do not risk the functionality of the product.

Because of the material properties of Biodolomer and the fact that it is made up of mostly biogenic and inert materials, it is theoretically well suited for a number of different end-of-life disposal options, like material recycling, biological treatment (anaerobic digestion with bio-methane recovery) and energy recovery. The physical properties make the material easy to re-process. The mostly biogenic components mean that carbon dioxide emissions from combustion, either in a waste to energy plant or in cement kilns, can be considered to have a very low global warming impact.

Sensitivity analyses of critical assumptions in the study, showed that the assumptions had significant impact on the results. However, those individual impacts would not have altered the main conclusions of the study.

[4] When looking at the results, it should be noted that the project did budget for extensive data collection regarding the life cycle of the Biodolomer® material. For the comparisons with other materials, however, less resources were available, which meant that we relied heavily on data available in the Ecoinvent database for inventories for the other materials. The data quality is thus quite different and significantly higher for the Biodolomer life cycle than for the other materials.

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# Appendix A - Underlying data

Table 8 Marginal electricity production mixes for 2019 as modelled in the project. Northern European mix is used both for production in Sweden and in Europe. In parenthesis, the average electricity mixes for Sweden, Brazil and Thailand according to IEA Statistics for 2016 (IEA 2018) are shown for comparison. NB! The average electricity mix is not correct to use for this study, since it is a consequential LCA

| Energy source | Northern Europe, marginal mix 2019 (Sweden, average mix 2016) | Brazil, marginal mix 2019 (Brazil, average mix, 2016) | Thailand, marginal mix 2019 (Thailand, average mix 2016) |
|---|---|---|---|
| Coal | 75 % (1%) | 25 % (4 %) | 25 % (19 %) |
| Natural gas | 10 % (0%) | 50 % (10 %) | 75 % (65 %) |
| Oil | 0 % (0%) | 25 % (3 %) | 0 % (0 %) |
| Biomass | 15 % (6 %) | 0 % (8 %) | 0 % (10 %) |
| Wind | 0% (10 %) | 0 % (6 %) | 0 % (0 %) |
| Hydro | 0 % (40 %) | 0 % (66 %) | 0 % (4 %) |
| Solar | 0 % (0 %) | 0 % (0 %) | 0 % (2 %) |
| Nuclear | 0 % (40 %) | 0 % (3 %) | 0 % (0 %) |
| Waste | 0 % (2 %) | 0 % (0 %) | 0 % (0 %) |

Table 9 Important transport routes, transport distances and mode of transport for the different materials/bags.

| Material | Origin | Destination | Distance [km] | Mode of transport |
|---|---|---|---|---|
| Biodolomer | | | | |
| - PLA | Thailand | Helsingborg (SE) | 17 800 | Ship |
| - Chalk ($CaCO_3$) | Norway | Gothenburg (SE) | 635 | Ship |
| - Chalk ($CaCO_3$) | Gothenburg (SE) | Helsingborg (SE) | 220 | Truck |
| - PBAT | Germany | Helsingborg (SE) | 2 000 | Train |
| - Vegetable oil | Karlshamn (SE) | Helsingborg (SE) | 340 | Truck |
| Bio PE | | | | |
| - Granulates | Brazil | Germany | 10 500 | Ship |
| - Bags | Germany | Helsingborg (SE) | 2 000 | Train |
| Fossil PE | | | | |
| - Bags | Germany | Helsingborg (SE) | 2 000 | Train |
| Paper | | | | |
| - Bags | Germany | Helsingborg (SE) | 2 000 | Train |

Table 10 Ecoinvent datasets used for the modelling of raw materials used for the production of alternative granulate- and bag materials.

| Material | Product | Ecoinvent dataset name |
|---|---|---|
| Bio PE | Bioethanol | Ethanol, without water, in 95% solution state, from fermentation {BR}\| ethanol production from sugarcane \| Conseq, U - Profu |
| Fossil PE | Polyethylene | Polyethylene, low density, granulate {GLO}\| market for \| Conseq, U |
| Paper | Kraft paper | Kraft paper, unbleached {GLO}\| market for \| Conseq, U |

Table 11 Ecoinvent datasets used for the modelling of transports.

