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Assessing the Sustainable Potential of Corrugated Board-Based Bundle Packaging of PET Bottles: A Life Cycle Perspective—A Case Study

Roman Jannes [1,*], Pieter Vanhauwermeiren [1], Peter Slaets [2] and Marc Juwet [1]

[1] Department of Mechanical Engineering, KU Leuven Campus Gent, 9000 Gent, Belgium; pieter.vanhauwermeiren@kuleuven.be (P.V.); marc.juwet@kuleuven.be (M.J.)
[2] Department of Mechanical Engineering, KU Leuven Campus Leuven, 3000 Leuven, Belgium; peter.slaets@kuleuven.be
* Correspondence: jannes.roman@kuleuven.be

Abstract: Large amounts of PET bottles are used worldwide as primary packaging for numerous liquids, including water and soft drinks. In many cases, between two and eight of such bottles are bundled for transport and sales using plastic collation shrink film. This study evaluates paper-based alternatives for plastic bundling material using a life cycle assessment (LCA) of four different types of bundle packaging: LDPE shrink film, recycled Low-Density Polyethylene (rLDPE) shrink film, Ecogrip (existing paper-based bundle packaging) and Ecobundle (new paper-based bundle packaging). The study focuses on the case of bundling six bottles of 1.5 L of sparkling water. The most environmentally friendly option is identified, taking into consideration the material usage, effects on human health and effects on the biosphere. It is concluded that the new corrugated board-based bundling method (Ecobundle) is very promising. Further optimization of the design, minimization of material, improved choice of materials and improved design of the production machinery may result in a corrugated board performing even better than rLDPE shrink film in terms of the global warming potential.

Keywords: corrugated board; life cycle assessment (LCA); packaging; plastic; global warming potential (GWP)

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1. Introduction

Every year, an estimated amount of approximately 90 million tons of plastic waste infiltrates the Earth's oceans from coastal regions [1]. Measured in terms of quantity, 80 to 85% of the marine litter found on beaches consists of plastics: 50% corresponds to single-use plastic products and 27% represents the total products associated with fisheries [2]. Single-use plastic products encompass a wide range of commonly used and short-lived consumer items that are intended for disposal after a single use, are rarely recycled and often end up as litter. Therefore, the prevalence of single-use plastic items represents a significant issue concerning marine pollution, endangering marine ecosystems, biodiversity, human health and affecting industries such as tourism, fishing and shipping.

Guidelines have been established by governments, along with laws and standards, to regulate packaging practices. In addition, there are a comprehensive range of analytical methods that can be applied to packaging methods, such as the Life Cycle Assessment (LCA) methodology (ISO 14040 family), which allows for the calculation of various environmental impacts, including the Global Warming Potential (GWP). These methodologies provide valuable tools for evaluating and quantifying the sustainability performance of packaging solutions.

1.1. Legislation

There are numerous guidelines, laws and directives in place to support effective waste management practices. It is important to be aware of the legislation when developing new packaging solutions. The following are key regulations that play a crucial role in shaping waste policies and strategies.

1.1.1. EN 643:2014 [3]

This European standard provides an overview of all the types of paper and board that are used as raw materials in the paper industry for the production of paper and board products during the recycling process. Additionally, the composition of paper and board for recycling is clearly defined in this standard, along with tolerances for unwanted materials; prohibited materials are also specified [3].

Table 1 presents the tolerances for unwanted materials that apply to this research; namely, group 1.04.00, 1.04.01 or 1.04.02. These codes refer to the classification groups in the European norm, EN 643. The percentage of unwanted material is relatively high for the category of packaging waste in comparison to the other categories.

Table 1. Allowed unwanted materials [3].

Corrugated Paper and Board—1.04, 4.05				
Code	**Name**	**Description**	**Non-Paper Components in % (max)**	**Total Unwanted Material in % (max)**
1.04.00	Corrugated paper and board packaging	Used paper and board packaging, containing a minimum of 70% of corrugated board, the rest being other packaging papers and boards.	1.5	3
1.04.01	Ordinary corrugated paper and board	Used paper and board packaging, containing a minimum of 70% of corrugated board, the rest being other paper and board products.	1.5	3
1.04.02	Corrugated paper and board	Used paper and board packaging, containing a minimum of 80% of corrugated board, the rest being other paper and board products.	1.5	3
1.05.00	Ordinary corrugated board	Used boxes and sheets of corrugated board of various qualities, may include 10% of other packaging papers and boards.	1.5	2.5
1.05.01	Corrugated board	Used boxes and sheets of corrugated board of various qualities, may include 5% of other packaging papers and boards.	1.5	2.5

1.1.2. Directive 2019/904/EC [4]

Directive 2019/904EC of the European Commission and Council on the reduction in the impact of certain plastic products on the environment was established after recognizing the negative impact of plastics on our environment. The wide usability, favorable properties and low cost of plastics have led to their increasing prevalence in our daily lives. In particular, the growing use of plastics in short-lived applications has negative consequences and does not align with the circular economy action plan. Therefore, this directive aims to prevent and reduce the effects of certain plastic products on the environment—especially the aquatic environment—and human health. It also provides opportunities for innovative and sustainable business models that promote the transition to a circular economy.

The definition of single-use plastics (SUP) must be clearly defined to ensure the effective implementation of this directive. For the comprehensive definition, reference is made to the standard [4]. It is important to note that the updated definition of plastics also includes rubbers based on polymers. Additionally, biodegradable plastics and plastics derived from biomass intended to biodegrade over time are included, even though they are derived from biomass. On the other hand, paints, inks and adhesives are excluded and can be freely used as polymers. This is a significant exception, allowing for the use of coatings applied during the printing process to protect paper.

When no suitable alternative is available, the use of SUP for such applications is permitted. However, it is expected that the consumption of these plastic products will significantly increase. To counteract this trend, member states must be obliged to take the necessary measures. An example of such measures includes awareness-raising rules. Member states implement measures to educate consumers and encourage responsible consumer behavior to reduce the littering of the products covered by this directive.

1.1.3. Packaging and Packaging Waste Directive

The packaging and packaging waste directive (PPWD) [4] is the main regulation concerning packaging and packaging waste. This directive was established in 1994 to harmonize the various national measures concerning the management of packaging and packaging waste. The main objectives are to ensure a high level of environmental protection and to guarantee the functioning of the internal market by preventing distortions of competition. To achieve this, a series of measures have been introduced, focusing primarily on waste prevention, followed by packaging reuse, recycling and recovery.

The original version of 1994 has been amended several times. The current version, from 2018, will most likely be replaced by a new directive or regulation in 2023. It sets even higher standards for waste prevention, reuse and recycling, to protect, preserve and create a better environment. It also considers human health, the efficient and rational use of natural resources, the promotion of the circular economy principle, the increased use of renewable energy, the improvement of energy efficiency and the reduction in the Union's dependency on imported resources. These measures aim to create new economic opportunities and promote long-term competitiveness.

In this study, paper-based packaging is compared to plastic packaging in the context of this PPWD. The objectives concerning these packaging materials are highly relevant. By 2023, the minimum target is to recycle 50% by weight of plastic and 75% by weight of paper and corrugated board. By 2030, these targets increase to 55% and 85%, respectively. Eurostat [5] provides clear and interactive graphs which illustrate the situation for paper and corrugated board in Belgium and Europe. It can also show the situation for plastic in Belgium and Europe. It can be observed that Belgium has already achieved the 2030 target for paper and corrugated board. With such a high rate of recycling, there is a demand for applications to efficiently utilize recycled material. In this context, Ecobundle and Ecogrip could make significant contributions, as both are made from 100% recycled fibers.

1.2. Bundle Packaging

In previous research [6,7], an extensive search was conducted to explore alternatives to collation shrink bundle packaging (Figure 1a). The aim was to develop a packaging solution that could be applied to a wide range of bundles, including shampoo bottles, milk cartons, small bottles and even larger 2 L bottles in bundles ranging from four to eight. The research was conducted with a specific focus on a bundle consisting of six 1.5 L PET bottles. This collaborative development effort involved the VPK company as a fiber-based material expert, and two packaging solutions were developed, as shown in Figure 1b,c.

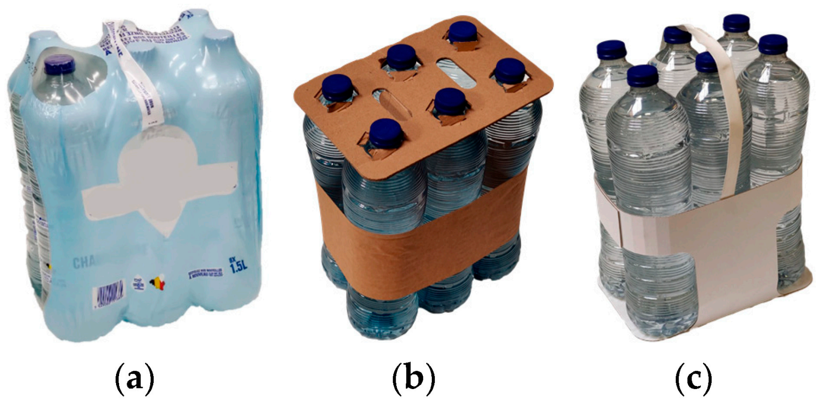

Figure 1. (**a**) Collation shrink film, (**b**) Ecogrip, (**c**) Ecobundle.

