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Comparative life cycle assessment of polyethylene terephthalate (PET) and multilayer Tetra Pak juice packaging systems

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Food packaging provides many vital functions including protection, storage and preservation of products, as well as, information to consumers. However, the overall packaging life cycle generates significant environmental impacts since its production exploits natural resources and energy and causes environmental emissions. Moreover, packaging wastes generate increasing disposal issues, being the second largest fraction of municipal wastes after the organic fraction.
During the last years there is focus on the environmental performance of juice packaging systems. Polyethylene terephthalate (PET) bottles and Tetra Pak multilayer packaging arethe dominant juice packaging options. Life cycle assessment (LCA) techniques are used to improve the understanding, as well as, to compare the environmental characteristics of different packaging systems.
This research assesses the environmental impact of the two commonest juice packaging options, including their production along with their final disposal (landfilling, incineration and recycling). The aim is to compare the footprints of PET and Tetra Pak packaging, identify the hot spots and finally discover the most environmentally benign juice packaging. LCA was performed using GABI software, following the ISO 14040 series recommendations, while the impact assessment was carried out using ReCiPe 2016.
The results showed that Tetra Pak was environmentally superior to alternative PET packaging in 12 of the 18 total impact categories. In fact, their differences were significant in climate change and fossil depletion caegories, the environmental importance of which is assessed by the Federal Environment Agency as "very high" and "high" respectively. Considering the extended shelf life of juices with Tetra Pak, andthe reduced environmental footprint, it can be concluded that there are clear environmental advantages for multilayer Tetra Pak juice packaging over PET bottles.

Keywords: climate change, environmental footprint, end-of-life

1. Introduction

The traditional functions of food packaging are to contain and protect food from degradation processes, as well as, to provide information to consumers about the included ingredients and the nutritional value. Packaging provides three main categories of protection: physical protection against mechanical damage during distribution; biological protection against microorganisms, insects or animals and chemical protection against modifications in composition caused by exposure to gases (usually oxygen), moisture or light (Ramos et al., 2015).
The beverage sector uses millions of tonnes of packaging per year with juice packaging being the most competitive segment in the global beverage packaging industry. Packaging constitutes a major issue in preserving fruit and vegetable juices. As a result of the emerging consumption of juices, the global juice

packaging market has achieved a strong growth and the packaging industry has greatly evolved over the last two decades mainly in terms of packaging materials (Falguera and Ibarz, 2014; Borah and Dutta, 2019).

The use of plastics and especially polyethylene terephthalate (PET) in juice packaging is increased due to the low raw material's cost and its functional advantages, such as the excellent mechanical and optical properties (Falguera and Ibarz, 2014; Ramos *et al.*, 2015). However, plastics' variable permeability to light, gases and low molecular weight molecules (Ramos et al., 2015) along with the poor protection of the quality of oxygen-sensitive beverages over long periods are major concerns for their use in juices (Ros-Chumillas et al., 2007).

Nowadays consumers' demand for safer products with higher quality lead the industrial packaging sector to face some remarkable advances (Ramos et al., 2015). One of them is Tetra Pak multilayer packaging, which is produced by laminating six layers of stiff paper (75% of the packaging mass), low density polyethylene (LDPE) (20%) and aluminium foil (Al) (5%). The combination of materials results in the added advantage of properties from each individual material and specifically the rigid shape of paper, the outstanding barrier properties against light, water vapour, oxygen and microorganisms of Al and the layer bonding function of LDPE. Its low weight and cost and the extension of juice shelf life are among the advantages of Tetra Pak multilayer packaging. However, the recycling of Tetra Pak still remains a challenge (Zawadiak, 2017). Nowadays, PET and Tetra Pak packaging systems present the most common options for the packaging of fruit juice products.