| Mode | Ecoinvent dataset name |
|---|---|
| Ship | Transport, freight, sea, transoceanic ship {GLO}\| market for \| Conseq, U |
| Truck | Transport, freight, lorry >32 metric ton, euro6 {RER}\| market for transport, freight, lorry >32 metric ton, EURO6 \| Conseq, U |
| Train | Transport, freight train {GLO}\| market group for \| Conseq, U |

Table 12 Main materials and resources used to produce 1 kg of bio PE. (Profu's estimation based on data from Hong et al 2014 and Liptow and Tillman 2009)

| Bioethanol [kg] | Fuel oil [kg] | Natural gas [MJ] | Electricity [kWh] | Water [kg] |
|---|---|---|---|---|
| 1,7 | 0,085 | 0,3 | 3,73 | 0,8 |

Table 13 Main materials and resources used to produce 1 kg of PE bags. (data from Bisinella et al 2018)

| Polyethylene granulate [kg] | Electricity [kWh] | Heat [MJ] | Water [kg] | Titanium dioxide [kg] | Printing ink [kg] |
|---|---|---|---|---|---|
| 1,05 | 0,741 | 1,522 | 0 | 0,034 | 0,011 |

# Appendix B - Detailed result tables

## GWP [g $CO_2e$/bag]

Table 14 GWP results for bag products in the "High" environmental impact scenario.

| GWP (High impact) | Material production | Bag production | Use of bag | End of life | Net effect |
|---|---|---|---|---|---|
| Biodolomer | 66,5 | 5,8 | -78,4 | -3,3 | -9,5 |
| Bio PE | 135,9 | 39,6 | -78,4 | -1,5 | 95,5 |
| Fossil PE | 142,2 | 40,0 | -78,4 | 77,2 | 181,0 |
| Paper | 54,0 | 16,1 | -23,1 | -40,1 | 7,0 |

Table 15 GWP results for bag products in the "Low" environmental impact scenario.

| GWP (Low impact) | Material production | Bag production | Use of bag | End of life | Net effect |
|---|---|---|---|---|---|
| Biodolomer | 66,5 | 5,8 | -101,5 | -11,6 | -40,8 |
| Bio PE | 135,9 | 39,6 | -101,5 | -3,3 | 70,7 |
| Fossil PE | 142,2 | 40,0 | -101,5 | 51,0 | 131,7 |
| Paper | 54,0 | 16,1 | -34,3 | -47,1 | -11,3 |

Table 16 GWP results for bag products in an average scenario.

| GWP (Average) | Material production | Bag production | Use of bag | End of life | Net effect |
|---|---|---|---|---|---|
| Biodolomer | 66,5 | 5,8 | -90,0 | -7,5 | -25,1 |
| Bio PE | 135,9 | 39,6 | -90,0 | -2,4 | 83,1 |
| Fossil PE | 142,2 | 40,0 | -90,0 | 64,1 | 156,3 |
| Paper | 54,0 | 16,1 | -28,7 | -43,6 | -2,1 |

## CED (Non-renewable) [MJ/bag]

Table 17 Non-renewable CED results for bag products in the "High" environmental impact scenario.

| CED (High impact) | Material production | Bag production | Use of bag | End of life | Net effect |
|---|---|---|---|---|---|
| Biodolomer | 1,09 | 0,09 | -1,04 | -0,16 | -0,03 |
| Bio PE | 1,86 | 0,53 | -1,04 | -0,48 | 0,87 |
| Fossil PE | 2,74 | 0,65 | -1,04 | -0,48 | 1,87 |
| Paper | 0,67 | 0,27 | -0,29 | -0,56 | 0,10 |

Table 18 Non-renewable CED results for bag products in the "Low" environmental impact scenario.

| CED (Low impact) | Material production | Bag production | Use of bag | End of life | Net effect |
|---|---|---|---|---|---|
| Biodolomer | 1,09 | 0,09 | -1,55 | -0,24 | -0,62 |
| Bio PE | 1,86 | 0,53 | -1,55 | -0,74 | 0,10 |
| Fossil PE | 2,74 | 0,65 | -1,55 | -0,74 | 1,10 |
| Paper | 0,67 | 0,27 | -0,44 | -0,61 | -0,11 |

Table 19 Non-renewable CED results for bag products in an average scenario.