Ecobundle [6] and Ecogrip [7] have proven to be effective alternatives to traditional collation shrink film while retaining the essential functionality [6,7]. These innovative packaging solutions exhibit remarkable resistance to alternating horizontal inertial forces and outperform conventional collation shrink-based bundles [6,8]. Both of these packaging concepts have been subjected to stringent testing, demonstrating compliance with protocols such as Eumos [9] and Rahif [6].

Furthermore, these packaging solutions fulfill various critical functional requirements in the industry. They are designed to bundle goods efficiently, facilitating easy manipulation by customers, while also allowing for effective product branding. Additionally, they enable secure palletization and the safe transportation of goods, maintaining stability even under challenging environmental conditions such as rainy weather or high humidity through the use of bio-coating.

2. Materials and Methods

For this scientific study, a comparative LCA is conducted to evaluate four distinct packaging options: option 1, utilizing corrugated board; option 2, employing a stretchable paper band; option 3, utilizing LDPE plastic; option 4, utilizing recycled LDPE. The LCA analysis aims to assess the environmental impact of these packaging alternatives under the assumption that the packaging is disposed after a single use.

To conduct LCA studies, a range of Life Cycle Impact Assessment (LCIA) methods are available. The International Standard for LCA (ISO 14040-14044) does not prescribe a specific LCIA method, leading to variations in the choice of LCIA method in different studies [10]. Several studies have compared different LCIA methods [8,11] and have consistently found that the selection of LCIA method significantly influences the results and conclusions. The variations observed can be attributed to inherent distinctions in characterization models, resulting in divergent characterization factors (CFs) for the same substance, and in some instances, different contributing substances for a given impact category. These differences arise due to variations in the processes considered, the temporal and regional scales accounted for and the specific research emphases of the institutions developing the assessment methods. Ref. [8] recommends adopting the most recent LCIA methodology, but it is essential to recognize that updates to these methods could potentially alter the conclusions derived from LCA case studies.

The chosen approach, ReCiPe 2016 [12], provides a harmonized implementation of cause–effect pathways for calculating both midpoint and endpoint characterization factors. The update of ReCiPe aimed to address certain limitations by providing CFs that are globally representative, while still allowing for country-specific CFs for certain impact categories and improving the characterization models to determine the mid-to-endpoint factors. This enhancement represents a significant step forward in refining the LCIA methodology and addressing the challenges in characterizing environmental impacts.

2.1. Goal and Scope

The goal of this study is to assess the environmental impact of four different packaging solutions, as summarized below. The first packaging solution, Ecobundle, comprises a corrugated board tray with a paper handle. The second solution, called Ecogrip 2.0, consists of a corrugated board element combined with a stretchable strip of kraft paper. The third solution involves plastic film made of LDPE with a Monoaxially Oriented Polypropylene (MOPP) handle, which is commonly used for transporting plastic bottles. The fourth solution is the same as solution three, using recycled LDPE called rLDPE.

Additionally, a water-repellent coating (Ter-Coat VPK 1, developed for this application) is applied to the bundles to ensure their resistance to moisture, particularly when transporting them in rainy environments. Moreover, for outdoor storage of the bundles, pallet packaging plays a crucial role in providing the necessary water repellency. These measures are implemented to ensure the integrity and performance of the bundles, even in challenging environmental conditions.

Attachment A provides an overview of the products including all necessary data. To evaluate the environmental impacts of these products, a model will be developed using the Simapro software version 9.3.0.3.

2.2. Functional Unit

The chosen functional unit for this study is a packaging unit consisting of six 1.5 L PET bottles of mineral water bundled together with secondary packaging. This unit is deemed representative for assessing the environmental impacts of the packaging, considering its dimensions and weight. By understanding the impacts of a specific packaging format, it becomes possible to compare it with other packaging formats based on weight. This selected unit allows for the evaluation of the environmental impact of packaging of varying sizes, making it a valuable tool for comparison and analysis.

While packaging serves functions such as protecting the contents during storage and transport and acting as a marketing tool, this study solely focuses on examining the life cycle and environmental impact of the packaging. The functional properties and requirements related to durability and transportation handling are subjects of extensive research in other studies, but are not the primary focus here.

2.3. System Boundaries

The boundaries of the system under consideration in this study were defined as "cradle to grave". This includes everything concerning the production, transport and end-of-life of the product. To facilitate analysis, the system can be divided into three modules, as summarized in Table 2 below. Not considered in the study is the use phase of the product, which encompasses the period from when the packaging leaves the packaging plant until just before it is discarded by the consumer. This simplification has little impact, as the weight of packaging during transport compared to the weight of the packaged goods is negligible.

Table 2. System diagram PCR "packaging".

UPSTREAM	Raw material supply Transport Manufacturing
CORE	Packaging Forming
DOWNSTREAM	Transport to recovery/disposal EOL scenarios

2.4. Life Cycle Inventory

The LCA model utilized in this study was developed with inputs collected from three main sources: data provided by the case company, the Ecoinvent® database (version 3.6) and the relevant literature. The SimaPro software 9.3.0.3 was employed for all calculations and analyses. The study focused on quantifying the environmental aspects of the system, such as energy usage and material inputs, and assessing the life cycle impacts associated with these aspects. Below is a breakdown of the data used for the study, categorized as follows:

Primary data:

Specific data from the year 2021, obtained from Blue Box Partners [13] were utilized, encompassing the following aspects:

1. Qualitative information on raw materials used;
2. Weight of the finished product;
3. Electricity consumption during the packaging forming phase.

Secondary data:

For production processes and technologies, along with the impacts of raw and auxiliary materials, datasets from the Ecoinvent 3.6 database were employed. The selected processes and material productions have European geographical coverage, with efforts made to align them with the relevant geographical area wherever possible.

Proxy data:

No proxy data were used in the analysis.

The combination of primary data from the case company, relevant datasets from the Ecoinvent database and information from the literature allowed for a comprehensive assessment of the environmental and impact aspects within the life cycle of the packaging systems under study. Process names are visualized in *cursive grey*.

2.4.1. (Recycled) Shrink Film Packaging

Figure 2 provides an overview flowchart of the shrink film packaging process. The process starts with LDPE and MOPP production, which are then transported to the site where the water bottles are packaged. The transport steps indicated in the figure signify the use of adjustable values (explained in 2.4.4 Transport), as transport distances can range from small to large values.

In total, 84 of these water bottle packages will be placed on a pallet with corrugated board interlayers and stretch film wrapping. In the model, the indicated numbers will be adapted to the life cycle of one declared unit. The use phase will not be taken into consideration. For the end-of-life phase, both transport and disposal are included.

For the packaging film, the "*Packaging film, low-density polyethylene RER—production—Cut-off, S + Transport2*" process was used. This process includes both the production of LDPE film and the transportation to the packaging plant. By manually incorporating transportation, the distance can be varied as needed.

In regard to rLDPE, because the Ecoinvent database does not include a process for recycled LDPE, the process for recycled HDPE—"*Polyethylene, high density, granulate, recycled {Europe without Switzerland}|production, |Cut-off, S*"—was used. The auxiliary data and energy associated with converting HDPE granulate to packaging film were gathered from the "*Extrusion, plastic film {GLO}|market for |Cut-off, S*" process. In the Ecoinvent dataset, the mass input of the material was re-proportioned to obtain a more realistic value.

The MOPP handle utilizes the "*Oriented polypropylene film E*" process, which is not an Ecoinvent process, but is included in the industry data 2.0 database; no additional transport is accounted for.

In the case of the shrink film packaging solution, multiple recycled corrugated board interlayers are employed, as described earlier. The process for the corrugated board is "*Corrugated board (recycled base paper) + transport,*" which includes transportation from the corrugated board factory to the packaging plant.