The packaging sector produces approximately 2% of the gross national product in developed countries and about half of this packaging is used in food industry. Overall, despite its undeniable usefulness, the life cycle of packaging creates significant environmental impacts. Indeed, its production exploits natural resources and energy and causes environmental emissions (Bertolini et al., 2016). In addition, packaging waste creates disposal issues, making it the second largest fraction of municipal waste after the organic fraction and the percentage is increasing every year (Pasqualino et al, 2011). The contribution of packaging to the overall environmental impact on food supply chains has led to legislation, such as the European Council (1994), but also to a number of studies focusing on packaging management (Tencati et al., 2016; Beitzen-Heineke et al., 2017).

The contribution of juices to food packaging fraction is the highest (Pasqualino et al. , 2011). It is therefore crucial to assess the environmental impacts of their entire life cycle in order to implement improvements that promote their sustainability. The first step towards improving a process or product is to properly record the current situation in order to evaluate and compare it with any future changes (Boustead, 1993). The comparison of materials and processes to determine the optimum choice presents difficulties.

Life Cycle Analysis (LCA) is a scientific method developed to help address the acute environmental problems of recent years, presenting a wide variety of variations (Guinee, 2002). LCA is the most suitable and valid tool to cover the need for assessment of environmental behavior of products and processes in a reliable way since it is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle, as defined by the International Organization for Standardization in the ISO 14040:2006 (ISO, 2006).

The aim of the present study is the assessment of the environmental impact of the two commonest juice packaging options, namely PET and Tetra Pak multilayer packaging systems, including their production along with their final disposal (landfilling, incineration and recycling). The packagings will be compared with each other in terms of their environmental aspects in order to discover the most environmentally benign alternative.

2. Materials and Methods

LCA study was performed on GABI ts (v8.7.0.18) software following the ISO 14040 series recommendations (14040:2006 and 14044: 2006). The impact assessment was carried out using ReCiPe 2016 (H) and midpoint impact categories focusing on single environmental problems.

2.1 Goal and Scope

The goal of this LCA was to evaluate and compare, in terms of their environmental impacts, two different process chains for the manufacturing and end-of-life of two fruit juice packaging systems: polyethylene terephthalate (PET) bottles and Tetra Pak multilayer packaging. This study's goal was to find the packaging having the lowest environmental impact.

2.1.1 Functional Unit

The functional unit was defined as the packaging containing 10^{-3} m^3 (one liter) of juice, excluding the cap. PET packaging of 10^{-3} m^3 of refrigerator juice weighted 48.80 g and Tetra Pak packaging 34.96 g.

2.1.2 System Boundaries

The production and end of life of PET and Tetra Pak packaging systems are the processes that present the greatest changes in the environmental footprint of these packagings. Therefore, processes, such as the filling with juice, the transport and distribution, as well as, the consumption of the products were excluded from the study since they increase the complexity without showing large differences between the two packagings.

2.2 Life Cycle Inventory Analysis (LCIA)

After defining the goal and scope of LCA, the next step was the Life Cycle Inventory Analysis (LCIA), which connects all the activities with quantitative data according to the selected functional unit. The data used in this study are derived from laboratory measurements (weight and surface area), publications in scientific papers, Tetra Pak reports and GaBi and Ecoinvent LCA data bases.

Regarding PET bottles, their production included the production of PET granules (raw material), their drying and their extrusion, whereas their end-of-life included recycling at a rate of 30%, incineration at a rate of 40% and landfilling at a rate of 30%.