| CED (Average) | Material production | Bag production | Use of bag | End of life | Net effect |
|---|---|---|---|---|---|
| Biodolomer | 1,09 | 0,09 | -1,30 | -0,20 | -0,32 |
| Bio PE | 1,86 | 0,53 | -1,30 | -0,61 | 0,48 |
| Fossil PE | 2,74 | 0,65 | -1,30 | -0,61 | 1,48 |
| Paper | 0,67 | 0,27 | -0,36 | -0,58 | -0,01 |

## CED (Renewable) [MJ/bag]

Table 20 Renewable CED results for bag products in the "High" environmental impact scenario.

| CED (High impact) | Material production | Bag production | Use of bag | End of life | Net effect |
|---|---|---|---|---|---|
| Biodolomer | 1,04 | 0,01 | 0,09 | 0,00 | 1,14 |
| Bio PE | 3,54 | 0,15 | 0,09 | -0,01 | 3,76 |
| Fossil PE | 0,16 | -0,02 | 0,09 | -0,01 | 0,22 |
| Paper | 1,76 | 0,11 | 0,01 | -1,41 | 0,47 |

Table 21 Renewable CED results for bag products in the "Low" environmental impact scenario.

| CED (Low impact) | Material production | Bag production | Use of bag | End of life | Net effect |
|---|---|---|---|---|---|
| Biodolomer | 1,04 | 0,01 | 0,04 | 0,01 | 1,10 |
| Bio PE | 3,54 | 0,15 | 0,04 | -0,02 | 3,71 |
| Fossil PE | 0,16 | -0,02 | 0,04 | -0,02 | 0,16 |
| Paper | 1,76 | 0,11 | -0,08 | -1,61 | 0,18 |

Table 22 Renewable CED results for bag products in an average scenario.

| CED (Average) | Material production | Bag production | Use of bag | End of life | Net effect |
|---|---|---|---|---|---|
| Biodolomer | 1,04 | 0,01 | 0,06 | 0,00 | 1,12 |
| Bio PE | 3,54 | 0,15 | 0,06 | -0,02 | 3,73 |
| Fossil PE | 0,16 | -0,02 | 0,06 | -0,02 | 0,19 |
| Paper | 1,76 | 0,11 | -0,04 | -1,51 | 0,32 |

## WC [litre/bag]

Table 23 WC results for bag products in the "High" environmental impact scenario.

| WC (High impact) | Material production | Bag production | Use of bag | End of life | Net effect |
|---|---|---|---|---|---|
| Biodolomer | 1,98 | 0,04 | -0,57 | 0,00 | 1,46 |
| Bio PE | 13,96 | 0,95 | -0,57 | -0,05 | 14,29 |
| Fossil PE | 0,67 | 0,26 | -0,57 | -0,05 | 0,31 |
| Paper | 2,05 | 0,18 | -0,16 | -1,66 | 0,41 |

Table 24 WC results for bag products in the "Low" environmental impact scenario.

| WC (Low impact) | Material production | Bag production | Use of bag | End of life | Net effect |
|---|---|---|---|---|---|
| Biodolomer | 1,98 | 0,04 | -0,46 | 0,01 | 1,57 |
| Bio PE | 13,96 | 0,95 | -0,46 | -0,10 | 14,34 |
| Fossil PE | 0,67 | 0,26 | -0,46 | -0,10 | 0,36 |
| Paper | 2,05 | 0,18 | -0,34 | -1,90 | 0,00 |

Table 25 WC results for bag products in an average scenario.

| WC (average) | Material production | Bag production | Use of bag | End of life | Net effect |
|---|---|---|---|---|---|
| Biodolomer | 1,98 | 0,04 | -0,52 | 0,00 | 1,51 |
| Bio PE | 13,96 | 0,95 | -0,52 | -0,08 | 14,32 |
| Fossil PE | 0,67 | 0,26 | -0,52 | -0,08 | 0,34 |
| Paper | 2,05 | 0,18 | -0,25 | -1,78 | 0,21 |

# Appendix C – Executive Summary, version without references to different sections of the report

GAIA specializes in developing and adapting biomaterials based on fiber for applications in existing production facilities for plastic products. According to GAIA, fiber based biomaterials can replace up to 80% of volume plastics currently manufactured from traditional, fossil based raw materials.