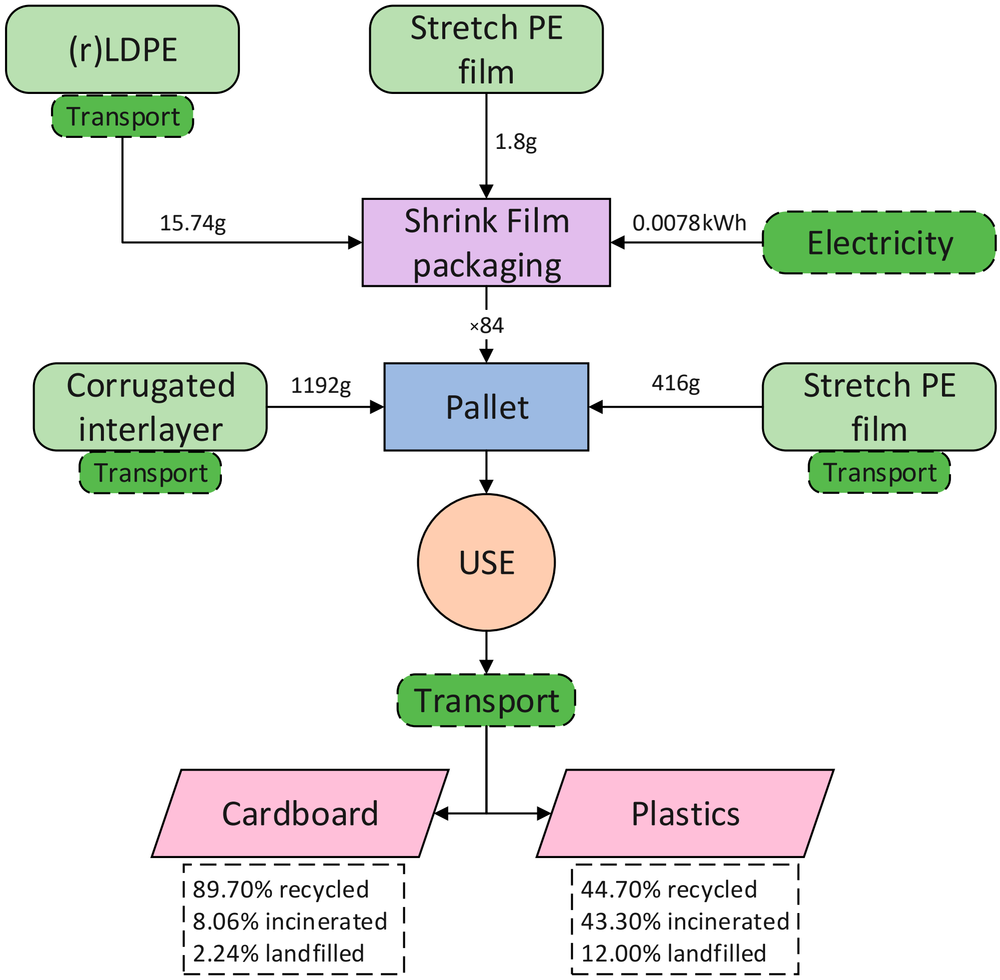

Figure 2. SimaPro model (recycled) Collation shrink film.

Furthermore, a heat-shrink film is used, which shares the same plastic as the packaging itself. Thus, the "*Packaging film, low-density polyethylene RER—production—Cut-off, S + Transport*" process is employed. This film consistently utilizes virgin LDPE. As this type of film is used across all three packaging methods, the choice has minimal impact.

Specific details of the packaging process are not disclosed in the available data. However, the energy consumption associated with the Variopac Pro packaging machine of Krones [14] used for forming the 6-bottle pack is attributed to the "*Electricity, medium voltage RER—market group for—Cut-off, S*" process.

Given that the use phase is not considered in the model, it assumes that the packaging is discarded immediately after production. Transport of the materials to the disposal site is included, as discussed in 2.4.4 Transport. The end-of-life scenario used is "*Packaging waste (waste scenario)(modified) BE—treatment of packaging waste—Cut-off, S*.

In addition, a heat-shrink film is used. This is associated with the same plastic as in the shrink film process; the *Packaging film, low-density polyethylene RER—production—Cut-off, S + Transport* process is thus used. This process for transport packaging is identical for all four packaging concepts.

2.4.2. Ecobundle

Figure 3 provides an overview flowchart of the Ecobundle packaging process. The process starts with corrugated board, paper and glue production. These are then transported to the site where the water bottles are packaged. If transport is indicated, it means this is a variable that can be altered, as explained in 2.4.4 Transport. Subsequently, 84 of these packages will be placed on a pallet with corrugated board interlayers and stretch film wrapping. In the model, the indicated numbers are adapted for only one declared unit. The use phase will not be taken into consideration. For the end-of-life phase, transport and the disposal itself are included.

Corrugated board is made from two types of so-called base papers and fluting medium in between these two layers, as shown in Figure 4. Depending on the origin of these base papers, different names may be used. Linerboard can be split into kraftliner (virgin material) and testliner (recycled). Fluting medium can be split into semi-chemical fluting (virgin material) and wellenstof (recycled). The final corrugated board for this packaging consists of 64% linerboard and 36% fluting medium (based on mass fraction) [13,15,16].

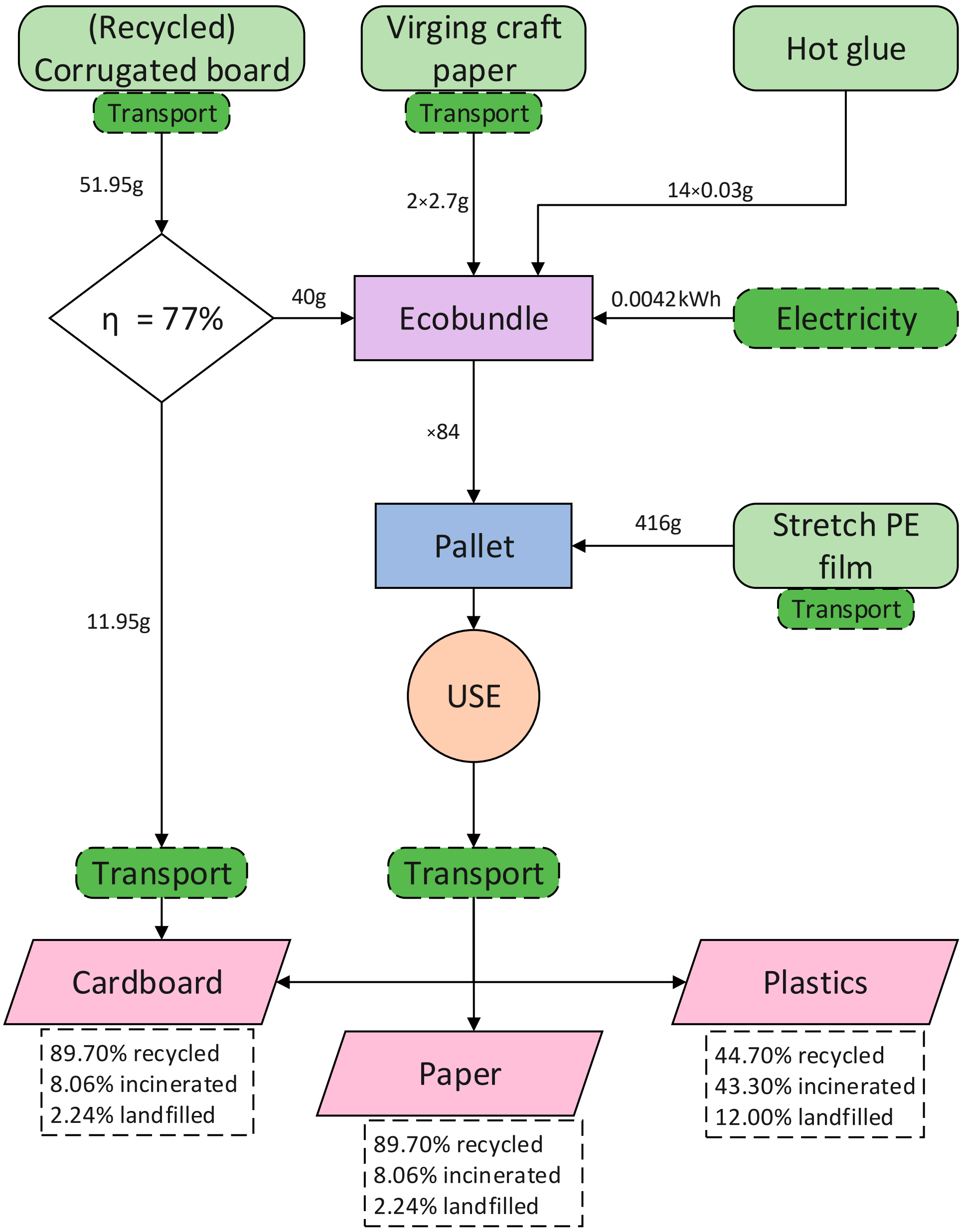

Figure 3. SimaPro model Ecobundle.

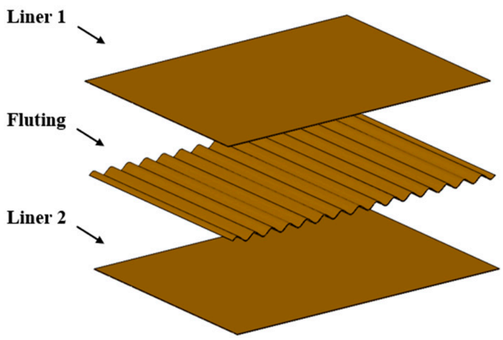

Figure 4. Corrugated board.

