WHEN PLASTIC PACKAGING SHOULD BE PREFERRED: LIFE CYCLE ANALYSIS OF PACKAGES FOR FRUIT AND VEGETABLE DISTRIBUTION IN THE SPANISH PENINSULAR MARKET

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Abstract

Food packaging is an important industrial sector that has great influence on food loss and waste. The search of optimal conditions to minimize the negative impacts of food packaging on the environment must promote the selection of the best available packages. This work has evaluated the environmental impact of the distribution of fruit and vegetables in the Spanish peninsular context using reusable plastic crates and single-use cardboard boxes. Discussion and decision at each phase and step of the methodology were provided, being an example to follow for similar studies in the future. For the analysis, five different impact categories were considered: global warming potential, acidification potential, eutrophication potential, ozone depletion potential and photochemical oxidant creation potential. In addition, energy and water consumption were taken into account. According to the results of the analysis, the use of reusable plastic crates should be selected, since the values of all impact categories and energy consumption indicators were higher in the case of single-use cardboard boxes. The sensitivity analysis revealed a robust preference for plastic crates in comparison with cardboard boxes even in alternative scenarios, and only the hypothetic reduction of the quality of the cardboard resulted in significant lower impacts for cardboard boxes in comparison to plastic crates in photochemical oxidant creation potential, acidification potential, and energy consumption. This work demonstrates that plastic packaging should not be totally excluded or banned, since it can be the most environmentally friendly option in certain applications.

Keywords: Life Cycle Assessment (LCA); Fruit and Vegetables; Packaging; Distribution; Reusable Plastic Crates; Single-Use Cardboard Boxes.

1. Introduction

The packaging industry must be considered a relevant industrial sector since it is playing a more active role in the world economy (Rabnawaz et al., 2017). For example, the European packaging market accounted for €195 billion turnover in 2018, and, with an annual growth rate around 2%, it is expected to achieve €214 billion by 2023 (Platt, 2018). Meanwhile, total value in the global packaging industry will surpass $1 trillion in 2023, and, by 2028 an additional $150 billion will have been added to this market (Smithers-Pira, 2018). Packaging is much more than a simple container: packaging must satisfy protection, commercial, and logistics requirements from a sustainable perspective (González-Boubeta et al., 2018). This compromise towards sustainability has promoted a growing demand for returnable packages to be reused. The reuse principle, which refers to the repeated use of products and components for the same purpose for which they were conceived, is considered in the waste management hierarchy promoted by the EU in Directive 2008/98/EC as the second most preferable option just below prevention. Consequently, packaging reuse can become a critical strategy among waste prevention activities within the new framework defined by circular economy (Rigamonti et al., 2019).

The concept of circularity in the context of sustainable production describes the restorative and preservative character of a product. In contrast to the scheme in a linear economy (take, make, and dispose), circular economy proposes a scheme that requires the fabrication of products made out of renewable or recycled materials, produced using renewable energy and, being compostable, recyclable, or reusable after their service life (Pauer et al., 2019). In this context, the European Union has adopted a new set of measures, commonly referred to as the Circular Economy Package, to promote the transformation of Europe's economy into a more sustainable one (European Commission, 2015). In the particular case of packaging, these measures include several legislative proposals on waste, focused on increasing recycling rates, enhancing uptakes of secondary materials, and reducing food waste. For correctly choosing the proper waste circularity alternative, life cycle assessment (LCA) is the most commonly used methodology, being the impact allocation issues the most controversial (Civancik-Uslu et al., 2019a). Besides, the amended Directive 94/62/EC on Packaging and Packaging Waste both reinforce the role of LCA and complement the objectives above, since the proposed higher recycling rates require the redesign of packaging and higher investments in recycling infrastructures (Jora et al., 2018), preferably including different actors in the production chain (Civancik-Uslu et al., 2019b).

The growing public awareness about the negative impacts of packaging on the environment is becoming a crucial aspect to have in mind. Packaging accounts for 15-25% in volume of total municipal solid waste in most countries (Tencati et al., 2016; UNEP, 2018a; Margallo et al., 2019), and plastic packaging accounts for 50% in weight of the total plastic waste in the world (UNEP, 2018b). The use of plastic polymers in the technosphere has recently received increased attention given the gradual accumulation of mismanaged plastics in different environmental compartments, such as agricultural sediments, lakes or the marine environment (Schwarz et al., 2019). In fact, a recent report by UN Environment estimates that approximately 8.3 Mt of plastics may be reaching the ocean on an annual basis, both in the form of microplastics due to different types of leakages (city dust, tire abrasion, cosmetics …), and macroplastics, due mainly to waste mismanagement and littering (UNEP, 2018c). The consequences of this accumulation, although still not sufficiently understood, include negative impacts on human wellbeing, particularly fisheries, heritage or recreation, as well as physical and toxic effects to marine biota (Beaumont et al., 2019; Jang et al., 2014). Unfortunately, a complete littering assessment model from a life cycle perspective has not been developed yet (Civancik-Uslu et al., 2019c). This has led many countries to act on plastics by limiting or banning the use of single-use plastics (Shahnawaz et al., 2019), with Directive 2019/904 on the reduction of the impact of certain plastic products on the environment as example. However, it must be noted that despite the bad press that plastic polymers have received due to marine littering, their use in the technosphere has shown to be extremely useful. For instance, plastics improve public health, providing cleanliness to drinking water supplies and a wide range of medical devices. Moreover, the use of plastics in the packaging of food and beverages has allowed a reduction in the weight of packages thanks to their high strength-to-weight ratio, contributing to reduce other impacts along the life cycle of packaging (Andrady and Neal, 2009). A clear example of the importance to reduce weight to decrease impact can be found within the aviation sector, for which about 90% of the impact of cabin waste is due to the weight of the items, such as cutlery (Blanca-Alcubilla et al., 2019). Mixing plastics with minerals and other functional fillers has led to new and better functions with less use of fossil-based resources (Civancik et al., 2018).

In addition to environmental impacts, packaging significantly affects entire supply chains, with important implications in terms of transportation (Raugei et al., 2009), warehousing (Balaguera et al., 2018), order processing and information, inventory carrying, lot sizing, and, in the case of food packaging, it has a great influence on food loss and waste (FLW) (Meherishi et al., 2019). The reduction of FLW is an emerging challenge for global sustainability. The agenda for the United Nation's Sustainable Development Goals includes halving food waste at the retail and consumer level as one of the important worldwide targets for ensuring sustainable consumption and production patterns (Garcia-Herrero et al., 2018; Heller et al., 2019). From an environmental point of view, FLW leads to the excessive consumption of materials and energy attributable to further waste treatment and additional food production to compensate the losses (Hoehn et al., 2019; Yokokawa et al., 2018). To avoid FLW due to packaging itself, the latter should protect food from physical and biological damage, be easy to reseal to avoid deterioration, be correctly designed for emptying completely, be available in sizes that avoid leftovers and provide adequate necessary information to consumers, such as content, composition, or expiration date (Williams and Wikström, 2011). Progress to improve the physical, chemical, sensory, and microbiological protection of food to improve shelf life and to reduce FLW include new technological advances, but special attention must be paid to the needs, attitudes, and behavior of consumers (Wikström et al., 2019). Therefore, all the parts involved in the packaging design should understand the demands of the packaging across the whole supply chain to optimize their product for reducing FLW and environmental impacts (Wohner et al., 2019).

The importance of food packaging justifies the need to evaluate the corresponding environmental impacts since packaging may be responsible for a considerable part of the environmental burden of a product, despite its very short use phase (Licciardello, 2017). Life Cycle Assessment (LCA) appears as the most complete and adequate tool for assessing the potential environmental impacts of food packaging and their implications (Barros et al., 2018). The application of LCA to compare different alternatives for food and beverages packaging (mainly cardboard versus plastic) has been performed for several products, such as olive oil (Navarro et al., 2018), bread (Koskela et al., 2014), eggs (Zabaniotou and Kassidi, 2003) or wine (Gazulla et al., 2010; Vázquez-Rowe et al., 2012). However, most of these studies are focused on primary packaging, and the analysis of secondary and tertiary packaging has not been covered adequately. Taking into consideration that fruit and vegetable waste is the most relevant in terms of volume as compared to other food categories (Vázquez-Rowe et al., 2019), the sustainability of specific packaging for fruits and vegetables distribution has been previously studied by several studies. Due to the very different characteristics of reusable packages, such as plastic crates or wooden boxes, when compared to single-use packages made of cardboard, the resulting scenarios are characterized by high complexity, and the results derived from their analysis can differ. While most published studies, both in the European countries (Accorsi et al., 2014; ADEME, 2000; Albrecht et al., 2013; Tua et al., 2019) and the North and South American contexts (Bernstad Saraiva et al., 2016; Franklin Associates, 2016; Singh et al., 2006), found that the reusable plastic crates perform generally better than the single-use wooden and cardboard boxes; other studies showed that the single-use cardboard boxes should be preferred within certain specific scenarios (Battini et al., 2016; Bortolini et al., 2018; Levi et al., 2011).

However, the results cannot be directly employed to extrapolate and provide a clear-cut answer for defining the friendliest option, since changes in the system conditions and hypotheses (the different geographical coverage, the weights of products, the transportation distances, the actual recycling infrastructures, the rate of mismanaged waste or any other country-specific condition) affect the results considerably. In the particular case of Spain, the Polytechnic University of Valencia, in collaboration with ITENE, conducted a comparative study on cardboard boxes and folding plastic crates for the distribution of fruit and vegetables (Capuz and Aucejo, 2005). Their results concluded that recyclable cardboard boxes are the best option when analyzed using environmental and economic criteria. A more recent study carried out by the same research group confirmed the preferability of cardboard boxes over plastic crates (Capuz et al., 2018). However, in both cases, the results consider exporting fruits and vegetables over long one-way distances to European markets and not combined multiple trips within European pool logistic systems.

Therefore, the analysis of the distribution of fruits and vegetables within the Spanish market has not been previously covered. Hence, the current study has been defined as an exhaustive analysis adapted to the Spanish reality. Therefore, the main objective is to obtain information on the environmental impact associated to the distribution of fruits and vegetables in the Spanish peninsular market, analyzing two alternative packaging solutions: single-use cardboard boxes and reusable plastic crates, but excluding wooden boxes, which are currently barely used in Spain. To our best knowledge, this work is certainly the first one published for the Spanish region, based on the use of direct data from industry, which came from three different companies coping more than 90% of the market. The Spanish market was studied as a pool system, and only once it was previously studied at European level (Albrecht et al., 2013). Since other studies were based on long distance trips, the obtained resulted were not directly applicable to the case of a domestic market with shorter distances, and this could create confusion. This confusion about optimal packaging must be cleared by application of a methodology under a life cycle assessment point of view.

The paper is structured as follows: Section 2 presents the LCA methodology including the goal of this study, the definition of the functional unit and the system boundaries, the allocations methods and the selected environmental categories and the data, limitations, assumptions and hypotheses considered in this study; Section 3 gives a detailed description of the system and presents the life cycle inventory; Section 4 explains the obtained results and the sensibility analysis; and lastly Section 5 provides the main conclusions of the work.

2. Methodology

LCA methodology was employed in accordance with the recommendations provided by the ISO 14040 and 14044 standards (ISO 2006a, 2006b). This approach enables the analysis of the environmental impact associated with every stage in the life of the packages, from the extraction of raw materials for their production until they become a waste. As prescribed by the standard, an LCA study must comprise the definition of goal and scope, the life cycle inventory (LCI) analysis, the life cycle impact assessment (LCIA) and an iterative interpretation of results.