The production of Tetra Pak included the production of raw materials: 4 LDPE layers (20% of total packaging mass), one layer of stiff paper (75%) and one layer of aluminum foil (5%); their bonding and lamination and the final production of the multilayer packaging. Tetra Pak end of life referred to 26% recycling according to latest official global recycling data of Tetra Pak (Tetra Pak, 2020). The remaining 74% was destined to incineration (39%) and landfilling (61%). During recycling, the majority of Tetra Pak units (97 out of 170) recycle only 75% of the packaging (the paper fraction) (Tetra Pak, 2020) and produce paper fibers at a rate of 80% of the paper mass (Xie *et al.*, 2013) used to produce non-packaging paper products, so the same percentages were assumed in the study. From 1 kg of packaging led to recycling, 0.6 kg of paper fibers were produced, while the remaining amount (0.4 kg), which consisted of 0.20 kg of polyethylene, 0.5 kg of aluminum and 0.15 kg of non-recyclable paper, was disposed of for incineration (39%) and landfilling (61%) according to Gabi database. Tetra Pak recycling process is initially carried out in a pulper, data for which were found on the official websites of pulper manufacturers. An average capacity (250 tons per day) was assumed and the energy and water consumptions were found given the final moisture content of the pulper at the end of the process. In total, from 1 kg of Tetra Pak packaging, 0.16 kg was recycled, 0.33 kg was incinerated and 0.51 kg was transported to landfills. Tables 1 and 2 list the input and output data for the main production processes of PET and Tetra Pak packaging systems, respectively.

Table 1. Life cycle inventory with input and output data for the production of PET

Processes	Inputs/ Outputs	Flows	Amounts	Units
Drying	Inputs	Electricity	$1.50\ 10^{-4}$	MJ
		PET	$4.89\ 10^{-2}$	kg
		Thermal Energy	$1.45\ 10^{-2}$	MJ
	Outputs	PET	$4.88\ 10^{-2}$	kg
		Water Vapor	$9.74\ 10^{-5}$	kg
Extrusion	Inputs	Compressed air	$1.17\ 10^{-3}$	Nm^3
		Electricity	$1.35\ 10^{-1}$	MJ
		Lubricating oil	$6.88\ 10^{-6}$	kg
		PET	$4.88\ 10^{-2}$	kg
		Thermal Energy	$2.09\ 10^{-2}$	MJ
	Output	¡ • ¤ bottle	1.00	pcs

Table 2. Life cycle inventory with input and output data for the production of Tetra Pak packaging

Processes	Inputs/ Outputs	Flows	Amounts	Units
Tetra Pak production	Inputs	Al foil	$1.36\ 10^{-3}$	kg
		LDPE film	$7.95\ 10^{-4}$	kg
		Powder coating	$1.37\ 10^{-4}$	kg
		Corrugated board	$8.03\ 10^{-4}$	kg
		Liquid packaging board (LPB)	$2.13\ 10^{-2}$	kg
		Electricity	$2.49\ 10^{-2}$	MJ
		Light fuel oil	$2.26\ 10^{-6}$	kg
		Liquefied petroleum gas (LPG)	$2.69\ 10^{-5}$	kg
		Natural Gas	$2.02\ 10^{-4}$	kg
		Fresh water	$8.83\ 10^{-3}$	kg
	Outputs	Tetra Pak packaging	1.00	pcs
		Hazardous waste	$2.57\ 10^{-5}$	kg
		Nitrous oxide	$9.64\ 10^{-9}$	kg
		Volatile organic compounds (VOC)	$7.85\ 10^{-6}$	kg
		Sulphur dioxide	$1.18\ 10^{-8}$	kg
		Non- methane VOC	$4.83\ 10^{-8}$	kg
		Carbon dioxide	$5.30\ 10^{-4}$	kg
		Carbon monoxide	$2.02\ 10^{-7}$	kg
		Dust (>PM10)	$1.43\ 10^{-9}$	kg
		Methane	$4.85\ 10^{-8}$	kg
		Nitrogen dioxide	$5.34\ 10^{-7}$	kg

3. Results and Discussion

The environmental footprint of the production and end-of-life of Tetra Pak and PET juice packaging systems is presented in Figure 1 in detail for the most significant ReCiPe impact category of climate change.