For the Simapro model, a new process is defined that takes the corrugator process into account. Data for this process are obtained from an LCA by FEFCO (European Federation of Corrugated Board Manufacturers) [15]. For fluting, the Ecoinvent process—"*Containerboard, fluting medium {RER}—containerboard production, fluting medium, recycled—Cut-off, S*"—is used; for linerboard, the "*Containerboard, fluting medium {RER}—containerboard production, linerboard, testliner, recycled—Cut-off, S*" process is used.

In the report by FEFCO, a category called residues, consisting of waste- and by-products, is added. The assumption is that these materials can be used in different processes, and the responsibility for processing them falls on the process that utilizes them. This is the case because the cut-off by classification system is used. It is thus a good assumption to neglect them. Also, transport from the corrugated board factory to the packaging plant and cutoff of the corrugated board tray is included.

The paper handle of stretchable kraft paper was associated with the "*Kraft paper, unbleached RER—production—Cut-off, S + transport*" process. This module includes the European production of unbleached kraft paper in an integrated mill. Transport to the packaging plant is manually added.

The glue used for Ecobundle is EVA-based hotmelt: it was associated with the Ecoinvent *dataset Ethylene vinyl acetate copolymer RER—market for ethylene vinyl acetate copolymer—Cut-off, S*. Because this is a market process, average transport distances are included. No extra transport step is modeled.

The exact details of the packaging process are not disclosed in the data. Only the energy consumption for the formation of the 6-bottle pack was associated with the processing of *Electricity, medium voltage RER—market group for—Cut-off, S*. Because the use phase is not taken into account, the model assumes that the packing is thrown out directly after production. Transport of the materials to the disposal site is included.

2.4.3. Ecogrip

Figure 5 shows the flowchart of Ecogrip 2.0 and shows the similarities with the Ecobundle process given in Figure 3. The main difference is that this packaging does require corrugated board interlayers. The processes for corrugated board, glue and stretchable paper are the same. Table 3 compares Ecogrip and Ecobundle in terms of corrugated board and paper use. The total mass of the corrugated board and paper is almost identical. It is thus assumed that the eventual results will be similar. Only the different production methods of paper and corrugated board will play a role.

Table 3. Total weight comparison of Ecogrip and Ecobundle.

Material	Ecogrip	Ecobundle
Corrugated board	47.40 g	51.95 g
Paper	10.00 g	5.40 g
Corrugated board + Paper	57.40 g	57.35 g

2.4.4. Transport

Transportation is a critical component in the life cycle of the given products, contributing to their overall environmental impact. Transportation encompasses various stages, including the transportation of materials, product distribution to consumers and transportation to end-of-life disposal.

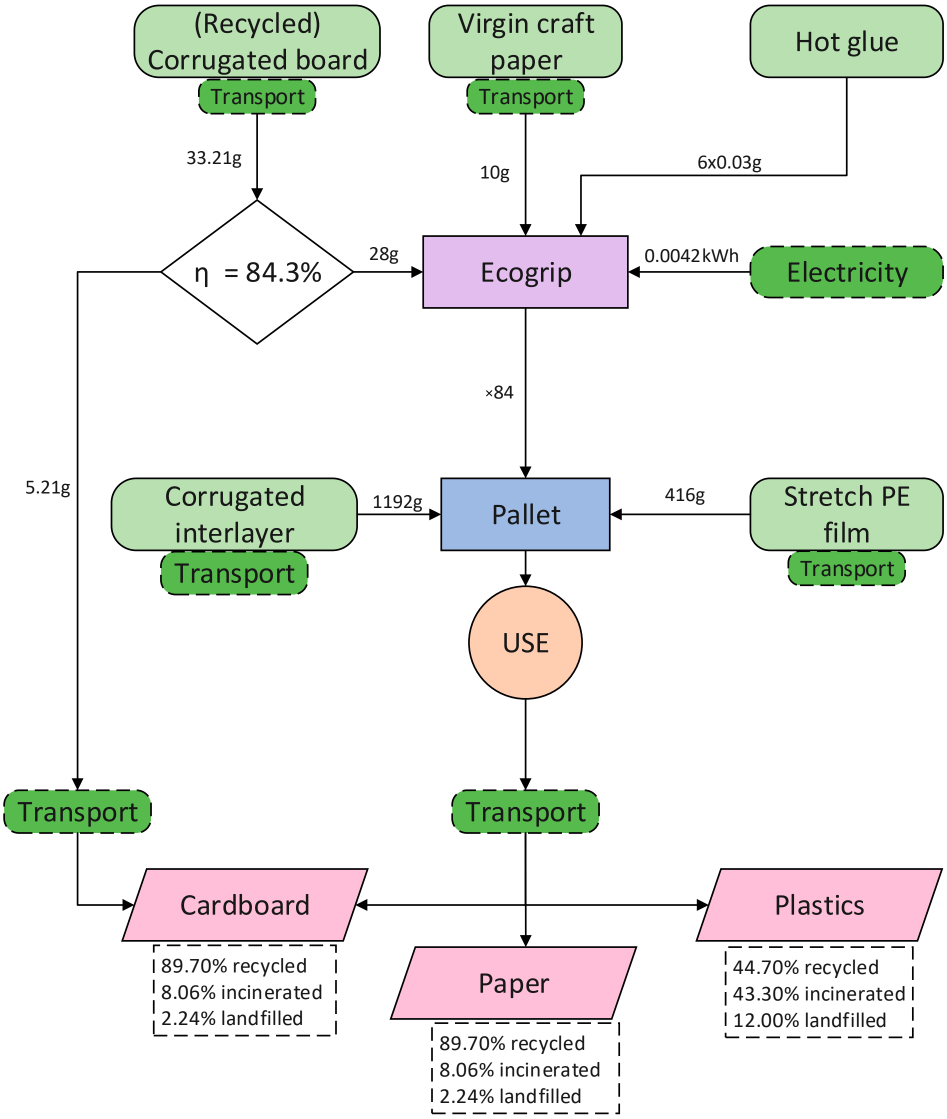

Figure 5. SimaPro model Ecogrip.

To assess the transport impacts, the concept of the "location of the average consumer" is employed. This location is defined as the demographic center point of Belgium, which is determined by averaging the geographic locations of the 50 most populous municipalities in Belgium [17]. The result is the demographic center coordinate: (50.89, 4.37), located just above Brussels. Several transportation steps are considered:

- Transport from the VPK corrugated board factories to water plants in Europe: the transportation distance from VPK corrugated board factories [18] to major bottling companies in Europe [18] is taken into account.
- Transport from the water factory to the average consumer in Belgium: the transportation distance from the water factories [19] to the average consumer in Belgium is considered. These data are not used in the model because this transport is part of the use phase.

- Transport from the consumer to the waste disposal: the transportation distance is determined based on the location of incinerators in Belgium [20] and the demographic center; the average distance is 60.614 km.

Only two distances will be implemented in the model. The first distance, from consumer to disposal, is taken as 60.614 km and will be kept constant. The second distance implemented is the transport between the material production sites and packaging plant. In this step, the distance from VPK corrugated board factories in Europe to the water plants in Europe will be used. Considering the values, given all possible combinations, a representative distance of 500 km was chosen. For plastic packaging, materials are assumed to be transported over the same distance.

This means that for the shrink film version, transport is included for (r)LDPE, corrugated board for interlayer and film for wrapping. For Ecogrip, this transport includes corrugated board (packaging and interlayer), paper and film for wrapping. For Ecobundle, this transport includes corrugated board, paper and wrapping film. All these materials will be transported over the same distance, chosen initially as 0 km. This distance will later be changed to 500 km for sensitivity analysis. These distances will be implemented as road transport using the *Transport, freight, lorry, unspecified RER—market for transport, freight, lorry, unspecified—Cut-off, S process*.

Materials not listed either have no transport included or are market processes, where average distances are used.

2.4.5. End of Life

The end-of-life scenario is evaluated through a modified version of the packaging waste process that is integrated into the Ecoinvent database: *Packaging waste (waste scenario)(modified) BE—treatment of packaging waste—Cut-off, S*. The recycled fractions are adjusted using the data from 'statistiek Vlaanderen' [21] and shown in Table 4. The fractions of waste that are not recycled are distributed, with 78.3% allocated to incineration and 21.7% to landfill disposal.

Table 4. End of life (Belgium, 2020) [21].

Material	Fraction Recycled [%]
CORRUGATED BOARD AND PAPER	89.7
GLASS	96.9
METALS	96.2
PLASTICS	44.7

An average transport distance of 50 km was applied to all of the considered waste, using the "*Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 |Cut-off, S*" process.

3. Results

This section will discuss the impact of the four products. To achieve the most complete assessment, first, the midpoint indicators calculated with the ReCiPe 2016 Midpoint (H) V1.04/World (2010) H are analyzed. The results for all of the midpoint indicators will be compared for all of the products and, subsequently, the life cycle networks for each product will be individually inspected to gain insight into the impacts of each step in the life cycle. Next, the aggregated endpoint results are calculated using ReCiPe 2016 Endpoint (H) V1.04/World (2010) H and the results are discussed.