2.1. Goal and scope

As a consequence of the dissemination of environmental information without significant scientific support that can add public pressure against some packaging materials (Maye et el., 2019; Sarmadi, 2016; Tyson, 2010), this study aims to obtain objective scientifically-based information on the real environmental impact associated with fruits and vegetables distribution in the domestic Spanish (peninsular) market, by comparing two packaging solutions: reusable plastic crates and single-use cardboard boxes (Figure 1).

Figure 1

On the one hand, cardboard boxes are domestically produced and transported to the local producers of fruits and vegetables. Once they are filled, they are taken to the distribution centers and consumption points. Whenever their purpose has been fulfilled, they are managed as waste. On the other hand, after their service life, plastic crates are collected, inspected, washed, repaired (when necessary) and distributed again among local fruit and vegetable producers to be used for successive times. Once their whole useful life is over, and they can no longer be reused and repaired, the crates are managed as waste and replaced with new ones.

The considered fruit and vegetable distribution systems guarantee the proper distribution of the product, but, in addition, the compared packages fulfill appropriate labelling, ergonomic, hygienic and safety conditions among other characteristics typical of packaging. Further information concerning the main characteristics of the packages can be found in Table S1.1 in the Supplementary Material (SM). The modification of 11 different model parameters was also analyzed, which could respond to possible changes in the distribution systems, in order to identify more accurately which of the two options is preferable from an environmental point of view. Moreover, this study analyzes two possible scenarios regarding the parameters that define the service life of the crates: in the conservative scenario (which is taken as baseline) the useful life is 10 years and 10 rotations per year are considered, while the technical scenario extends the use to 15 rotations per year and maintains the lifetime (10 years). This last scenario corresponds to the average technical operating conditions of the pool of plastic crates of the industrial partners belonging to ARECO (*Asociación de Operadores Logísticos de Elementos Reutilizables Ecosostenibles*).

2.2. Function and functional unit

The functional unit is the measurement of the function of the systems analyzed which enables them to be totally comparable. In this study, the function was set as the ability of a specific packaging container to repeatedly carry a certain amount of food in the most sustainable possible way. Therefore, initially, the outset functional unit (FU) was defined as the distribution of 1000 metric tons of fruits and vegetables in plastic crates or cardboard boxes. To translate this FU into reference flows of crates and boxes, the weight of load of the packages has been taken into account: both boxes and crates can carry 15 kg of product. This implies that the transport of the 1000 metric tons requires 66,667 units of packages.

On the one hand, in the conservative scenario, plastic crates have a 10-year lifetime and are reused in 10 rotations per year. This means that during the 10 years of the crates' useful lifetime, they could have more than 6.6 million fillings. To consider the effect of the rotations, the outset

FU was redefined for the conservative scenario as the distribution of 6,666,700 packages full of fruits and vegetables, with a transported weight of 15 kg, in single-use cardboard boxes or reusable plastic crates.

On the other hand, in the technical scenario, plastic crates have a higher number of rotations per year, so during this time they could have more than 10 million fillings. Once again, to compensate the effect of the rotations, the outset FU was redefined for the technical scenario as the distribution of 10,000,050 packages full of fruits and vegetables, with a transported weight of 15 kg, in single-use cardboard boxes or reusable plastic crates.

In the case of the plastic crates, some of them may have to be repaired or replaced by new ones to continue fulfilling their function, so the production of these additional crates should also be included in the analysis. The replacement was calculated taking into consideration the average data provided by companies belonging to ARECO, which have found a breakage index of 0.51% per use. The input data for the manufacturing, use and end of life stages of the two analyzed scenarios for both systems are detailed in Figure 2, taking into account the reference flows in each case.

Figure 2

2.3. System boundaries

This study contemplates the full life cycle of both distribution systems, considering the stages of extracting the raw materials for manufacturing the packages, the distribution and use stages, and the end-of-life processing as waste. Auxiliary systems such as transporting raw materials for manufacturing the packages, obtaining electric power from primary energy sources, extracting and burning fuel for transport of packages and waste are also included in the analysis. Nevertheless, the production of capital goods (equipment, machinery or trucks) was placed beyond the limits of the proposed system, since these are in general not relevant in the analysis due to the depreciation per product made or transported.

Once the packages are managed as waste, secondary material to be reused in other products is obtained. Furthermore, energy is recovered when the remains are incinerated. This fact entails the incorporation of new functions to the transport and distribution of fruits and vegetables. Consequently, for both systems to be equivalent, the environmental impacts among the different functions must be allocated and account only for the part covering the main function shared by both systems. This allocation is complex and can be avoided by system expansion, which entails subtracting the environmental impact associated with obtaining materials and energy from alternative production sources. Figure 3 is a schematic view of the boundaries of the initial and expanded systems and a further description of the different stages included in the system will be covered in Section 3.

Figure 3

2.4. Allocation

Some processes included in the life cycle of plastic crates or cardboard boxes are simple, since all consumption of materials and energy, as well as the process emissions, are associated with the product that comes out of that process. However, other systems, in addition to the main products, also produce additional goods or co-products. In these cases, methods to distribute the consumption of materials and energy, as well as the emissions and waste generated between the different co-products of the process, must be established. An allocation hierarchy is suggested by ISO 14044 and these methods were employed in the unavoidable cases:

- In both systems, for refinery products (diesel, naphtha, fuel-oil and lubricant oils), the emission allocation has been based on mass, while the energy demand has been assigned as a function of the energetic content of each product in relation to the crude oil consumption.

- In the cardboard boxes system, the pulp and paper production process has been assigned as a function of the weight of the different produced paper qualities.

- In the plastic crates system, where ethylene and propylene monomers were required to manufacture the crates, the impacts of the products obtained by steam cracking (ethylene, propylene, butadiene, pyrolysis gas, hydrogen and heating gas) have been assigned according to their energy content.

2.5. Life cycle impact assessment methods

The categories of environmental impact and the energy indicators analyzed are compiled in Table 1. These have been developed by the Centre for Environmental Science at Leiden University (CML) (Guinée et al., 2001; Heijungs et al., 1992) and updated in April 2015. For the category of Photochemical Oxidant Creation Potential, the characterization factors provided in the IMPACT 2002+ (V2.1) assessment method have been employed (Jolliet et al., 2003). Additionally, total freshwater use indicator has also been considered.

Table 1

Public concern for climate change is a relevant aspect in our society and this environmental impact is measured through the Global Warming Potential. The protection of the ecosystems is related to the exposure to substances such as sulphur and nitrogen oxides and phosphorous compounds, which are directly related to the Acidification Potential and Eutrophication Potential. Another of the impact categories included refers to the Ozone Depletion Potential, considered within the Montreal Protocol about substances that deplete the ozone layer. The formation of tropospheric ozone threatens the protection of the environment, health and quality of life and it has been considered with the Photochemical Oxidant Formation impact category. Regarding toxicity indicators, they have not been included in this analysis because the packages considered must fulfil quality requirements that avoid the use of toxic substances. ~~Water depletion as a resource has not been included in the analysis. This impact category depends on local conditions and adequate methodology to determine this impact is still under development and not agreed at international scientific level.~~

2.6. Data, limitations, assumptions and hypotheses

For the manufacturing stages of plastic crates and cardboard boxes the data were obtained from the GaBi database 2016 (GaBi, 2016). For example, the consumption of electric energy to produce the packages was assessed from the representative Spanish electricity production mix for the 2012-2018 period. Likewise, the raw materials or some ancillary materials used in the process were extracted from the same database, in order to include the most recent data available. For the distribution and inverse logistics (in the case of plastic crates) stages, data provided by the companies belonging to ARECO regarding fruit and vegetable distribution in Spain for 2015 were used. Data collected were validated using existing and published data from different sources (Eyerer 1996; Eyerer and Reinhardt 2000; GaBi, 2008, 2003; IKP, 2005) or by consulted experts. The GaBi 7 Life Cycle Assessment engineering software was employed for modelling and obtaining results (GaBi, 2016).

According to the recommendations of the International Reference Life Cycle Data System (ILCD, 2011), the absorption and emission of CO_2 from biogenic sources has been considered neutral in this study. For this purpose, both the absorption of biogenic CO_2 in obtaining the paper needed for cardboard boxes and its release after the useful life is over by incineration of the waste generated have been taken into account.

The electricity recovered in the incineration process is assumed to replace the electric power mix of Spain. The model for plastic and cardboard incineration included in GaBi database considers electric and thermal energy recovery. However, Spanish incineration installations are not designed for thermal recovery, so a model to transform the recovered thermal energy into electricity has been proposed according to the efficiency rates compiled in the corresponding

BREF document (MARM, 2011). Since the efficiency values in this document range from 17 to 30%, an average 23.5% rate was employed to represent the transformation of thermal energy to electricity.

The main characteristics of both types of packages have been considered equivalent, although several studies have demonstrated that different packages can imply different performance characteristics in aspects like cooling rates, temperature uniformity, energy consumption or fruit quality (Bishop et al., 2007; Chonhenchob and Singh, 2005, 2003; Gruyters et al., 2019).

A 100 km distance between the waste generation point and the incineration installation was estimated. Furthermore, the centers for the inspection, washing and reparation of the plastic crates do not coincide with the distribution centers and an average distance value of 100 km, based on ARECO estimations, was considered between them.

The value of the recycled granules was fixed as 70% of the value of the virgin material (Albrecht et. al, 2013). The waste granules derived from the manufacturing process of the crates (1.5%-6.0%) were used in a closed loop for the production of crates in the same industrial process. The value of the recycled paper was fixed as 90% of the value of Wellenstoff quality. The maximum number of times paper fibers can be recycled is 3 (Delgado-Aguilar et al., 2015). The percentage of cardboard boxes targeted to be recycled was defined as 80%, while the resting 20% has been supposed to be incinerated with energy recovery (REPACAR, 2014). The number of boxes and craves leaving the system because of misuse, theft or other incidences was considered negligible.

3. System description and life cycle inventory

The modeling of the two distribution systems was carried out in a modular way, including all stages of their life cycle “from the cradle to the grave”. For each of these stages, the corresponding data inventory was prepared to quantify the energy and material flows entering and leaving the systems. Resource consumption and emissions to water, soil and air are considered in the analysis.

3.1. Manufacture (production stage)

3.1.1. Manufacture of cardboard boxes

The raw materials for the manufacture of cardboard boxes are hard and soft wood from forestry and also paper and wood waste. For the inventory, updated data from the GaBi 2016 database were used (GaBi, 2016). Specifically, the following processes were used:

- For softwood: The process includes the growth of trees and the transport to the sawmill. Data were obtained from industry and completed with literature data. It is representative for the period 2015-2018.
- For hardwood: The process includes the growth of trees and the transport to the sawmill. Data were obtained from industry and completed with literature data. It is representative for the period 2015-2018.
- For wood residues: Data obtained from consultations with industrial partners (not included in the GaBi database) were used.
- For recycled paper: It was considered that this entrance has no environmental impact, following the cut-off allocation method and neglecting the collection and transport stages.

The pulp production process has been updated with the data provided by FEFCO (European Federation of Corrugated Board Manufacturers). These data were complemented with data on forestry, energy production, fuel and auxiliary chemicals from GaBi 2016 and updated Thinkstep databases (Gabi, 2016). For the production of the cardboard boxes, semi-chemical pulp (for the fluting) and Kraftliner (for the liner) were used. Electrical energy was obtained from the pulping processes, which was used in the same industrial process; and additional thermal energy and steam are recovered, which are used in other industrial processes. Considering that this adds new functions to the system, requiring the application of a system expansion perspective, it was considered that the impact of the production of an equivalent thermal energy was avoided, based on a European average representative for the 2015-2018. The produced corrugated cardboard sheets are cut in the shape and measure established to become packing boxes. Once cut, they are assembled and palletized, or palletized without mounting before being sent to customers. The impacts related to the assembly of the boxes were included in the analysis.