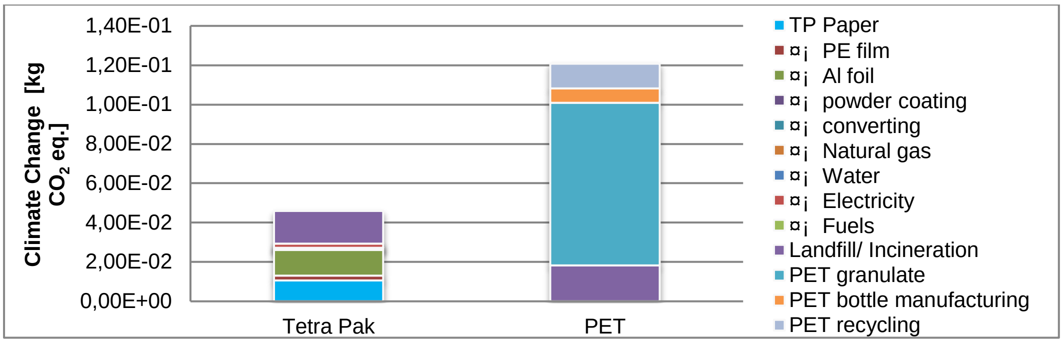

Figure 1.Production and end-of-life effects of Tetra Pak (TP) and PET juice packaging on climate change impact category (expressed in kg carbon dioxide equivalent - kg CO_2 eq.)

Climate change is solely due to CO_2 emissions and to a lesser extent to methane and • $_2$Ÿ emissions from combustion of gas for thermal processes and lignite for electricity generation (Huijbregts *et al.*, 2016).
The carbon footprint of Tetra Pak is equal to 0.046 kg CO_2 eq., while the footprint of PET packaging is 2.6 times higher and equal to 0.121 kg CO_2 eq. These results are in line with Tetra Pak reports (Kartonverpackungen, Gmbh and Gmbh, 2007) and Finkbeiner's study (Finkbeiner *et al.*, 2010). The main factors of Tetra Pak that have the greatest burden in climate change are paper production, aluminum film production and the end-of-life including only landfilling and incineration, whereas regarding PET packaging, the production of PET granules has the greatest share. The converting process plays a minor role.
PET granulates have a great share since PET is a fossil based material and has negative impact on the environment. In addition, the weight of PET packaging is higher than that of Tetra Pak and this fact burdens even more the load. In Tetra Pak juice packaging, paper production has a high impact since trees harvested for paper fibers production no longer absorb carbon dioxide and convert it to organic compounds. Concerning aluminum foil, during its production, the largest contributions of greenhouse gases are attributed to the electricity production for electrolysis and thermal energy production for alumina refining (56% and 13% respectively) (Nunez and Jones, 2016).
The end-of-life sector related to incineration and landfilling is also considered important in climate change category for both types of packaging due to greenhouse gas emissions during the incineration of packaging materials in municipal solid waste facilities (Markwardt *et al.*, 2017). Tetra Pak recycling footprint is included in the electricity and water consumption sectors. The environmental footprints of the production and end-of-life of PET and Tetra Pak juice packaging systems on the other 17 ReCiPe impact categories are shown in Table 3.

Table 3. Results for midpoint impact categories for production and end-of-life of Tetra Pak and PET packaging