ReCiPe stands out as a state-of-the-art impact assessment method widely adopted by professionals in the field of life cycle assessment. Its comprehensive approach addresses various environmental aspects at the midpoint level and subsequently aggregates these midpoints into three endpoint categories, as depicted in Figure 6. At the endpoint level, the method characterizes the impacts on the areas of protection, including human health, ecosystems and resources. In essence, the endpoint offers a measure of the overall damage caused by a stressor at the end of the cause–effect chain, expressed in terms of human life years lost, years lived with disability, species extinction and resource depletion [12].

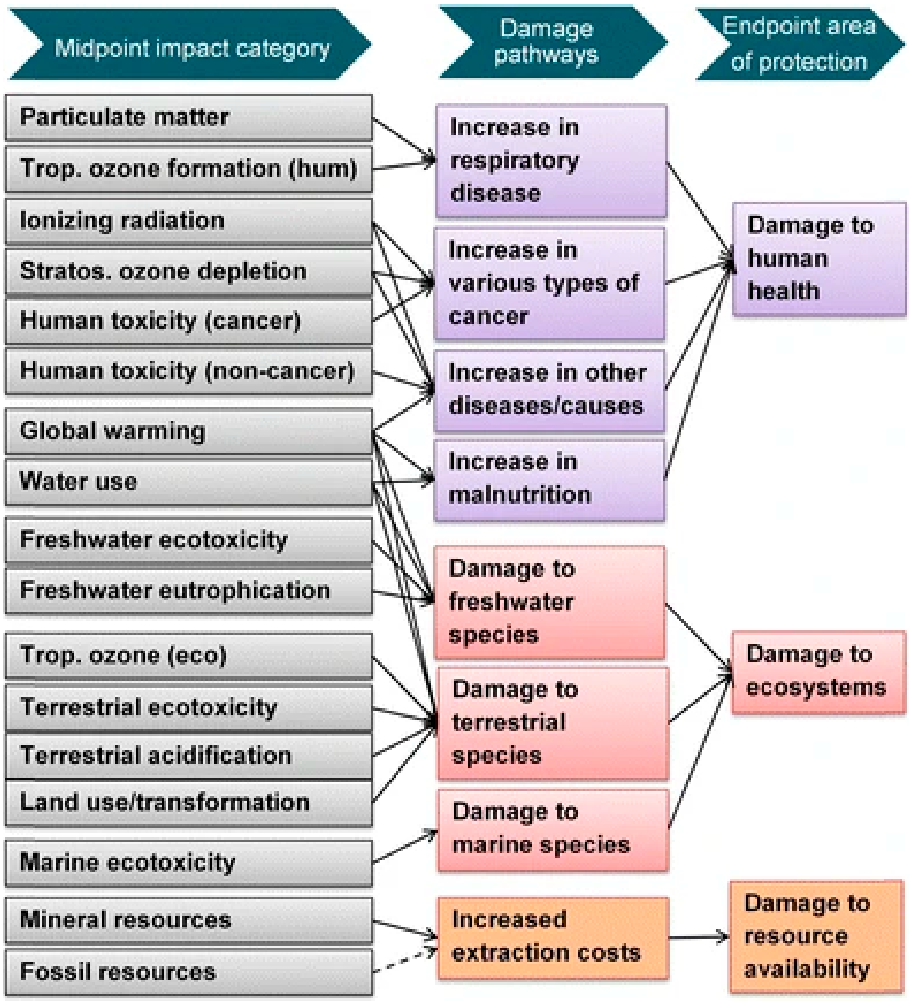

Figure 6. Overview of the impact categories that are covered in the ReCiPe 2016 method and their relation to the areas of protection [12].

LCA practitioners have the flexibility to select impact indicators at various points within the cause–effect pathway, whether at the midpoint or endpoint level, based on their specific research objectives. This allows for a comprehensive assessment of the environmental impacts throughout the life cycle of a studied system, providing valuable insights for decision making and sustainable product development.

Within a Life Cycle Impact Assessment (LCIA), two main approaches are employed to analyze the environmental impacts of a product: midpoint methods and endpoint methods. Midpoint methods assess the effects of emissions before any damage to the areas of protection occurs, offering relatively low uncertainty but presenting challenges in interpreting complex results due to the multitude of included impact categories. Conversely, endpoint methods track the consequences of emissions until they lead to actual damage, providing more accessible outcomes for non-experts, although introducing additional uncertainty during the conversion from mid- to end-point impacts. Endpoint results can be aggregated, yielding a single score that comprehensively represents the product's environmental impacts. However, this process requires normalization and weighting, which may introduce subjective choices and increase uncertainty.

To facilitate the interpretation of midpoint impact scores in life cycle assessments, normalization is commonly applied by dividing the scores by reference values from a specific situation, such as an average world citizen's share of global emissions and resource use. Normalization transforms complex units into fractions, making the scores easier to comprehend across various impact categories. ReCiPe offers multiple normalization factors, and in this case study, the impact of an average world citizen was utilized as the reference situation.

3.1. Midpoint Assessment

Figure 7 shows the total global warming impact of the different packaging options. It shows that both Ecogrip and Ecobundle have an improved impact on the GWP compared to conventional LDPE packaging. Compared to each other, they score similar, as predicted in Section 2.4.3.

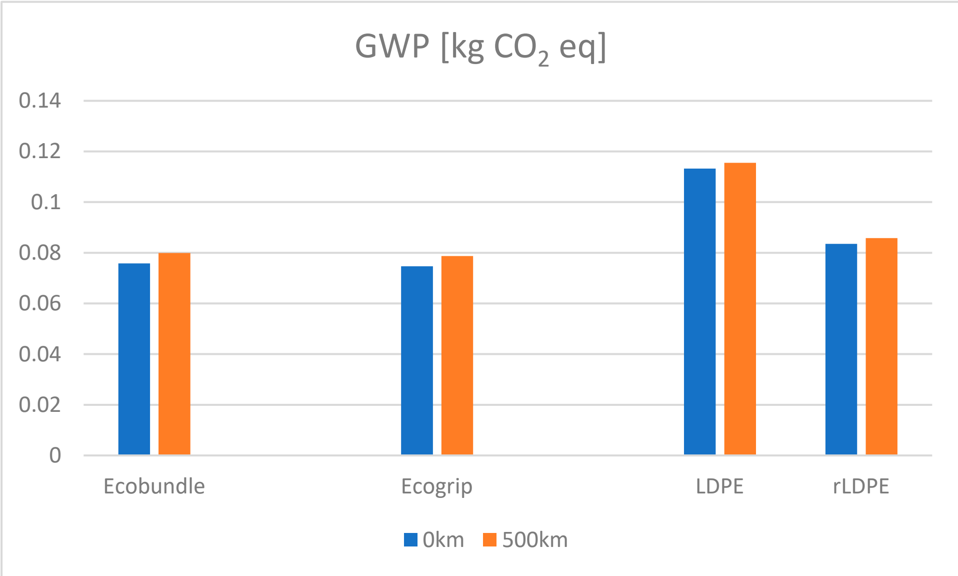

Figure 7. Global warming impact.

The use of corrugated board and paper instead of LDPE explains the improved score on almost all of the 18 indicators (Appendix B). It is clear that the shrink film consistently has a higher environmental impact compared to the other packaging options.

For the completeness of the study, four additional indicators were selected from the eighteen indicators to evaluate the packaging. For this purpose, the parameters with the highest absolute impact were chosen, while ensuring that one indicator was selected from each impact class (Ecological, Human Health and Resources) [22]. Tables A2 and A3 in attachment B shows the midpoint results. It is important to note that the results are normalized, meaning that each impact category is not weighted in relation to the others. Therefore, comparisons should be made within a single impact category rather than across different categories.

Figure 8 illustrates that Ecobundle is consistently the lowest impact solution among the evaluated solutions. In three out of the four impact categories, Ecogrip emerges as the second most favorable option.

The results for terrestrial ecotoxicity, shown in Figure 8, are dominated by the end-of-life processes. The impact of the fiber-based solutions is almost double that of the two plastic-containing packaging options. The dominance of pesticide emissions to agricultural soil and the utilization of sulphuric acid and steam during the conversion process play substantial roles in driving the terrestrial ecotoxicity impact.