The distribution of the boxes from the production sites to the points where these boxes are used (cooperatives and other fruit and vegetable producers) was included in the production stage of the boxes. An average distance of 50 km with an average load percentage of trucks of 46% was considered.

3.1.2. Manufacture of plastic crates

Data related to the manufacture of the plastic boxes were provided by representative industrial partners, such as Bekuplast (Germany), Didak Injection (Belgium) and Schoeller Arca Systems (Switzerland), which are among the most relevant suppliers of polypropylene (PP) and high-density polyethylene (HDPE) plastic crates.

The raw material for the production of HDPE and PP is crude oil. The main monomers for obtaining these plastics, ethylene in the case of HDPE and propylene in that of PP, are obtained by a cracking process of naphtha or diesel in a steam cracker. The impact of oil extraction and refinement was included in the inventory data for the production of HDPE and PP extracted from the GaBi 2016 database (GaBi, 2016).

The HDPE polymerization is performed in a low-pressure process by different technologies (solution polymerization, suspension polymerization or gas phase polymerization). In this study, the gas phase polymerization technology in a fluidized bed reactor was selected because it is the most used option (McKenna, 2019). Data gathered for the production of HDPE were extracted from the GaBi 2016 database (GaBi, 2016). They correspond to an average production based on data from several German producers. The average was calculated based on the production capacity of the different companies, using polymerization by a fluidized bed reactor. These data were representative for the period 2015-2018. The impact associated with the extraction, transport and refining of crude oil was also included.

As in the case of HDPE, there are also different polymerization technologies for PP (solution polymerization, liquid propane polymerization or gas phase polymerization). Data collected in this case is a 50:50 combination of the two gas-phase polymerization technologies most used in the market: polymerization in a fluidized bed reactor (as used by Union Carbide / Shell) and polymerization in a vertical reactor (as used by BASF) (Gorbach et al., 2000; Khan et al., 2016). For the production of PP, data were extracted from the GaBi 2016 database (GaBi, 2016). They correspond to an average production based on data from several German producers. The average was calculated based on the production capacity of the different companies. Data are representative for the 2015-2018 period. The impact associated with the extraction, transport and refinement of crude oil was also included.

In general, pure plastic granules are not stable against sunlight, heat and other external agents. For this reason, it is necessary to add certain additives in their composition. In this case, UV and antioxidant absorbers are used for fruit and vegetable distribution packages. In this study, data obtained from the packaging manufacturers were used. Specifically, 0.13% by weight of the PP and HDPE granules were considered standard UV absorbers and 0.5% antioxidants. Data used in the model for the production of UV absorbers were extracted from the GaBi 2016 database (GaBi, 2016).

According to data provided by ARECO, 43% of reusable plastic crates are made of PP and 57% of HDPE, in both cases of virgin raw material, without any contribution of recycled material. For the transport of plastic granulates to the package factory, a truck-trailer was selected from the GaBi 2016 database (GaBi, 2016). It was considered in both cases that a distance of 1000 km is traveled from the granule producer to the manufacturer plants.

The manufacturing process of the crates is based on an injection molding process (more information on this industrial process can be obtained from Liang et al., 1993). Data for this process correspond to a representative process of the injection process provided by the industrial partners consulted. The production process requires between 50-70 seconds, 1.88 kWh and below 0.001 L of lubricating oil per box. The losses are between 1.5-6% (mean value 2.75%), but are re-granulated and reintroduced in other injection applications like the production of beer boxes. This waste reconditioning process can be carried out internally or externally.

The produced crates are packaged by different systems. To calculate the amount of packaging needed (film and PP strapping), data provided by industrial manufacturers were used, which correspond to a consumption of 2 g of film and 0.04 g of PP strapping per crate. The distribution of the crates from the production sites to the points where these boxes are used (cooperatives and other fruit and vegetable producers) was included in the production stage of the boxes. An average distance of 500 km with an average loading rate for trucks of 56% was considered.

3.2. Use (service life stage)

~~One~~ On the one hand, the use stage of cardboard boxes is characterized by the fact that they are employed only once during their useful life. Once they have been manufactured, a box fulfills a transport function and is then sent to a recycler. The impacts associated with the use stage are directly linked to transport. Since cardboard boxes are lighter than plastic crates, the weight of the boxes appears as a very relevant factor. On the other hand, plastic crates can be reused. This implies that, in addition to transport (as in the case of cardboard boxes), in this case other tasks are for the effective reuse with safety and health guarantees, including inspection and washing processes before they can be sent back to fruit and vegetable producers. Unlike in the case of cardboard boxes, the relevant factors for plastic crates are the useful life, the number of rotations per year, the number of fillings and the travel distances for the reverse logistics. In both cases, the complete use stage can be divided in two main phases. The first one includes the transport of fruits and vegetables from the producer (or packaging center) to the final consumer (point of sale), going through the corresponding distribution centers. In the second phase, once the product has been distributed to the points of sale, the packages are collected to be sent back to the distribution logistics centers. Thereafter, the plastic crates are sent to an inspection and cleaning center to be ready for reuse, while the cardboard boxes are sent to a waste manager (Figure 4).

Figure 4

3.2.1. Distribution from producers to points of sale

For the transport phase from the producers (or packaging centers) to the intermediate distribution center, a theoretical percentage of load was calculated assuming that 48 boxes or crates fit in a pallet and 33 pallets in a truck, resulting in 1,584 packages per truck. Since each package carries 15 kg of fruits and vegetables, this implies a total of 720 kg of fruits and vegetables transported per pallet, regardless of the weight of the boxes, crates, and pallets (0.807, 1.790 and 12 kg respectively). Table 2 shows the calculation of the weight of a complete truck considering the specifications of the two types of packages.

Table 2

In order to perform a comparative LCA of the 2 systems, a common representative transport for the two systems must be established. From the real movements made by the packages since they are rented until they are collected, the industrial partners have estimated an average distance in both cases of 400 km. For the inventory, a truck has been selected from the GaBi 2016 database. The theoretical percentage of load calculated (Table 2) and used is 94% for cardboard boxes and 100% for plastic crates.

The transport of fruits and vegetables from the intermediate distribution center to the final points of sale was considered within the model as a local distribution of the product. The weight of the packages and the corresponding contents were considered to calculate the loading rates of the trucks for the transport to the distribution centers to the point sales. The resulting loading rate was fixed at 89% for cardboard boxes and 95% for plastic crates. The average distance considered from the distribution center to the retailer was 100 km (according to ARECO's data).

3.2.2. Backhauling from consumers to reuse or revalorization

The first task in the return logistics is the transport of the packages back from the points of sale to the distribution centers, where only the transport of empty boxes was considered. Although some cardboard boxes can be sent directly to the recycler from the point of sale without going through a logistics center, data are not available. Therefore the model considered that all boxes were sent to the distribution center before being transported to the recycler (from the environmental point of view this fact will not have too much incidence, since the boxes, whether they pass or not through a logistics center, they will be transported to a recycler and will have a truck and a distance associated). The average distance considered was 100 km, as in the case of the transport of fruit and vegetables from the intermediate distribution center to the final points of sale (reverse local distribution).

The backhauling of empty plastic crates is an issue that must be discussed in depth. This task has a very important weight in logistics and system costs, but not so much from an environmental point of view. Due to the foldable nature of the crates, they can be transported efficiently, passing from 48 unfolded to 264 folded crates per pallet. Therefore, one truck exceeds to return the empty crates previously transported by four full trucks. In the worst case, for 4 full truck loads, a truck full of empty boxes and 3 totally empty trucks would be mobilized.

According to the data provided by the industrial partners, most distribution companies use the backhauling of trucks from the points of sale to transport other goods to the distribution centers (approximately 80% of cases apply this strategy). Therefore, the impact of this transport should be directly attributed to the goods that are being transported back. The remaining 20% of the trucks become empty both in the case of distribution in plastic crates and cardboard boxes. Consequently, the only difference between the two systems is the percentage of trucks ~~(a value of 18% has been considered)~~ that have empty plastic crates as load when return to the distribution centers. A value of 18% was calculated taking into account that 264 empty folded crates fit in a pallet, instead of 48 when they are unfolded, as referred in the technical specifications of the product. The full impact of the transport of these empty crates has been fully attributed to the distribution system in plastic crates. Figure 5 shows a scheme of backhauling logistics with the two types of packaging used, which exemplifies how it was modeled.

Figure 5

The plastic crates are sent from the distribution centers to inspection and washing centers where they are checked and conditioned for a new use. In many cases, the inspection and washing centers are located in the same distribution centers but, in other cases, these empty boxes must be transported to other facilities. Therefore, according to data provided by ARECO, an average distance of 100 km between the distribution centers and the washing centers was assumed, as well as the loading rate (55%).

In the washing plants, the crates are inspected before washing, and, if they are broken, they are removed and replaced by new ones. The average breakage index by use defined by the industrial partners for this study is 0.51% per use. This has implications for the calculation of the reference flow, that is, to calculate the number of plastic crates needed to comply with the extended use FU that has been defined, since the manufacture of 34,001 additional boxes in the case of the conservative scenario and 51,001 additional boxes in the case of the technical scenario is required. In most cases, the washing centers are managed by the same rental companies of the plastic crates and act at the same time as washing and storage centers.

The washing process is automatized, and the loading of the boxes can be either manual or automatic. The washing process allows to adjust the temperature, the washing time, or the type and amount of detergent used. After washing, the boxes go through an automatic drying process and are subsequently closed and stored on pallets. The inspection and washing process was modeled according to the data provided by the industrial partners. The consumption of water was defined as 0.5 L/crate and caustic detergent at 0.2% concentration was used. The production of electricity and natural gas was adjusted to the Spanish electric power mix. Once the plastic boxes have been inspected and washed, they are stored and ready to be returned to distribution centers or directly to fruit and vegetable producers (or packaging centers). Based on the data provided by the industrial partners, an average distance between these washing and storage centers and the producers of 200 km and a loading rate of 58% were considered.

When the packages have ended their lifespan (after unloading the product in the cardboard boxes and after breaking and not being able to be reused more in the case of plastic crates), these are transported to recycling or end-of-life centers. For cardboard boxes, it was assumed that 80% are recycled and used again in the manufacture of new boxes and that the remaining 20% are incinerated in a facility with energy recovery. In both cases, a distance of 100 km from the distribution centers to the treatment installations was considered. The loading rate used is 85% in both cases. The plastic crates that have passed through an inspection and washing center and are not considered suitable for new use are sent to recycling. The average distance that was considered from inspection and washing centers to recyclers (data provided by industrial partners) was 650 km and the loading rate 85%.

3.3. Recycling and valorization (end of life stage)

3.3.1. Management of cardboard boxes after end of life

To model the end-of-life of cardboard boxes, it was assumed that 80% were recycled and used again in the manufacture of new boxes and that the remaining 20% were incinerated in a facility with energy recovery. Nevertheless, the percentage of boxes that were sent to recycling or incineration was parameterized to be variable, so an analysis of its effects was carried out in the sensitivity analysis. System expansion was applied in order to take into account the environmental savings associated to paper material recovery. Transport and electricity production data were modeled with the GaBi 2016 database, which are representative for the period 2015-2018 (GaBi, 2016).

The biological CO_2 balance was considered neutral in the study. In other words, the CO_2 that is absorbed during tree growth will end up being released into the atmosphere during the end-of-life process at some point. This implies a series of assumptions in the case of cardboard boxes that were taken into account in the model (Figure 6). According to data from Delgado-Aguilar et al. (2015), the number of times that paper fibers can be recycled is 3. This was considered for the material used in the manufacture of paper boxes, since 20% were already recycled fibers and the remaining 80% virgin fibers. At the end-of-life, therefore, it was considered that for 80% of virgin fibers are recycled 3 times with their corresponding material savings, while in the case of recycled fibers only 2 cycles (with their corresponding saving of materials) were considered. Both waste from each of the recycling cycles and the resulting material after the total recycling cycles were considered to be incinerated in a plant with energy recovery. This implies the release of all the CO_2 that was once absorbed by the trees in the first production cycle. The energy recovered by the incineration was considered to replace the Spanish electric power mix.