Midpoint Impact category	Tetra Pak	PET	Unit
Fine Particulate Matter Formation	$2.75\ 10^{-5}$	$3.35\ 10^{-5}$	[kg PM2.5 eq.]
Fossil depletion	$0.89\ 10^{-2}$	$5.40\ 10^{-2}$	[kg oil eq.]
Freshwater Consumption	$2.01\ 10^{-3}$	$0.76\ 10^{-3}$	[m^3]
Freshwater eco-toxicity	$3.66\ 10^{-5}$	$3.04\ 10^{-5}$	[kg 1,4 DB eq.]
Freshwater Eutrophication	$9.60\ 10^{-7}$	$5.98\ 10^{-7}$	[kg P eq.]
Human toxicity, cancer	$1.05\ 10^{-5}$	$4.17\ 10^{-5}$	[kg 1,4-DB eq.]
Human toxicity, non-cancer	$2.00\ 10^{-3}$	$7.11\ 10^{-3}$	[kg 1,4-DB eq.]
Ionizing Radiation	$1.18\ 10^{-3}$	$0.64\ 10^{-3}$	[Bq C-60 eq. to air]
Land use	$5.57\ 10^{-4}$	$6.38\ 10^{-4}$	[Annual crop eq.·y]
Marine eco-toxicity	$0.58\ 10^{-4}$	$1.28\ 10^{-4}$	[kg 1,4-DB eq.]
Marine Eutrophication	$1.84\ 10^{-6}$	$0.73\ 10^{-6}$	[kg N eq.]
Metal depletion	$1.97\ 10^{-4}$	$1.97\ 10^{-4}$	[kg Cu eq.]
Photochemical Ozone Formation, Ecosystems	$0.50\ 10^{-1}$	$1.61\ 10^{-1}$	[kg NO_x eq.]
Photochemical Ozone Formation, Human Health	$3.07\ 10^{-2}$	$9.98\ 10^{-2}$	[kg NO_x eq.]
Stratospheric Ozone Depletion	$1.08\ 10^{-8}$	$1.48\ 10^{-8}$	[kg CFC-11 eq.]
Terrestrial Acidification	$0.92\ 10^{-4}$	$1.07\ 10^{-4}$	[kg SO_2 eq.]

Terrestrial eco-toxicity	0.97 10^{-2}	5.06 10^{-2}	[kg 1,4-DB eq.]

In fossil depletion category, the burden of PET packaging is six times higher than Tetra Pak since the former consists exclusively of PET, which is made from fossil fuels, whereas the second consists of 75% paper, which comes from non-fossil sources.
However, the impact of Tetra Pak juice packaging in freshwater consumption is higher than its alternative packaging. This is due to the production and recycling of paper, where huge volumes of water drawn from freshwater sources, such as rivers and lakes, are consumed during the mixing of cellulose fibres with water (paper production) and during the separation of cellulose fibres from foreign materials in the pulper (paper recycling). Except for water consumption, paper significantly contributes to the categories of eutrophication and freshwater eco-toxicity, where Tetra Pak presents a higher load than PET bottle. Paper production requires chemicals, such as acids/bases for pH control, aluminium sulphate for fibre retention improvement, fillers etc., which end up in freshwater recipients causing chemical contamination. In addition, it contributes organic compounds into surface waters leading to excessive oxygen- consuming reactions and resulting in lack of oxygen in the water (Markwardt *et al.*, 2017).
In contrast to freshwater eco-toxicity, in terrestrial and marine eco-toxicity, PET packaging results in a higher environmental load than Tetra Pak. This indicates that the main 1,4- DB emissions of Tetra Pak end up in lakes and freshwater aquifers, while the respective emissions from the production and end-of-life of PET packaging are directed to marine recipients and industrial soil. The elevated 1,4- DB releases of PET bottles are also depicted in the categories of human toxicity (cancer and non-cancer) and are presumably because of the use of antimony, a toxic and potential human carcinogen substance, as catalyst during PET production.
An important share of the high burden of PET packaging in the impact categories of photochemical ozone formation (both for ecosystems and human health) is the end of life. Nitrogen oxides (NO_x) are emitted as products of the waste incineration mainly through oxidation of nitrogen in the waste (at low temperatures) and less through oxidation of atmospheric nitrogen (at higher temperatures) (Nielsen, 2019). NO_x emissions contribute to photochemical ozone formation, but are controlled by strict legislation.
On the contrary, incineration and landfilling appear as credits in six impact categories: fine particulate matter formation, fossil depletion, ionizing radiation, land use, stratospheric ozone depletion and terrestrial acidification. Waste incineration leads to the production and recovery of heat and electricity, thus conserving oil and other conventional fossil fuels. This fact has direct benefits to both fossil depletion and ionizing radiation, which refers to anthropogenic emissions of radionuclides into the environment generated during the nuclear fuel cycle, coal burning and extraction of phosphate rocks (Huijbregts *et al.*, 2016). Comparing recycling with incineration and landfilling, the former waste management technique represents a better alternative concerning freshwater consumption, freshwater eco-toxicity, human toxicity, photochemical ozone formation (ecosystems and human health) and terrestrial eco-toxicity categories. A better comparison between the environmental footprints of the two studied juice packaging systems can be performed in Figure 2.