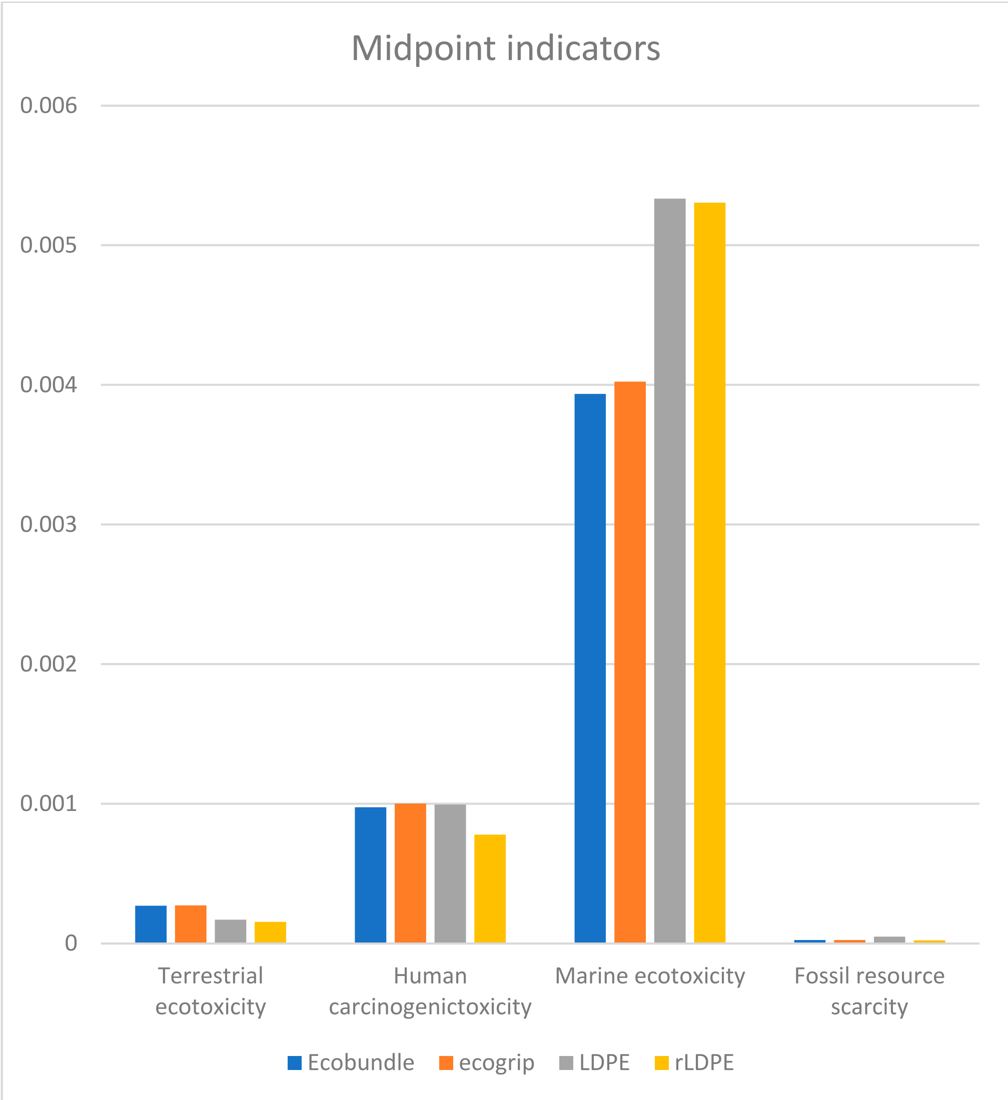

Figure 8. ReCiPe midpoint indicators.

Within Figure 8—specifically focusing on human carcinogenic toxicity—the overall impact predominantly arises from emissions originating during the manufacturing phase. The characterization factor associated with human toxicity encompasses several critical dimensions, encompassing a chemical's environmental persistence (fate), its potential accumulation in the human food chain (exposure) and its inherent toxicity (effect). Figure 9 provides a visual representation of the comprehensive cause–effect pathway, commencing with emissions into the environment, traversing through fate and exposure routes and culminating in disease incidences that ultimately compromise human health. Notably, within the three presented alternatives, the rLDPE option emerges as an exception, exhibiting a considerably reduced environmental footprint.

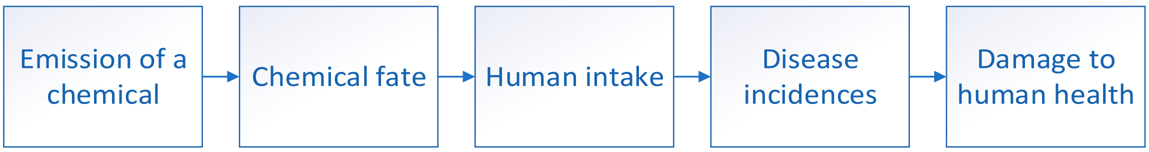

Figure 9. Cause–effect chain, from emissions to damage to human health.

In terms of marine ecotoxicity (METP), Figure 8 highlights a notable drawback of plastics in comparison to corrugated board at end-of-life. The potential environmental impact on marine ecosystems could be heavily influenced by the introduction of additional quantities of metals into oceans, which are known to trigger toxic effects. These metals encompass cobalt, copper, manganese, molybdenum and zinc. The difference between plastics and corrugated board in this regard is substantial, exposing a significant issue associated with plastic materials. Moreover, it is plausible that the actual effects of plastic waste on marine ecosystems might be underestimated [23] given that the existing data only encompass certain emissions resulting from the unregulated disposal of plastic waste (such as open dumping), while disregarding plastic waste leakage and littering in regions with organized waste management systems.

In the fossil depletion category (Figure 8), the impacts are caused by transport and manufacturing. It is evident that LDPE results in higher fossil depletion due to the production of plastics, whereas the fiber-based alternative has a significantly lower impact.

3.2. Endpoint Assessment

The endpoint analysis provides a different perspective on the results compared to the midpoint analysis, with the endpoint indicators considering weighted factors. Figure 10 provides a graph with a single score for all of the packaging options. Figures 11 and 12 give the distribution over the different classes. From these figures, it becomes apparent that human health is more significantly impacted compared to ecosystems or resources. Furthermore, the endpoint results indicate that the shrink film has a significantly higher impact compared to other packaging options. However, the analysis also clearly shows that using recycled shrink film has a larger positive impact compared to the alternative corrugated board options. The effect of transport is again small. The relative increase in the impact for corrugated board products is higher than for plastic products. Another observation is that the end-of-life has a higher impact on plastic packaging compared to the corrugated board packaging.

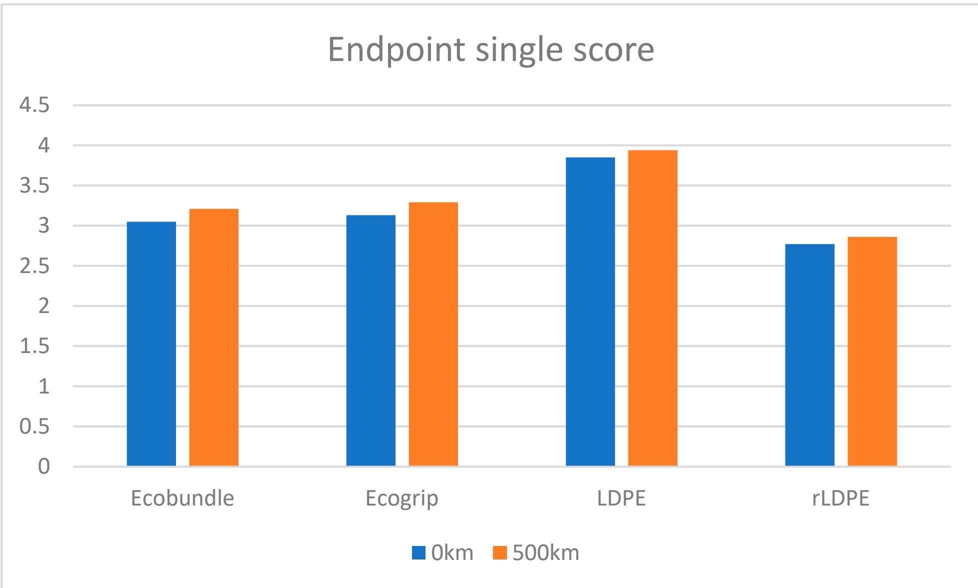

Figure 10. Endpoint single score.

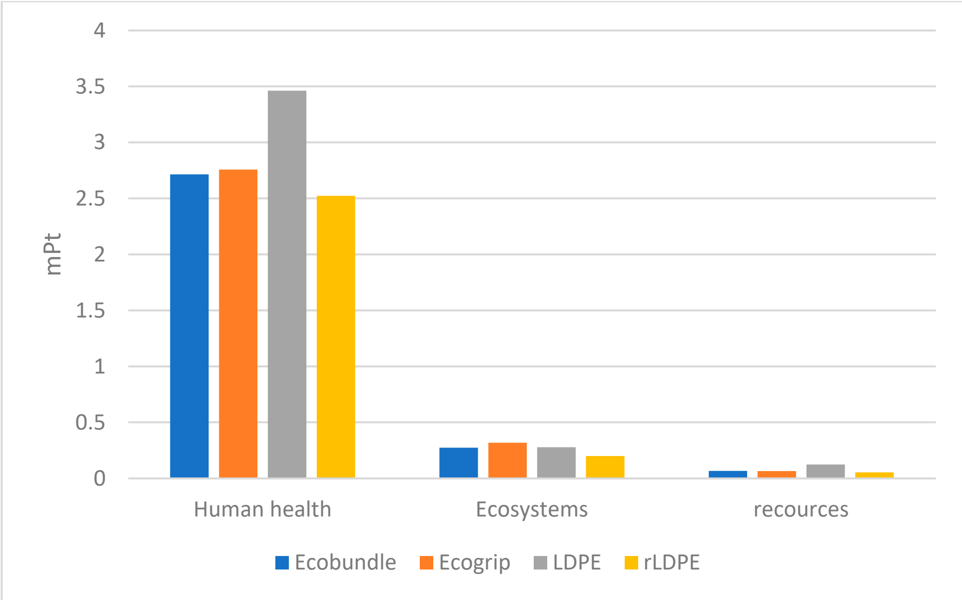

Figure 11. ReCiPe endpoint (0 km).