Figure 6

3.3.2. Management of plastic crates after end of life

In this study, 100% of the damaged crates that are identified in the inspection stage are sent to a recycler. In this work, a degradation rate of the polymer when crediting the amount of virgin plastic was considered, taking into account that a recycled polymer only substitutes 0.7 of virgin polymer (Albretch et al., 2013).

Rejections of recycling plants are sent to an incinerator with energy recovery. Transport and electricity production data were modeled with the GaBi database. Again, system expansion to consider the environmental savings due to plastic recovery was applied.

4. Results and discussion

4.1. Life cycle impact assessment

The summary of the overall impacts as disaggregated results is shown in Table 3, including disaggregated emissions and savings, as well as lump-sum total results (emissions minus savings) for both conservative and technical scenarios. Plastic crates present better environmental performance than the cardboard boxes for all the impact categories, which is directly related with a lower consumption of materials from renewable and non-renewable sources. Regarding energy consumption (Table 4), total consumption of primary energy from renewable and non-renewable sources is also lower in the case of plastic crates. It should be highlighted that the energy used in the manufacture and distribution of the packages that is recovered in the end-of-life phase represents 28% in the case of plastic crates and 74% in the case of cardboard boxes in the conservative scenario (in the technical scenario the recovery is 24% and 74%, respectively). Table 5 shows the results of the water indicator. As it has been observed, total freshwater use is 5 times higher for cardboard crates than for plastic crates for the conservative scenario and 6 times for the technical one. The avoided use of water due to the recycling of paper is not compensated by the consumption in production and service life stages. Regarding plastic crates, it is worth to mention that cleaning and hygienization of crates before being reused represents 32% and 38% of the total freshwater consumption for the conservative and technical scenarios respectively.

Table 3

Table 4

Table 5

In order to display a more easily comparable outlook to the obtained results, total environmental impacts and energy consumption in both scenarios were relativized with the package contributing most to each of the impact categories (cardboard boxes in both cases) as a reference. As shown in Figure 7, the results of both scenarios are very similar, just with slightly lower relative impacts of the plastic crates in the technical scenario. On the one hand, in the conservative scenario, the impact category with shortest distance (17.6%) between both packages is AP, while, on the other hand, the opposite situation is the ODP category, with a significant (97.4%) difference between both values. In terms of greenhouse gas (GHG) emissions, boxes present 87.6% more impact in this category in comparison to crates. Despite the important energy savings of the cardboard boxes, specifically in the non-renewable category (associated with the savings during the incineration that replace the electricity mix of Spain, which contains a large proportion of non-renewable energy), these packages have a greater (more than 99.5%) impact on the use of renewable primary energy. Therefore, total consumption of renewable and non-renewable energy (PE) is favorable to plastic crates, which consume 43% and 41% of the ones consumed by cardboard boxes in the conservative and technical scenarios, respectively.

Figure 7

To analyze the influence of the impact of the analyzed systems, the results of environmental impact were normalized to the mean EU-28 emissions for year 2000 (Sala et al., 2017). This was done for the impact categories analyzed with CML 2015 for which these mean emissions were available (all those included in the study except for POCP). From the results displayed in Figure 8, which correspond to the conservative scenario (the results of the technical scenario are shown in Figure S2.1 in the SM), it can be appreciated that the impact categories with the greatest contribution to European impact are GWP and AP.

Figure 8

When the difference between single-use cardboard boxes and reusable plastic crates is scaled from the FUs defined in this study to the total number of packages mobilized for the distribution organized in Spain over one year (roughly 550 million fillings according to the data provided by the industrial partners), the impact on the most influential impact category, GWP, would imply an annual saving of -785,240 metric tons of CO_2 eq. for the conservative scenario (Table 6). This amount represents 0.24% of the emissions generated by Spain in 2014 (MAGRAMA 2016). In the case of energy consumption, the annual saving is -2,828 TJ, which represents the 0.29% of the total electric consumption in Spain in 2018 (REE, 2018). When the technical scenario is considered, the saving is even greater given the lower unitary emissions per fillings under the technical conditions (extended effective lifetime of the crates). In fact, the technical scenario is characterized by lower unitary impacts and energy consumptions if compared to the conservative scenario, except in the case of EP category, which appears with totally equivalent unitary impacts (Table 7). The results comparing to Spanish total emissions must be taken carefully, as the numerator is life-cycle based while the denominator relates to direct emissions.

Table 6

Table 7

Figure 9 shows the resulting impacts and energy indicators disaggregated per life cycle stages for both packages in the conservative scenario. A homologous figure for the technical scenario (Figure S3.1) is provided in Section S3 in the SM, together with Tables S3.1-S3.4, which show absolute results for the impact categories and the energy consumption indicators.

Figure 9

On the one hand, as observed in Figure 9, for the case of plastic crates, most of the emissions and, thus, environmental impacts, are concentrated in the service life stage, followed by the production stage of the crates. As regards the savings, these are concentrated in the end-of-life stage for all impact categories. Regarding energy consumption, total renewable and non-renewable energy consumptions are concentrated in the production stages (44%) and service life (54%), while the energy savings are all concentrated in the end-of-life stage. On the other hand, in the case of cardboard boxes, except for GWP, most of the environmental impacts are concentrated in the production stage of the boxes. In the case of GWP, 38% of the impact is spread in the production stage and 61% in the end-of-life stage. As for savings, except in the case of GWP, in which there is a greater saving in the production stage of the boxes (due to the absorption of CO_2 from biological sources), for the other impacts practically all the savings are associated with the end-of-life stages. With regard to energy consumption, 95% of the total renewable and non-renewable energy consumptions are concentrated in the production stage and 4% in the end-of-life stage, so the contribution of the service life stage to this indicator is only

1%. As for savings, 98.5% are concentrated in the end-of-life stage and the remaining 1.5% in the production stage. Further information about the relative contribution of each process to the total impacts and energy indicators in each stage is shown in Section S4 in the SM.

4.2. Sensitivity analysis

A sensitivity study was conducted to analyze the influence on the results of some of the parameters which were employed. The objective of this sensitivity analysis is to determine how robust the results are and find out if any of the variables may modify the tendencies obtained. The parameters that were modified are compiled in Table 8. Those variables that affect reusable plastic crates and those that affect single-use cardboard boxes were distinguished and a separate analysis was performed.

Table 8

In all cases, Equation 1 was used to determine the improvement or not in the environmental impact of the packages by each variable:

$$\Delta IA = 100\frac{IA_M - IA_B}{IA_B} \quad (1)$$

where ΔIA is the environmental impact variation, IA_M the environmental impact with the modified parameter and IA_B the environmental impact of the baseline scenario. Therefore, a positive value implies that the option analyzed is worse than the baseline scenario, while a negative value means that the modified option has less environmental impact than the baseline scenario.

The results of the variation of the parameters on the environmental impacts of plastic crates boxes in relation to the baseline conservative scenario are detailed in Figure 10. As shown, none of the analyzed parameters produced a significant variation in the results (the corresponding environmental impact variations are below ± 25%). The parameter that has the greatest effect is P9 (corresponding to the percentage of plastic crates that are recycled at the end of the useful life of the boxes), with increases in GWP (+24%) and ODP (+11%), when the recycle percentage is reduced from 100 to 50%. It must be mentioned that POCP is a highly influenced impact category (between +12% for P11b to -12% in P6) and appears as the category with highest modification for most analyzed parameters.

Figure 10

The influence on results of the environmental impacts of cardboard boxes in relation to the impact of plastic boxes in the baseline conservative scenario by modifying the parameters are shown in Figure 11. Unlike in the case of plastic crates, in this case, there is one parameter (P1, corresponding to the cardboard quality) for which the variation in all impact categories, with the exception GWP (-18% variation), is significantly improved (in the range from -37 to -121%).

Figure 11

Parameter P1 defines the proportions of the different types of paper pulp in the production of the cardboard boxes. The production of cardboard boxes for transport of fruits and vegetables has high fluting ratios (63% semi-chemical pulp fluting and 37% Kraftliner for liners was the baseline formulation considered in this work) because high quality materials are required to fulfill the functions undertaken by the boxes. The baseline use of secondary fibers in the manufacture of the boxes has been estimated at 13%. The variation in the values of parameter P1 does not refer so much to the fact that there is a high uncertainty in the starting data used, and in particular in this mix, but to study the influence of the quality on the environmental impacts. It is worth mentioning that the variation in the proportions of the different types of paper (10% semi-chemical pulp, 22% Kraftliner, 34% Wellenstoff and 34% Testliner) was carried out as a hypothetical exercise. This composition does not correspond to any existing box in the market and there is no technical demonstration to prove if they could technically fulfill their function. The results of varying this parameter (Table 9 compares the impacts of the cardboard boxes in the modified and baseline situations) imply very significant improvements since recycled paper is given a value of zero environmental impact, since it is considered that recycled paper has no environmental burden, unlike the production of virgin paper. Therefore, a baseline situation where the proportion of recycled paper is 13% was compared to an improved situation with 71% recycled paper. Further details of the sensitivity analysis, particularly about the results of the modification of the resting parameters can be consulted in Section S5 of the Supplementary Material.

Table 9

Finally, once the effects of the parameters that could influence the environmental impacts of the packages were analyzed, a comparative analysis was carried out to determine if the application of these parameters would change the preference in the use of plastic crates with respect to the cardboard boxes. Table 10 compiles the results of the sensitivity analysis of all the parameters analyzed. The analysis scenarios and environmental impact indicators have been represented in the table, highlighting which of the two options (reusable plastic crates or single-use cardboard boxes) is the best alternative in each case, with a confidence degree of 25% (the environmental impact of a package for a given category of impact is 25% higher or lower than the other option). This confidence degree was considered a wide enough margin to compensate the effects due to possible uncertainty of the data used in the inventory.

Table 10

As observed in Table 10, for all the parameters modified in the sensitivity analysis, apart from P1 and P2, the clear environmental preference towards the selection of reusable plastic crates instead of single-use cardboard boxes is maintained. This fact is valid for all the impact categories and energy indicators, with the exception of AP, where the impact of one or another package can be considered similar. On the one hand, regarding P1, it should be noted that this analysis was intended to perform a theoretical exercise to see the influence on the results of using material in its manufacture of worse quality, without considering whether this could be technically implemented. The exercise reveals that, in this case, there would be a significant decrease in the environmental impacts of the cardboard boxes, which would give preference to single-use cardboard boxes for AP, EP and PE. On the other hand, regarding P2, the sensitivity analysis has considered that 100% of the cardboard boxes are recycled at the end of their useful life and incineration is avoided. Fully recycling the boxes would produce savings between 1% and 39% in the different impact categories analyzed, and 46% in energy consumption compared to the baseline conservative scenario. Nevertheless, even under these new improved conditions, plastic crates could be preferred after the comparison of the corresponding impacts, because only AP appeared as the favorable category for the boxes, while the energy consumption could be considered equivalent for both options.

5. Conclusions

The current study evaluated the environmental impact of the distribution of fruits and vegetables in Spain using two different types of packages: reusable plastic crates and single-use cardboard boxes. Two different scenarios were considered as a function of the lifetime of the crates and the number of annual rotations: the conservative one was defined by 10 years lifetime and 10 rotations per year, while the technical one considered 10 years too, but the number of rotations increased to 15. In addition, a sensitivity analysis was carried out modifying 11 parameters of the model to study the influence of these possible variations of the system on the selection of the most preferable packaging option.