The material Biodolomer® consists of a bio-based biodegradable ester that is mixed with fiber, calcium carbonate and vegetable oils. The material is manufactured and sold by GAIA, both in the form of granulates as well as in the form of products such as trays for meat and fish, aprons (for single-use purposes in the healthcare industry), waste bags and carrier bags.

On commission by the ongoing project "Biodolomer® For Life" (LIFE15 ENV/SE/000315), which is part of the European Commission LIFE program, Profu has performed a consequential LCA of the Biodolomer® material, both as a granulate and in the form of carrier bags. These products were also compared with other materials (for granulates: bio-based and fossil based polyethylene; for carrier bags: bags made out of bio-based and fossil based polyethylene respectively and paper bags) in order to draw conclusions on the strengths and areas of improvements for the Biodolomer® material from an environmental impact perspective.

In order to keep the scope of the LCA-study manageable, the three impact categories deemed most relevant were selected. These were:

- Global warming potential (GWP)
- Cumulative energy demand (CED) (both renewable and non-renewable) and
- Water consumption (WC)

The study has taken place during 2019. The time horizon of the impacts in this study was 100 years, and the temporal scope was 2019. The geographical scope differs with the different material (which is further explained in the report), since they are produced in different locations (including extraction and processing of various raw materials). For all materials, however, the use phase and end-of-life phase were set to occur in Sweden.

The project did budget for extensive data collection regarding the life cycle of the Biodolomer® material. For the comparisons with other material, however, less resources were available, which meant that we relied heavily on data available in the Ecoinvent database for inventories for the alternative materials. Data on energy and resource consumption for certain processes were gathered from literature sources (for more details on the data requirements and the data quality, see the full report).

Figure ES1 shows an overall summary of the results from the LCA of the Biodolomer® carrier bag and the comparison to the other bags studied.