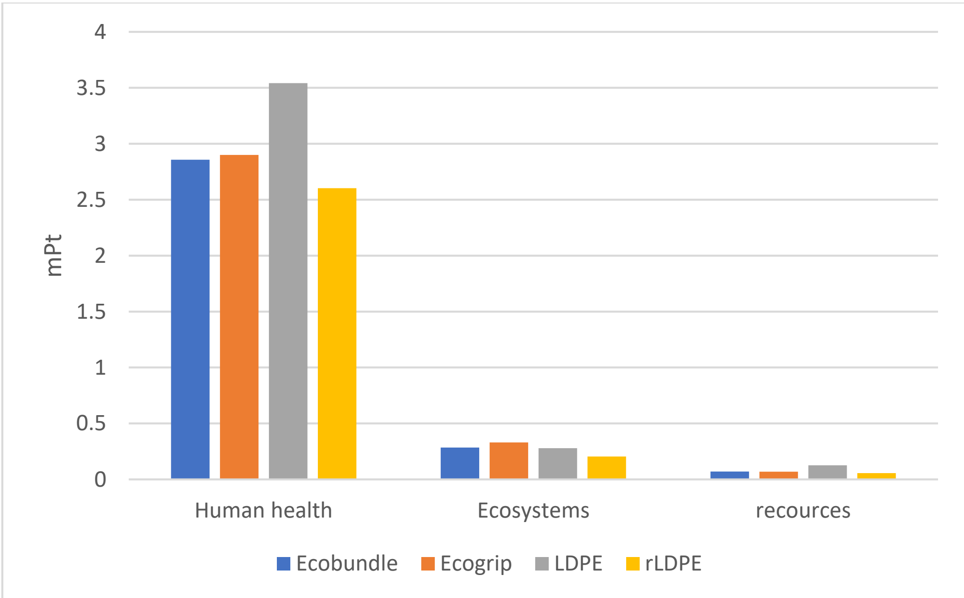

Figure 12. ReCiPe endpoint (500 km).

4. Discussion

The potential benefits of fiber-based packaging are evident, particularly when considering end-of-life scenarios [24]. Fiber-based packaging materials demonstrate a significantly higher recycling rate compared to plastics, with paper and corrugated board achieving an impressive 81.5% recycling rate in Europe in 2020 [5]. Moreover, the use of fiber-based materials contributes to a more sustainable cycle, releasing biogenic CO_2 and minimizing fossil CO_2 emissions during incineration.

The results also indicate that rLDPE emerges as a viable alternative to LDPE shrink film, which we aim to replace. However, our test results do not account for the availability of LDPE recyclate. At present, there is a shortage of recycled LDPE pellets in the market, leading to higher prices for rLDPE [25]. In addition, not all rLDPE is of good quality. Therefore, the available rLDPE could be applied to applications where it is impossible to replace the plastic with a corrugated-based alternative if Ecobundle is used to replace collation shrink film.

Despite the advantages of fiber-based packaging, the transition from LDPE to fiber-based materials comes with some concerns, primarily related to the increase in weight. Corrugated board, being a relatively heavy material, could lead to higher energy consumption and transport costs. However, the innovative design of Ecobundle addresses this issue by reducing the additional weight through the exclusion of heavy interlayer sheets from the transport packaging, instead utilizing the tray's bottom as an interlayer sheet.

5. Conclusions

Based on the findings of this study, it can be concluded that fiber-based packaging, particularly with the help of well-designed solutions like Ecobundle, may offer a functional and ecological alternative to LDPE packaging. However, for every specific bundle packaging, a specific optimization of the Ecobundle concept should be performed. The consequent LCA studies could benefit from enhancements in several areas, including accurately determining the distances for sourcing plastic materials and incorporating different transportation modes to better account for transportation impacts. More detailed assessments of the sub-processes involved in corrugated board production, additional data for the shaping process and the inclusion of other relevant factors should also be considered for a more comprehensive evaluation.

By continuously improving LCA methodologies and exploring innovative packaging designs, we can drive the transition to more sustainable and circular packaging practices, meeting both consumer expectations and environmental goals. The results of this study can provide valuable insights for the packaging industry and contribute to the collective effort towards a more sustainable future.

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Appendix A

Table A1. Products covered by the LCA study.

Product 01	

Table A1. *Cont.*

Commercial name	LDPE and rLDPE shrink film
Packaging type 'declared unit'	Bundle packaging for 6 PET bottles 1.5 L each
Materials	LDPE or rLDPE film and MOPP handle
Weight	Wrapping film: 15.74 g MOPP handle: 1.8 g
Max number of uses	01—Single use
Distribution packaging	Corrugated interlayer 14.19 g Stretch PE film 4.95 g
Product 02	
Commercial name	Ecogrip
Packaging type'declared unit'	Bundle packaging for 6 PET bottles 1.5 L each
Materials	Corrugated board + stretch kraft paper
Weight	Stretch band of virgin kraft paper: 10 g Corrugated recycle d board: 28 g Hot glue: 6 × 0.03 g
Max number of uses	01—Single use
Distribution packaging	Corrugated interlayer:14.19 g Stretch PE film 4.95 g
	
Commercial name	Ecobundle
Packaging type 'declared unit'	Bundle packaging for 6 PET bottles 1.5 L each
Materials	Corrugated board + stretch kraft paper
Weight	Virgin kraft paper handle: 2 × 2.7 g Corrugated recycled board: 40 g Hot glue: 14 × 0.03 g
Max number of uses	01—Single use
Distribution packaging	Stretch PE film 4.95 g

Appendix B

Table A2. Midpoint indicators 0 km transport.

0 km Transport					
Indicator	**Unit**	**Ecobundle**	**Ecogrip**	**Shrink Film**	**Shrink Film rLDPE**
Global warming	-	9.75×10^{-6}	9.59×10^{-6}	1.46×10^{-5}	1.07×10^{-5}
Stratospheric ozone depletion	-	9.04×10^{-7}	9.84×10^{-7}	5.57×10^{-7}	4.77×10^{-7}
Ionizing radiation	-	2.22×10^{-5}	2.28×10^{-5}	1.65×10^{-5}	1.15×10^{-5}
Ozone formation, Human health	-	1.17×10^{-5}	1.16×10^{-5}	9.86×10^{-6}	6.17×10^{-6}
Fine particulate matter formation	-	5.00×10^{-6}	4.99×10^{-6}	4.17×10^{-6}	2.76×10^{-6}
Ozone formation, Terrestrial ecosystem	-	1.39×10^{-5}	1.39×10^{-5}	1.22×10^{-5}	7.42×10^{-6}
Terrestrial acidification	-	6.47×10^{-6}	6.50×10^{-6}	6.39×10^{-6}	4.08×10^{-6}
Freshwater eutrophication	-	6.44×10^{-5}	6.44×10^{-5}	4.33×10^{-5}	2.99×10^{-5}
Marine eutrophication	-	1.79×10^{-6}	1.75×10^{-6}	1.51×10^{-6}	1.82×10^{-6}
Terrestrial ecotoxicity	-	0.00027	0.00027275	0.0001698	0.00015395
Freshwater ecotoxicity	-	0.0024582	0.00251061	0.0033465	0.00332101
Marine ecotoxicity	-	0.003936	0.00402324	0.0053337	0.00530539
Human carcinogenic toxicity	-	0.0009747	0.0010012	0.0009941	0.0007789
Human non-carcinogenic toxicity	-	0.0005092	0.00054975	0.0005123	0.00048157
Land use	-	1.10×10^{-5}	1.17×10^{-5}	5.80×10^{-7}	5.57×10^{-7}
Mineral resource scarcity	-	1.53×10^{-9}	1.54×10^{-9}	1.46×10^{-9}	1.18×10^{-9}
Fossil resource scarcity	-	2.48×10^{-5}	2.43×10^{-5}	4.81×10^{-5}	2.23×10^{-5}
Water consumption	-	4.74×10^{-6}	5.44×10^{-6}	6.95×10^{-6}	5.09×10^{-6}

Table A3. Midpoint indicators 500 km transport.