The results showed that reusable plastic crates implied significantly lower environmental impacts than the single-use cardboard boxes. All impact categories and energy consumption indicators were lower in the case of crates in both scenarios, except POCP, which could be considered comparable for both packages when taking into account a 25% security margin in the results to manage the uncertainty of the model and the data used.

On the one hand, the highest environmental impact of the cardboard boxes was related to the manufacturing stage (forestry, wood supply, and production), while the savings were concentrated in the end-of-life, mainly due to the recovery of secondary paper fibers. On the other hand, the highest environmental impact of the plastic crates was related to the use stage (including the backhaul from the points of sale to the distribution centers, the inspection and sanitation processes and the transport of the crates back to the fruit and vegetables producers), followed by the manufacturing stage (production of granulated polymer). Once again, the savings were also concentrated in the end-of-life stage due to the recovery of recycled plastic chips. Nevertheless, further research must be carried out to improve the design of these types of packages in order to minimize their environmental impacts, for instance, considering the employment of more environmentally friendly bioplastics.

The sensitivity analysis revealed that among the 11 parameters evaluated, only two presented remarkable influence on the results: the plastic recyclability ratio and the quality of the cardboard employed in the manufacture of the boxes. Nevertheless, the sensitivity analysis displayed a clear preference for plastic crates in comparison with cardboard boxes. In most cases, plastic crates had at least 25% lower impact than cardboard boxes, and a comparable impact in the remaining cases, although an exception was identified. The hypothetic reduction of the quality of the cardboard (from 63% virgin semi-chemical pulp for fluting and 37% virgin Kraftliner for liner to 10% virgin semi-chemical pulp and 34% recycled Wellenstoff for fluting and 22% virgin Kraftliner and 34% recycled Testliner for liner), composition that has not been experimentally tested as feasible, would result in 25% lower impacts for cardboard boxes in comparison to plastic crates in POCP, AP and energy consumption.

To sum up, the use of a multiple-use plastics solution rather than other packaging materials is justified in this case study, a case which is probably extendable to many other situations. However, for this preference to be true, supply chains must guarantee the correct management of the end-of-life processes. Otherwise, plastics lose attractiveness as a packaging option and may engender multiple problems when disposed inadequately, arriving to the natural environment as a hazard to biota. Therefore, we advocate for a case by case analysis of the appropriateness of using plastics for packaging, acknowledging the situations in which it will be the preferred option over other materials, but also identifying those supply chains in which its use multiples the environmental burdens that may arise.

For a decision from these types of comparisons to be fair, it is absolutely important that the study is transparent and critically reviewed by a panel of independent experts, with knowledge in LCA methodology and auditing procedures.

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Abbreviations

AP	Acidification Potential
EP	Eutrophication Potential
GWP	Global Warming Potential
HDPE	High-density polyethylene
FLW	Food loss and waste
FU	Functional unit
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
ODP	Ozone Depletion Potential
PE	Use of Primary Energy
PE-NR	Use of Primary Non-Renewable Energy
PE-R	Use of Primary Renewable Energy
POCP	Photochemical Oxidant Creation Potential
PP	Polypropylene

Captions

Table 1: Impact categories analyzed in this study.

Table 2: Assessment of truck loads for transport from producers to distribution centers.

Table 3: Absolute environmental impacts in the two scenarios considered.

Table 4: Absolute energy indicators in the two scenarios considered.

Table 5: Total freshwater use in the two scenarios considered.

Table 6: Resulting savings derived from the scaling to 550 million units of packages mobilized in Spain annually.

Table 7: Unitary environmental impacts and energy indicators per filling of the plastic crates in the two scenarios considered.

Table 8: Parameters and values of the sensitivity analysis.

Table 9: Results of the sensitivity analysis for variation of P1 (quality of material in the manufacture of cardboard boxes).

Table 10: Summary of the sensitivity analysis and the corresponding best options in each case.

Figure 1: Examples of the packages considered in this study.

Figure 2: Overview of the system characteristics and flows over the life cycle in the conservative (a) and technical (b) scenarios.

Figure 3: Schematic view of the boundaries of the initial and expanded systems.

Figure 4: Graphic scheme of the logistics of both package systems.

Figure 5: Graphic comparison of the backhauling of both package systems.

Figure 6: Considerations of biologic CO_2 and number of fiber recycling cycles in the Global Warming Potential (GWP) (based on Albrech et al, 2009).

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Figure 11: Results of the sensitivity analysis of the variables that have influence on single-use cardboard boxes.

Table 1: Impact categories analyzed in this study.

Impact category	Measuring unit
Use of primary energy (PE)	MJ
Use of primary renewable energy (PE-R)	MJ
Use of primary non-renewable energy (PE-NR)	MJ
Global warming potential (GWP)	kg CO_2 eq
Ozone layer depletion potential (ODP)	kg R11 eq
Acidification potential (AP)	kg SO_2 eq
Eutrophication potential (EP)	kg phosphate eq
Photochemical oxidant creation potential (POCP)	kg C_2H_4 eq

Table 2: Assessment of truck loads for transport from producers to distribution centers.

Specifications	Cardboard boxes	Plastic crates
Package content (kg)	15	15
Package weight (kg)	0.807	1.790
Pallet weight (kg)	12	12
Number of packages per pallet	48	48
Loaded pallet weight (kg)	771	818
Number of pallets per truck	33	33
Total truck load (kg)	25,434	26,994
Maximum truck load (kg)	27,000	27,000
Loading rate (%)	94	100

Table 3: Absolute environmental impacts in the two scenarios considered.

		Conservative scenario		Technical scenario	
Impact	**Unit**	**Plastic crates**	**Cardboard boxes**	**Plastic crates**	**Cardboard boxes**
Emissions					
AP	kg SO_2 eq	4,924	18,505	7,069	27,758
EP	kg phosphate eq	1,011	6,164	1,480	9,246
GWP	kg CO_2 eq	1,638,163	32,279,558	2,296,227	48,419,337
ODP	kg R11 eq	0.002	0.081	0.003	0.121
POCP	kg C_2H_4 eq	496	1,640	660	2,461
Savings					
AP	kg SO_2 eq	912	13,638	1,066	20,457
EP	kg phosphate eq	108	3,789	127	5,683
GWP	kg CO_2 eq	290,450	21,413,737	339,499	32,120,606
ODP	kg R11 eq	0.000	0.004	0.000	0.005
POCP	kg C_2H_4 eq	30	777	36	1,166
Total					
AP	kg SO_2 eq	4,012	4,867	6,002	7,301
EP	kg phosphate eq	902	2,376	1,353	3,563
GWP	kg CO_2 eq	1,347,713	10,865,821	1,956,728	16,298,731
ODP	kg R11 eq	0.002	0.077	0.003	0.116
POCP	kg C_2H_4 eq	466	863	624	1,295

Table 4: Absolute energy indicators in the two scenarios considered.

		Conservative scenario		Technical scenario	
Energy indicator	**Unit**	**Plastic crates**	**Cardboard boxes**	**Plastic crates**	**Cardboard boxes**
Consumption					
PE	MJ	36,157,015	229,069,722	48,720,993	343,604,583
PE-NR	MJ	33,098,358	79,062,871	44,373,586	118,594,306
PE-R	MJ	3,058,656	150,006,851	4,347,407	225,010,277
Saving					
PE	MJ	10,132,653	168,764,773	11,843,774	253,147,159
PE-NR	MJ	9,951,176	129,884,217	11,631,651	194,826,326
PE-R	MJ	181,477	38,880,555	212,123	58,320,833
Total					
PE	MJ	26,024,361	60,304,949	36,877,219	90,457,424
PE-NR	MJ	23,147,182	-50,821,347	32,741,935	-76,232,020
PE-R	MJ	2,877,179	111,126,296	4,135,284	166,689,444

Table 5: Total freshwater use in the two scenarios considered.

	Conservative scenario		Technical scenario	
Total freshwater use (tn)	Plastic crates	Cardboard boxes	Plastic crates	Cardboard boxes
Production	333,829	5,418,017	390,203	8,127,026
Service life	161,693	8,030	242,539	12,045
End of life	6,781	-2,903,904	7,927	-4,355,856
Total	502,304	2,522,144	640,669	3,783,215

Table 6: Resulting savings derived from the scaling to 550 million units of packages mobilized in Spain annually.

		Conservative scenario		Technical scenario	
Indicator	Unit	Plastic crates	Cardboard boxes	Plastic crates	Cardboard boxes
GWP	kg CO_2 eq	1,347,713	10,865,821	1,956,728	16,298,731
FU	fillings	6,666,700	6,666,700	10,000,050	10,000,050
Unitary GWP	kg CO_2 eq / filling	0.202	1.630	0.196	1.630
Real scale distribution	fillings / year	550,000,000	550,000,000	550,000,000	550,000,000
Annual GWP	kg CO_2 eq / year	111,185,757	896,425,724	107,619,516	896,425,724
Annual GWP savings	kg CO_2 eq / year	-785,239,967		-788,806,208	

		Conservative scenario		Technical scenario	
Indicator	Unit	Plastic crates	Cardboard boxes	Plastic crates	Cardboard boxes
PE	MJ	26,024,361	60,304,949	36,877,219	90,457,424
FU	fillings	6,666,700	6,666,700	10,000,050	10,000,050
Unitary PE	MJ / filling	3.904	9.046	3.688	9.046
Real scale distribution	fillings / year	550,000,000	550,000,000	550,000,000	550,000,000
Annual PE	MJ / year	2,146,999,087	4,975,133,433	2,028,236,914	4,975,133,433
Annual PE	GJ / year	2,146,999	4,975,133	2,028,237	4,975,133
Annual PE savings	GJ / year	-2,828,134		-2,946,897	

Table 7: Unitary environmental impacts and energy indicators per filling of the plastic crates in the two scenarios considered.

Impacts	Unit	Conservative scenario	Technical scenario	Ratio Technical/Conservative (%)
AP	kg SO2 eq/filling	$6.02 \cdot 10^{-4}$	$6.00 \cdot 10^{-4}$	99.8
EP	kg phosphate eq/filling	$1.35 \cdot 10^{-4}$	$1.35 \cdot 10^{-4}$	100.0
GWP	kg CO2 eq/filling	$2.02 \cdot 10^{-1}$	$1.96 \cdot 10^{-1}$	96.8
ODP	kg R11 eq/filling	$2.98 \cdot 10^{-10}$	$2.95 \cdot 10^{-10}$	99.0
POCP	kg C_2H_4 eq/filling	$6.99 \cdot 10^{-5}$	$6.24 \cdot 10^{-5}$	89.4
PE	MJ/filling	3.90	3.69	94.5

Table 8: Parameters and values of the sensitivity analysis.

Reference	Sensitivity parameter	Baseline	Variation
P1	Percentage of (semi-chemical) virgin fluting in the cardboard box	63%	10%
	Percentage of virgin liner (Kraftliner) in the cardboard box	37%	22%
	Percentage of recycled fluting (Wellenstoff) in the cardboard box	0%	34%
	Percentage of recycled liner (Testliner) in the cardboard box	0%	34%
P2	Percentage of cardboard boxes recycled at the end of the service live	80%	100%
P3	Value of secondary paper fibers in relation to Wellenstoff	90%	100%
P4	Percentage of recycled plastic used to manufacture the crates	0%	30%
P5	Percentage of virgin HDPE used to manufacture the crates	57%	100%
P6	Percentage of virgin PP used to manufacture the crates	43%	100%
P7a	Losses of granulate during the production of the crates	2.75%	1.50%
P7b	Losses of granulate during the production of the crates	2.75%	6.00%
P8a	Breakage index of the plastic crates during their service life	0.51%	0.20%
P8b	Breakage index of the plastic crates during their service life	0.51%	0.70%
P9	Percentage of plastic crates recycled at the end of the service life	100%	50%
P10	Value of the secondary plastic material in relation to the primary raw material	70%	100%
P11a	Number of annual rotations	10	12
P11b	Number of annual rotations	10	8

Table 9: Results of the sensitivity analysis for variation of P1 (quality of material in the manufacture of cardboard boxes).