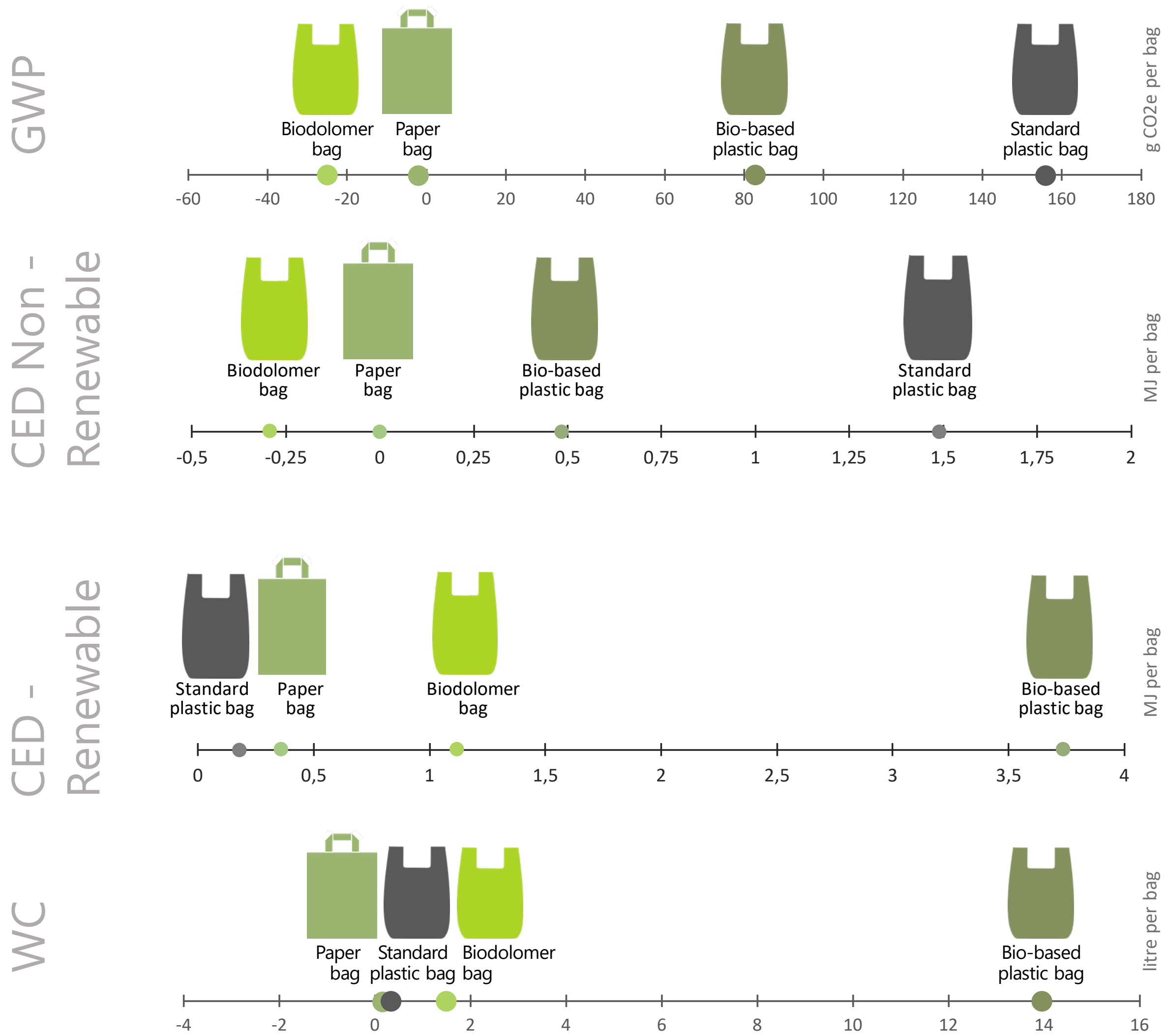


Figure ES1 An overall summary of the results from the LCA of the Biodolomer carrier bag and the comparison to the other bags studied. GWP = Global Warming Potential, CED = Cumulative Energy Demand and WC = Water Consumption. When looking at the results, it should be noted that the project did budget for extensive data collection regarding the life cycle of the Biodolomer® material. For the comparisons with other materials, however, less resources were available, which meant that we relied heavily on data available in the Ecoinvent database for inventories for the other materials. The data quality is thus quite different and significantly higher for the Biodolomer life cycle than for the other materials.

This LCA study has shown that the Biodolomer® had the lowest impact in the impact categories GWP and non-renewable CED, both when studied in a cradle-to-gate perspective (as granulate, compared to bio PE and fossil PE alternatives) and in a cradle-to-grave perspective (in the form of a carrier bag, compared to bio PE, fossil PE and paper alternatives). In the categories renewable CED and WC, the fossil PE and paper alternatives performed slightly better.

The material production phase and secondary use phase were identified as those with the largest contribution to the overall life cycle impact of the Biodolomer® carrier bag. PLA and PBAT were the material components which contributed the most to the material production phase of Biodolomer® where PBAT had the largest impact per unit mass. Out of the likely secondary use activities identified, the reuse as carrier bag proved to have the most important impact by displacing other products, thus saving resources and reducing emissions.

The study has also shown that most of the environmental impacts studied potentially could be reduced for the Biodolomer® material by:

- Increasing the share of PLA over PBAT
- Increasing the biogenic share of PBAT
- Reducing electricity consumption, both for raw material production and for Biodolomer® production

Another option for improving the environmental performance of Biodolomer is to consider increasing the share of calcium carbonate. Increasing the calcium carbonate content in Biodolomer has several environmental advantages:

- It lowers all studied environmental impacts in the material production phase (since it is the raw material with the lowest GWP, CED (both Renewable and Non-renewable) and WC per kg material)

- It provides more "free" $CaCO_3$ to the waste-to-energy plants in the end-of-life stage, thus reducing the need for added limestone in the flue gas treatment.

- It lowers the energy content of the Biodolomer bag, thus reducing the displacement of imported waste at the Swedish waste-to-energy plants.

It must be stressed, however, that these measures are only acceptable if they do not risk the functionality of the product.

Because of the material properties of Biodolomer® and the fact that it is made up of mostly biogenic and inert materials, it is theoretically well suited for a number of different end-of-life disposal options, like material recycling, biological treatment (anaerobic digestion with bio-methane recovery) and energy recovery. The physical properties make the material easy to re-process. The mostly biogenic components mean that carbon dioxide emissions from combustion, either in a waste to energy plant or in cement kilns, can be considered to have a low global warming impact.

Sensitivity analyses of critical assumptions in the study, showed that the assumptions had significant impact on the results. However, those individual impacts would not have altered the main conclusions of the study.