500 km Transport					
Indicator	**Unit**	**Ecobundle**	**Ecogrip**	**Shrink Film**	**Shrink Film rLDPE**
Global warming	-	1.03×10^{-5}	1.01×10^{-5}	1.49×10^{-5}	1.10×10^{-5}
Stratospheric ozone depletion	-	9.36×10^{-7}	1.02×10^{-6}	5.75×10^{-7}	4.95×10^{-7}
Ionizing radiation	-	2.24×10^{-5}	2.30×10^{-5}	1.66×10^{-5}	1.16×10^{-5}
Ozone formation, Human health	-	1.27×10^{-5}	1.27×10^{-5}	1.05×10^{-5}	6.77×10^{-6}
Fine particulate matter formation	-	5.22×10^{-6}	5.22×10^{-6}	4.30×10^{-6}	2.89×10^{-6}
Ozone formation, Terrestrial ecosystem	-	1.52×10^{-5}	1.52×10^{-5}	1.29×10^{-5}	8.13×10^{-6}
Terrestrial acidification	-	6.79×10^{-6}	6.82×10^{-6}	6.58×10^{-6}	4.26×10^{-6}
Freshwater eutrophication	-	6.49×10^{-5}	6.49×10^{-5}	4.35×10^{-5}	3.02×10^{-5}
Marine eutrophication	-	1.80×10^{-6}	1.76×10^{-6}	1.52×10^{-6}	1.83×10^{-6}
Terrestrial ecotoxicity	-	0.0003481	0.00035093	0.0002135	0.00019769
Freshwater ecotoxicity	-	0.0025355	0.00258799	0.0033897	0.0033643
Marine ecotoxicity	-	0.004098	0.0041854	0.0054245	0.0053961
Human carcinogenic toxicity	-	0.0010068	0.00103336	0.0010121	0.00079688
Human non-carcinogenic toxicity	-	0.00053	0.00057061	0.0005239	0.00049324
Land use	-	1.10×10^{-5}	1.17×10^{-5}	6.01×10^{-7}	5.77×10^{-7}
Mineral resource scarcity	-	1.66×10^{-9}	1.67×10^{-9}	1.53×10^{-9}	1.25×10^{-9}
Fossil resource scarcity	-	2.63×10^{-5}	2.58×10^{-5}	4.89×10^{-5}	2.31×10^{-5}
Water consumption	-	4.77×10^{-6}	5.47×10^{-6}	6.96×10^{-6}	5.10×10^{-6}

Appendix C

Table A4. Endpoint 0 km transport.

0 km Transport							
Impact Class	**Eenheid**	**Ecobundle**	**Ecobundle (Recycled)**	**Ecogrip**	**Ecogrip (Recycled)**	**Shrink Film**	**Shrink Film rLDPE**
Total	mPt	3.639	3.0554	3.6721	3.1395	3.8581	2.7749
Human health	mPt	3.0525	2.7151	3.0648	2.7569	3.4619	2.5228
Ecosystems	mPt	0.5316	0.2738	0.5535	0.3183	0.2726	0.1986
Resources	mPt	0.055	0.0664	0.0538	0.0642	0.1235	0.0534

Table A5. Endpoint 500 km transport.

500 km Transport							
Impact Class	**Eenheid**	**Ecobundle**	**Ecobundle (Recycled)**	**Ecogrip**	**Ecogrip (Recycled)**	**Shrink Film**	**Shrink Film rLDPE**
Total	mPt	3.7975	3.2139	3.8307	3.2981	3.9468	2.8636
Human health	mPt	3.1952	2.8578	3.2076	2.8997	3.5417	2.6027
Ecosystems	mPt	0.543	0.2853	0.5649	0.3298	0.279	0.205
Resources	mPt	0.0594	0.0708	0.0582	0.0686	0.126	0.0559

References

1. Howard, B.C.; Gibbens, S.; Zachos, E.; Parker, E. A Running List of Action on Plastic Pollution. 2018. Available online: https://www.nationalgeographic.com/environment/article/ocean-plastic-pollution-solutions?user.testname=none (accessed on 1 August 2023).
2. Council directive 2019/904 on the reduction of the impact of certain plastic products on the environment. *Off. J. L155* **2019**, *2019*, 1–19.
3. NEN-EN 643:2014 Paper and Board—European List of Standard Grades of Recovered Paper and Board. Available online: https://www.scribd.com/document/512558233/SR-EN-643-2014 (accessed on 1 August 2023).
4. Council directive 94/62/EC on packaging and packaging waste. *Off. J. L365* **1994**, *1994*, 10–23.
5. Eurostat—Recycling Rate of Packaging Waste by Type of Packaging. Available online: https://ec.europa.eu/eurostat/web/products-datasets/-/cei_wm020 (accessed on 11 September 2023).
6. Roman, J.; Verschueren, G.; Nica, W.; Slaets, P.; Juwet, M. Cardboard Eco-Bundle as an Alternative for Collation Shrink Film. *Open J. Appl. Sci.* **2023**, *13*, 94–108. [CrossRef]
7. Roman, J.; Nica, W.; Teerlinck-Boelens, G.; Slaets, P.; Juwet, M. Paper as an alternative for collation shrink film. *Packag. Technol. Sci.* **2022**, *35*, 485–495. [CrossRef]
8. Bueno, C.; Hauschild, M.Z.; Rossignolo, J.A.; Ometto, A.R.; Mendes, N.C. Sensitivity analysis of the use of Life Cycle Impact Assessment methods: A case study on building materials. *J. Clean. Prod.* **2016**, *112*, 2208–2220. [CrossRef]
9. Eumos 40509:2020 Standard—Test Method for Load Unit Rigidity. Available online: https://sicurezzadelcarico.it/index.php/en/laws-regulations/technical-standards/eumos-40509/ (accessed on 1 August 2023).
10. Finkbeiner, M.; Inaba, A.; Tan, R.; Christiansen, K.; Klüppel, H.-J. The New International Standards for Life Cycle Assessment: ISO 14040 and ISO 14044. *Int. J. Life Cycle Assess.* **2006**, *11*, 80–85. [CrossRef]
11. Hauschild, M.Z.; Rosenbaum, R.K.; Olsen, S.I. *Life Cycle Assessment: Theory and Practice*, 1st ed.; Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I., Eds.; Springer International Publishing: Berlin/Heidelberg, Germany, 2018. [CrossRef]
12. Huijbregts, M.A.J.; Steinmann, Z.J.N.; Elshout, P.M.F.; Stam, G.; Verones, F.; Vieira, M.; Zijp, M.; Hollander, A.; van Zelm, R. ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. *Int. J. Life Cycle Assess.* **2017**, *22*, 138–147. [CrossRef]
13. Blue Box Partners. Available online: https://www.packaging4europe.com/ (accessed on 2 August 2023).
14. Krones Variopac Pro. Available online: https://www.krones.com/en/products/machines/versatile-packaging-machine.php (accessed on 2 August 2023).
15. Production Line of Cardboard. Available online: https://www.fefco.org/technical--information/production-process (accessed on 2 August 2023).
16. European Database for Corrugated Board Life Cycle Studies. Available online: https://www.fefco.org/sites/default/files/documents/2022/FEFCO_LCA_2022.pdf (accessed on 2 August 2023).
17. List of Most Populous Municipalities in Belgium. Available online: https://en.wikipedia.org/wiki/List_of_most_populous_municipalities_in_Belgium (accessed on 2 August 2023).

18. VPK Locations. Available online: https://www.vpkgroup.com/be-nl/locaties (accessed on 2 August 2023).
19. Europe Bottled Water Companies. Available online: https://www.mordorintelligence.com/industry-reports/europe-bottled-water-market/companies (accessed on 2 August 2023).
20. Afvalverbrandingsinstallatie. Available online: URL:https://nl.wikipedia.org/wiki/Afvalverbrandingsinstallatie (accessed on 2 August 2023).
21. Verpakkingsafval. Available online: https://www.vlaanderen.be/statistiek-vlaanderen/milieu-ennatuur/verpakkingsafval (accessed on 2 August 2023).
22. Carvalho, A.; Mimoso, A.F.; Mendes, A.N.; Matos, H.A. From a literature review to a framework for environmental process impact assessment index. *J. Clean. Prod.* **2014**, *64*, 36–62. [CrossRef]
23. Silva, N.; Molina-Besch, K. Replacing plastic with corrugated cardboard: A carbon footprint analysis of disposable packaging in a B2B global supply chain—A case study. *Resour. Conserv. Recycl.* **2023**, *191*, 106871. [CrossRef]
24. Nguyen, A.T.; Parker, L.; Brennan, L.; Lockrey, S. A consumer definition of eco-friendly packaging. *J. Clean. Prod.* **2020**, *252*, 119792. [CrossRef]
25. 8 FAQS About Post Consumer Recycled Resin (PCR Resin). Available online: https://www.aaapolymer.com/post-consumer-recycled-resin/ (accessed on 9 October 2023).