Impact category	∆IA Plastic crates (%)	∆IA Cardboard boxes (%)
AP	0	-118
EP	0	-75
GWP	0	-18
ODP	0	-37
POCP	0	-54
PE	0	-121

Table 10: Summary of the sensitivity analysis and the corresponding best options in each case.

Scenario	Impact categories					
	AP	EP	GWP	ODP	POCP	PE
Baseline	grey	blue	blue	blue	blue	blue
P1	yellow	yellow	blue	blue	grey	yellow
P2	yellow	blue	blue	blue	blue	grey
P3	grey	blue	blue	blue	blue	blue
P4	grey	blue	blue	blue	blue	blue
P5	grey	blue	blue	blue	blue	blue
P6	grey	blue	blue	blue	blue	blue
P7a	grey	blue	blue	blue	blue	blue
P7b	grey	blue	blue	blue	blue	blue
P8a	grey	blue	blue	blue	blue	blue
P8b	grey	blue	blue	blue	blue	blue
P9	grey	blue	blue	blue	blue	blue
P10	grey	blue	blue	blue	blue	blue
P11a	grey	blue	blue	blue	blue	blue
P11b	grey	blue	blue	blue	blue	blue

blue	Best option plastic crates (>25%)
grey	Similar options (<>25%)
yellow	Best option cardboard boxes (>25%)

Figure 1: Examples of the packages considered in this study.

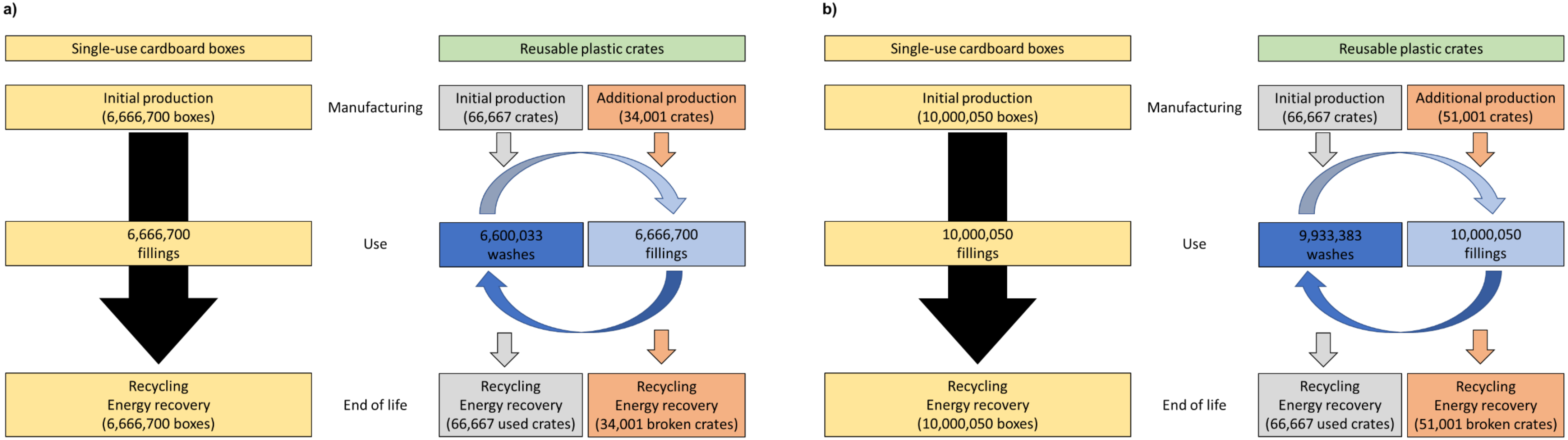


Figure 2: Overview of the system characteristics and flows over the life cycle in the conservative (a) and technical (b) scenarios.

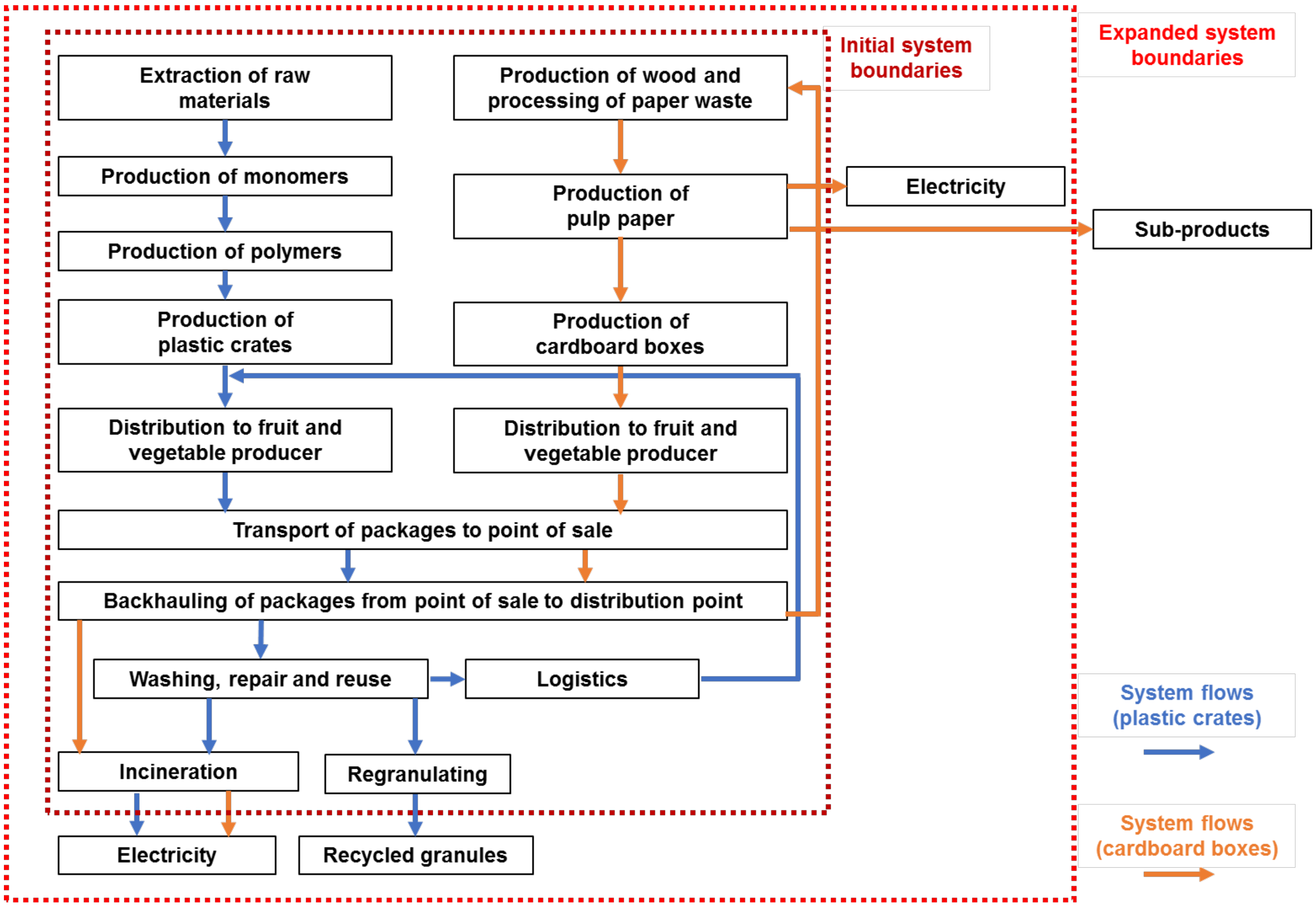


Figure 3: Schematic view of the boundaries of the initial and expanded systems.

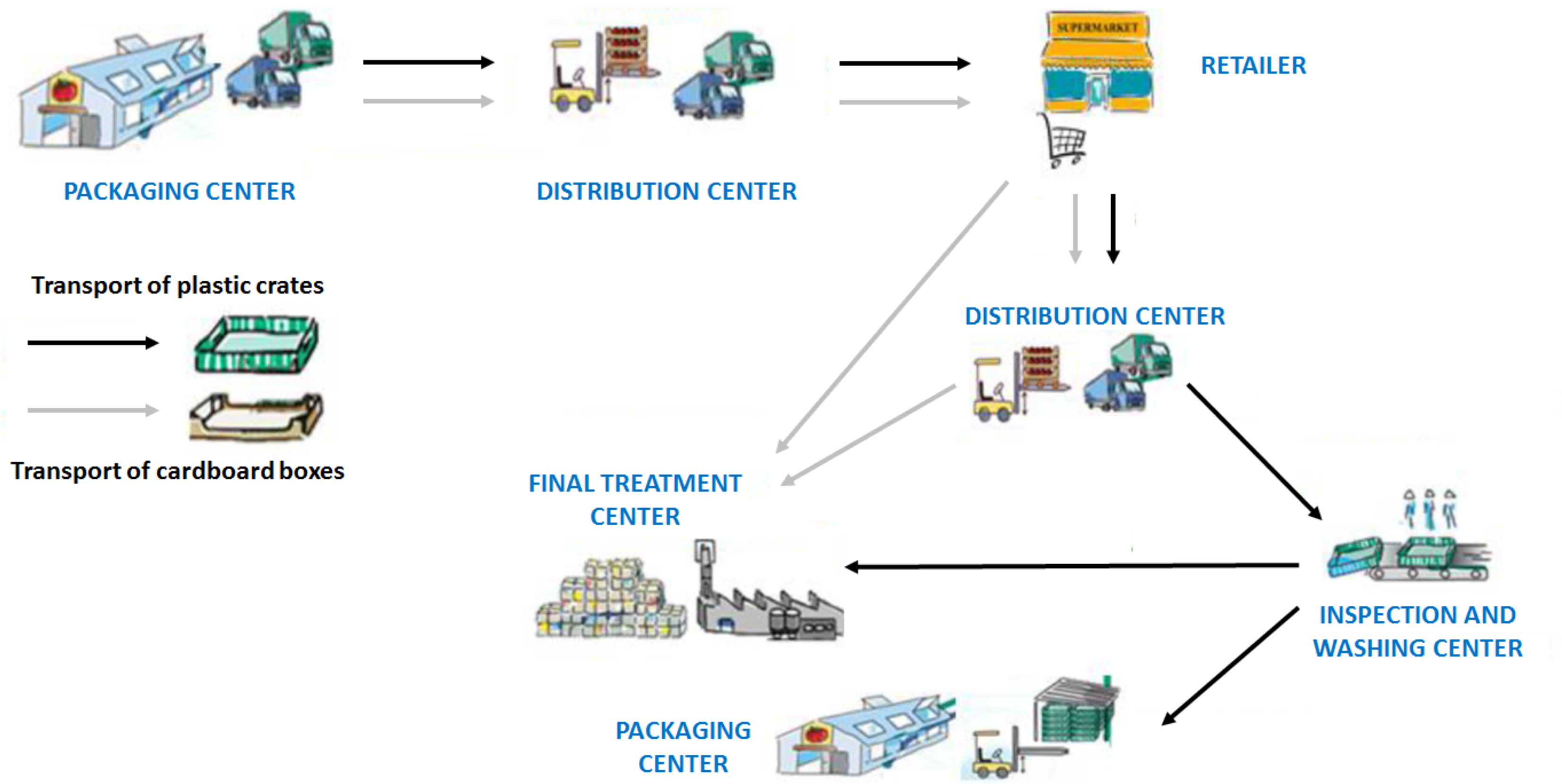


Figure 4: Graphic scheme of the logistics of both package systems.