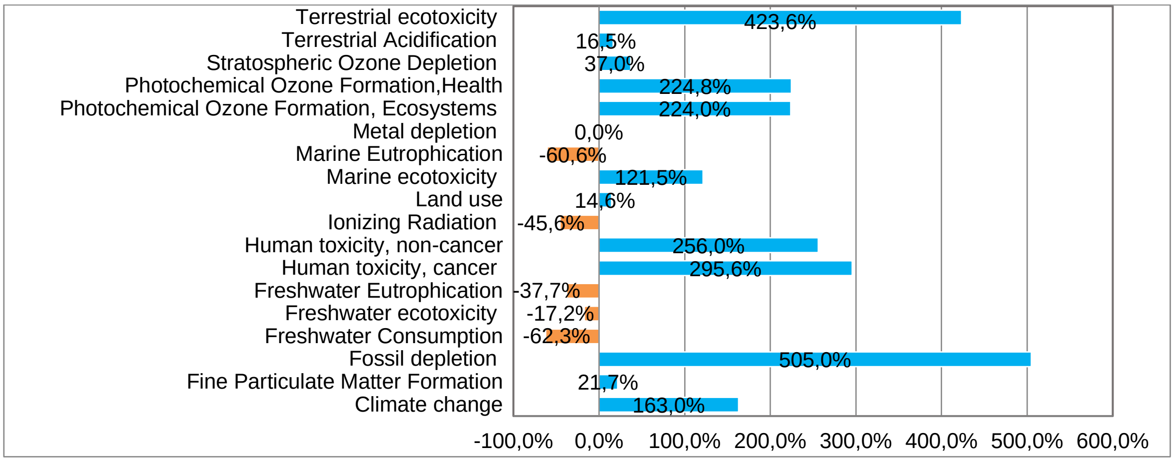

Figure 2. Rates at which the environmental footprint of Tetra Pak is better (blue) and worse (orange) than PET packaging for the eighteen ReCiPe 2016 impact categories (% change over Tetra Pak performance)

Figure 2 shows that Tetra Pak juice packaging demonstrates negative percentages, which indicate inferiority compared to PET packaging, in five categories that concern the aquifer, and more specifically the categories of freshwater and marine eutrophication, freshwater consumption and eco-toxicity. This is due to the production of paper, the main raw material of multilayer packaging, which constitutes 75% of the total packaging mass. On the contrary, PET packaging presents a heavier load in twelve out of eighteen impact categories with the production of PET granules burdening the environmental footprint to a very significant extent. The end-of-life associated with incineration and landfilling of PET bottles has a negative environmental footprint (environmental benefit) in eight categories; while in four categories (metal depletion, terrestrial eco-toxicity and photochemical ozone formation that affects health and ecosystems) is the main contributor in the environmental load due to the emissions produced during combustion.

4. Conclusions

In conclusion, Tetra Pak juice packaging is environmentally superior to PET packaging in twelve of eighteen total impact categories. In fact, the differences between the two packages are significant in the impact categories of climate change and mineral resources consumption, the environmental significance of which is assessed by the Federal Environment Agency as "very high" and "high" respectively (Kartonverpackungen, Gmbh and Gmbh, 2007). Considering the benefits of Tetra Pak juice packaging in the extended shelf life of the juices, as well as the reduced environmental footprint in most of the impact categories, it can be stated that there are clear environmental advantages for Tetra Pak juice multilayer packaging over PET packaging.

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