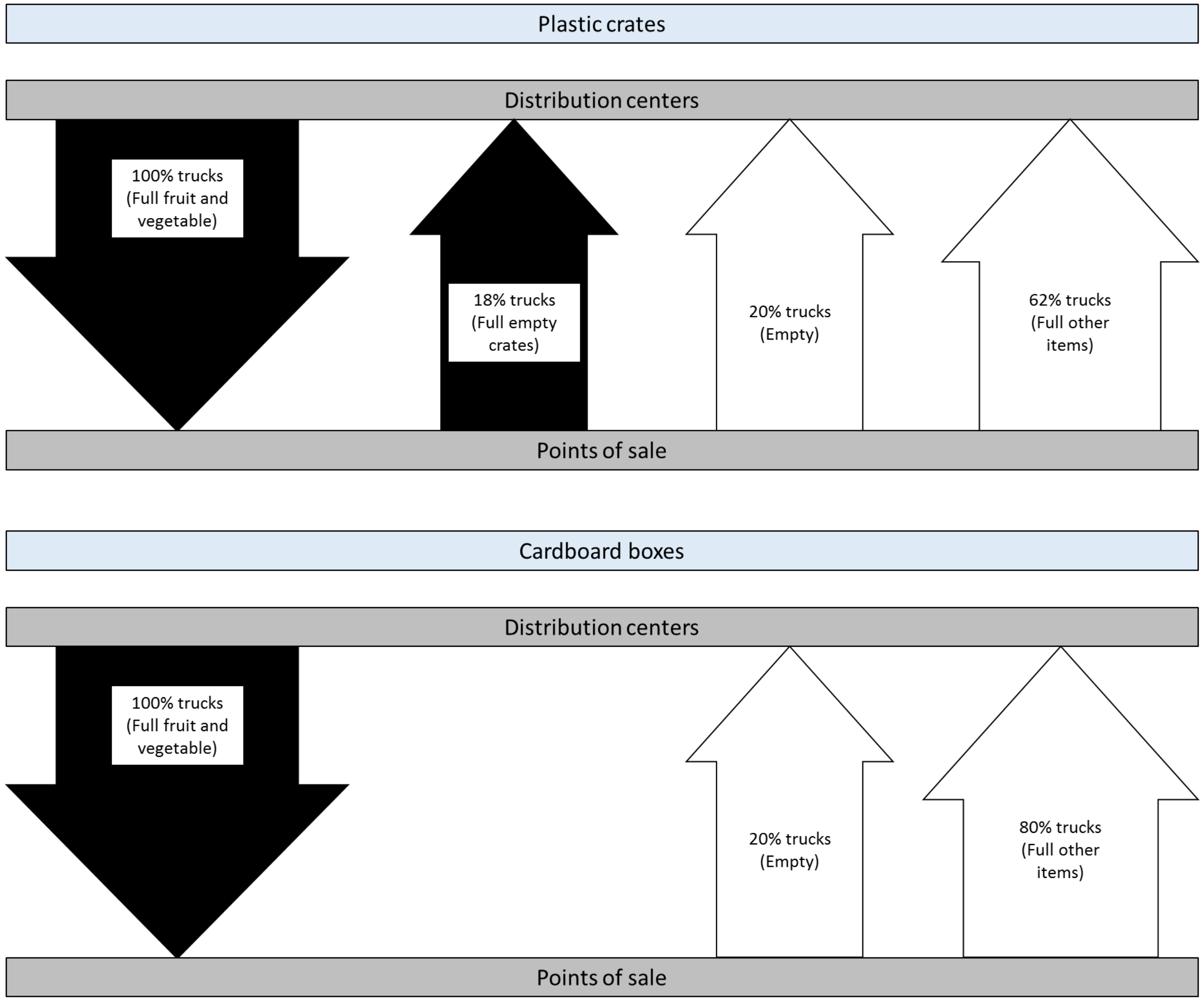


Figure 5: Graphic comparison of the backhauling of both package systems.

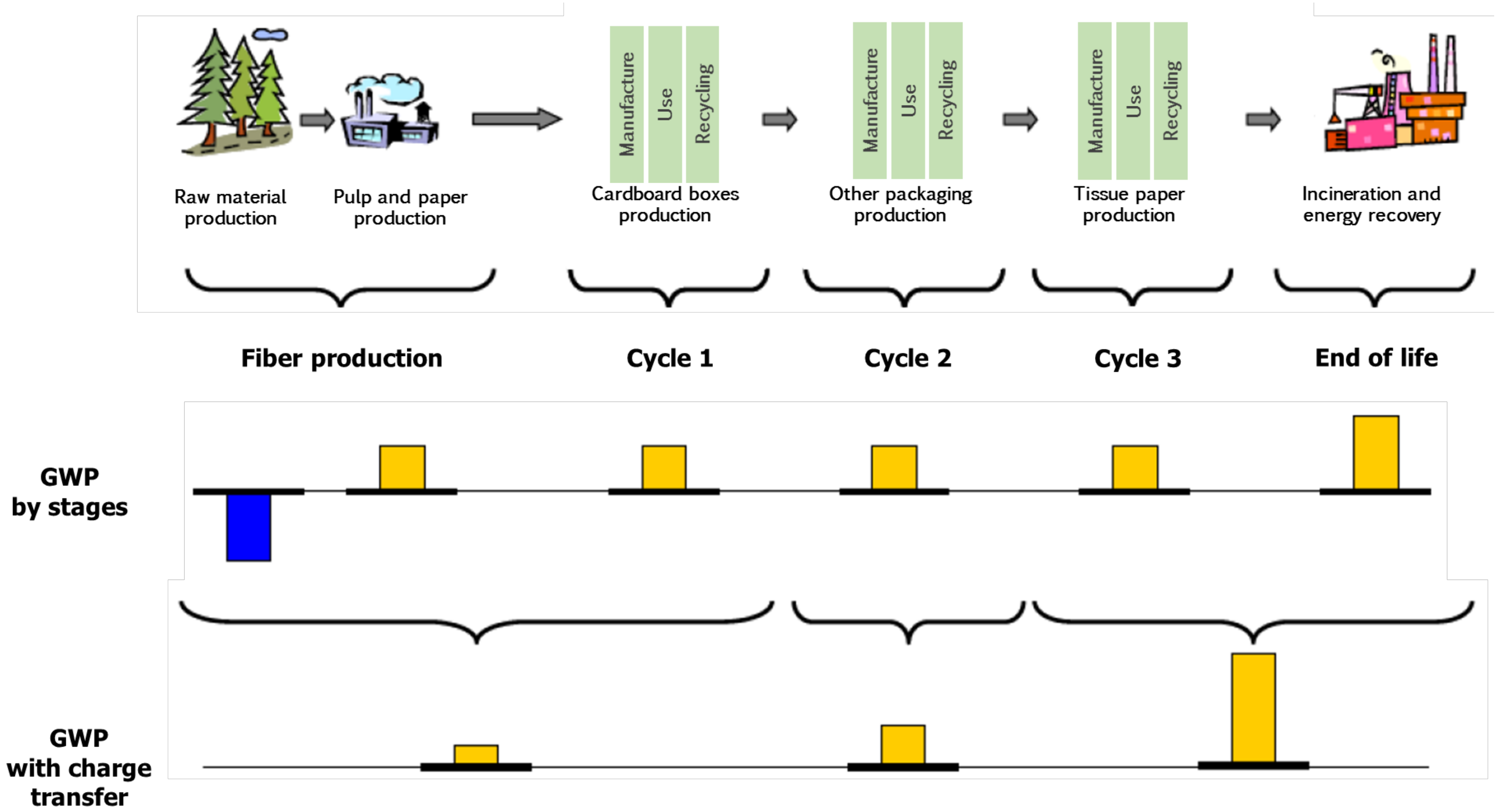
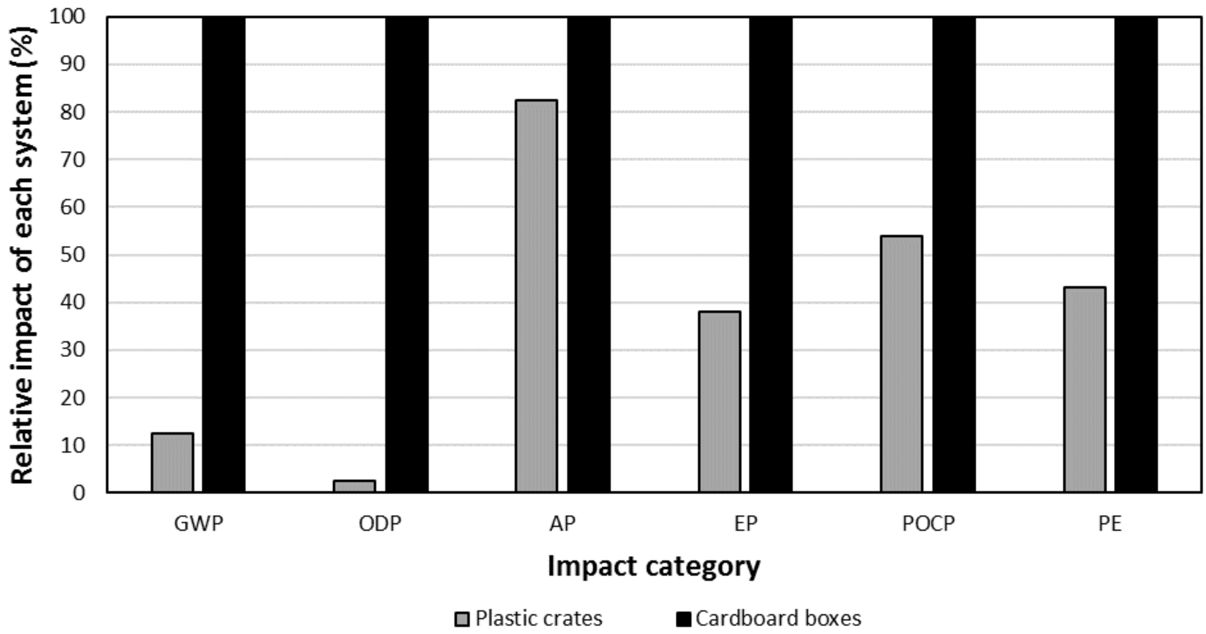


Figure 6: Considerations of biologic CO_2 and number of fiber recycling cycles in the Global Warming Potential (GWP) (based on Albrech et al, 2009).

a)



b)

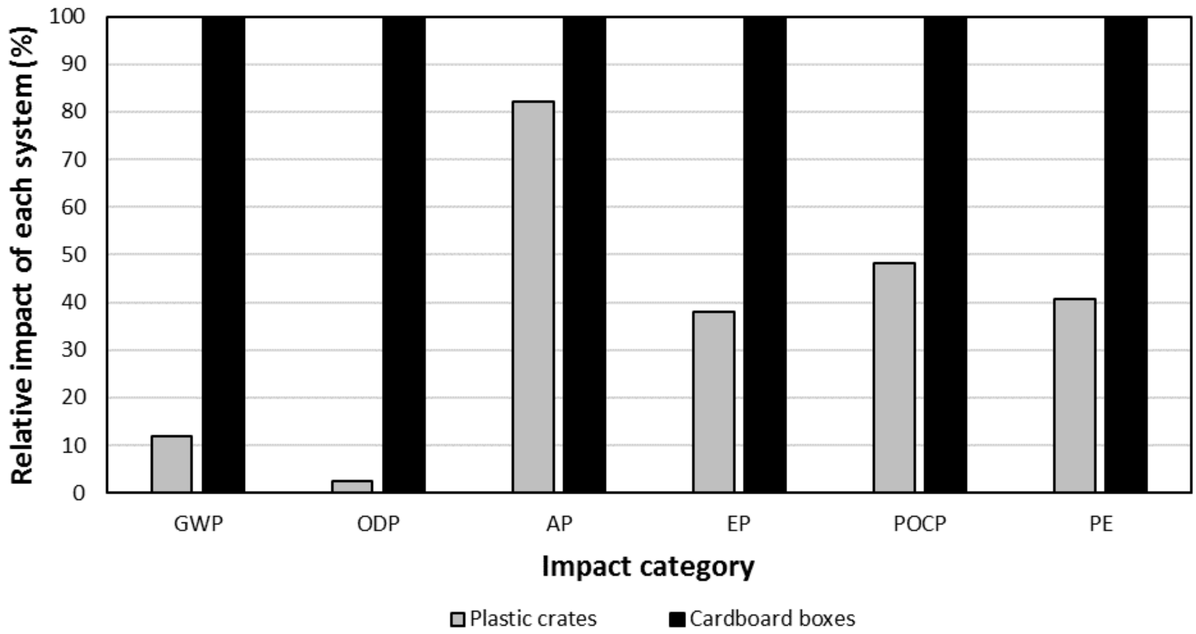


Figure 7: Relative results for the comparison of the impacts of both packages in the conservative (a) and technical (b) scenarios.

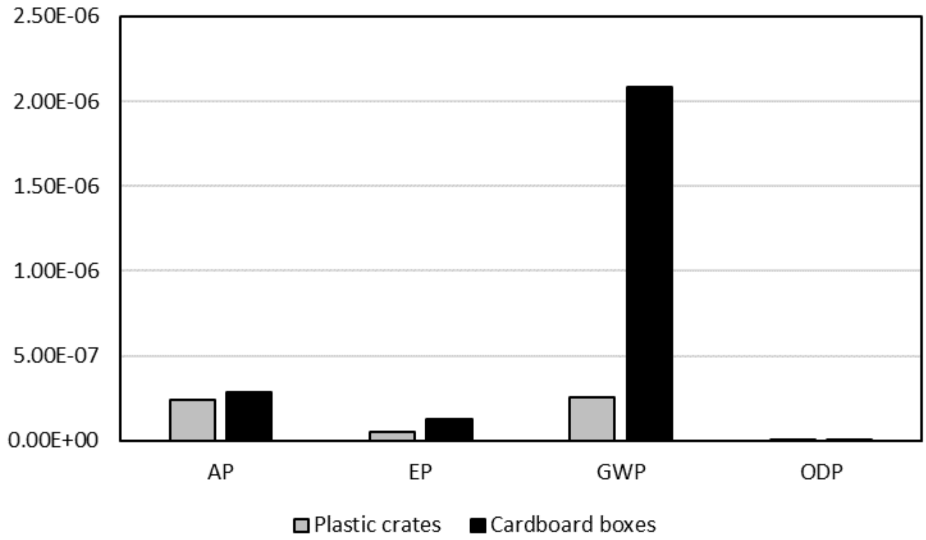


Figure 8: Environmental impact results normalized to the average regional emissions of Europe 25 (+3) for the year 2000 in the conservative scenario.

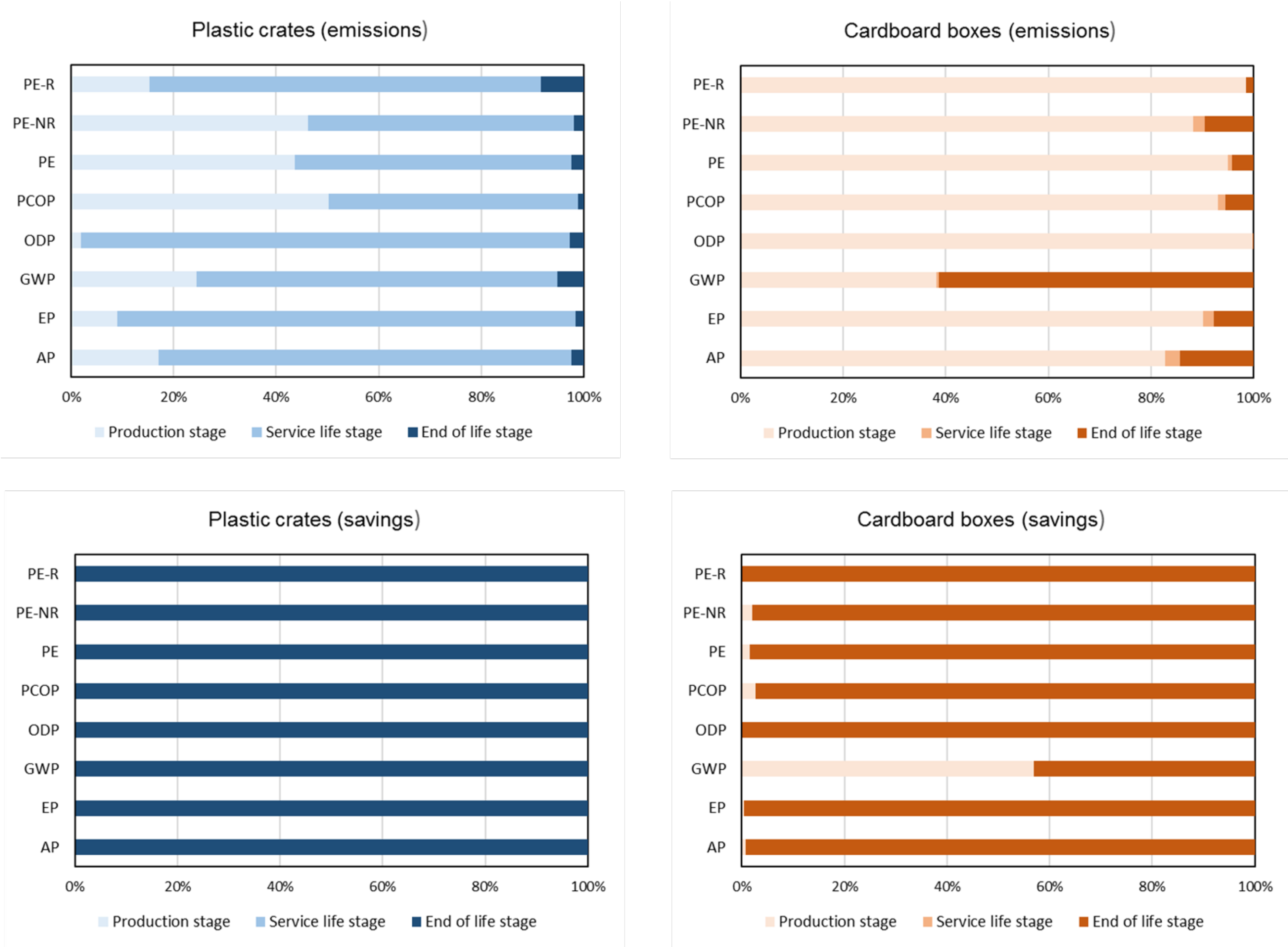


Figure 9: Relative contributions of each life cycle stage to the environmental indicators in the conservative scenario.

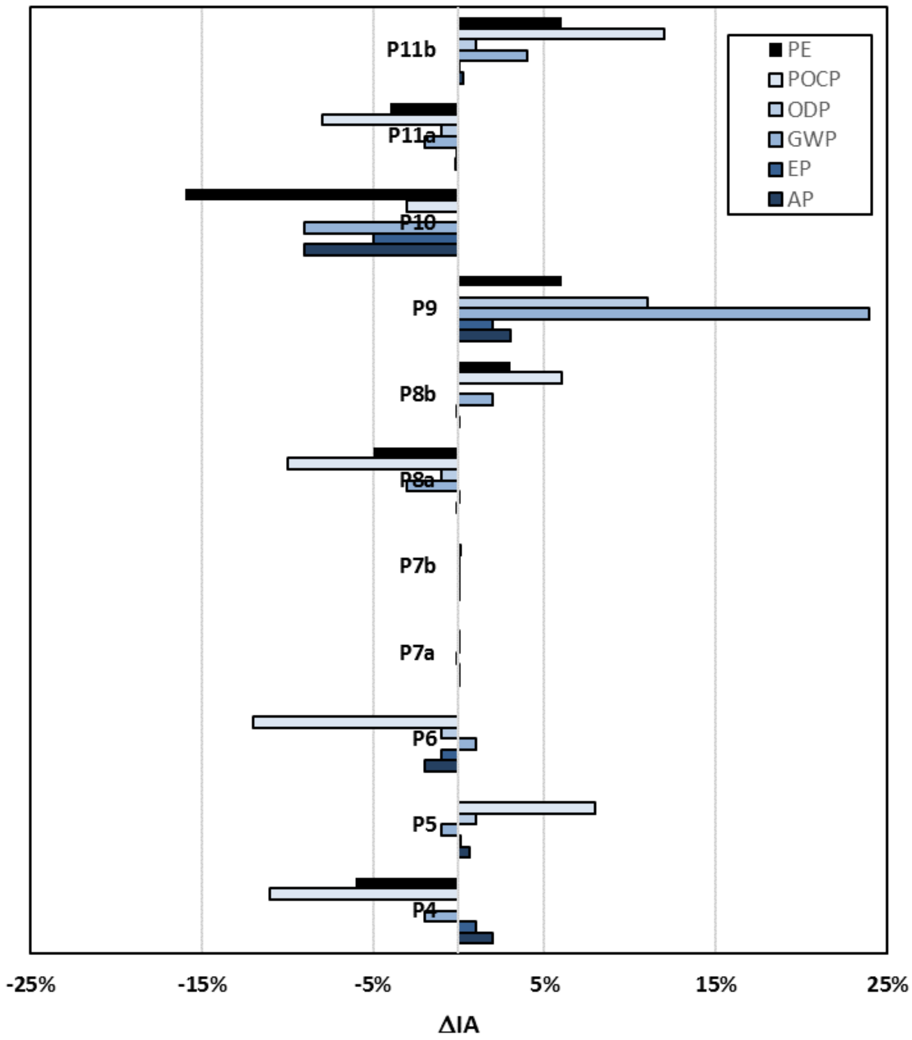


Figure 10: Results of the sensitivity analysis of the variables that have influence on reusable plastic crates.

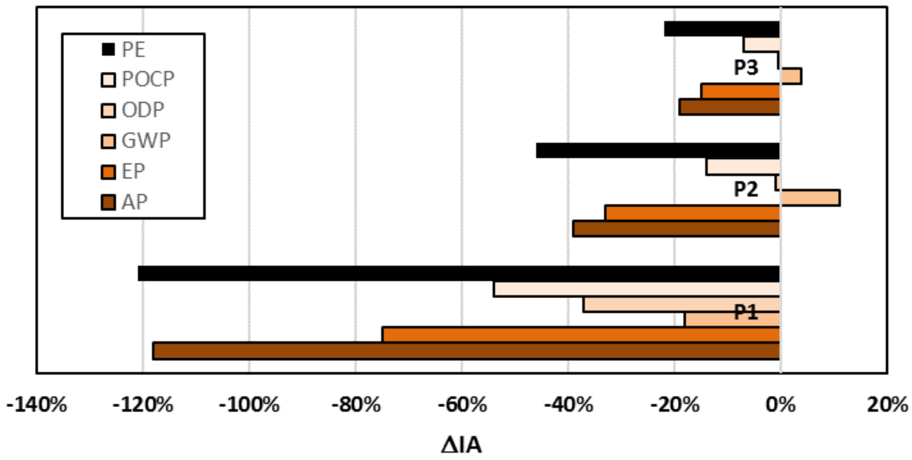


Figure 11: Results of the sensitivity analysis of the variables that have influence on single-use cardboard boxes.