Life Cycle Assessment (LCA) of biobased packaging solutions for Extended Shelf-Life (ESL) milk

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Abstract

The dairy market is one of the most important sectors worldwide and milk packaging contributes to over one third of the global dairy packaging demand. The end-of-life of the disposable packages is a critical stage of their life cycle, as demonstrated by the fact that disposable bottles are one of the litter items that are most found on beach shores.

The aim of this paper is to analyse the performance of Bio-plastic bottles compared to other alternatives currently in use in the milk packaging sector, using the Life Cycle Assessment (LCA) methodology. Bio-compostable plastic can be a powerful means to create a circular economy for disposable items. A PLA-based bottle is compared to a PET bottle, a HDPE bottle, a Multilayer carton and a Glass bottle. In the analysis, also secondary and tertiary packaging is included. The functional unit chosen is “the packaging needed to contain 1 litre of ESL milk and to guarantee a shelf life of 30 days”. Two sensitivity analysis are also performed in order to assess the influence of the end-of-life stage on the total impact.

The results show that Bioplastic system has a better performance than fossil-based systems and Multilayer carton in the categories of Climate Change, Ozone Depletion, Human toxicity and Freshwater Eutrophication. The recycling scenario strongly changes the impact of the Glass packaging system in the considered categories.

1. Introduction

The diary market is one of the most important worldwide and milk is the most consumed dairy product in the world. Contrary to the COVID-19 market disruptions and to the early expectations (FAO 2020), worldwide global milk production increased in 2020, leading to a peak in production of over 28.000 tons between September and October (CLAL 2021).

Milk is a highly perishable product because it is an excellent medium for the growth of microorganism that can cause spoilage and diseases in the consumers. Only with milk processing (FAO 2021) and effective methods of conservation, it is possible to preserve milk for days, weeks or months. Therefore, the primary task that packaging must fulfil is to provide protection. Limited to the available milk packages, various studies were made about the ability of protecting food from the environment and to preserve its quality. It was shown that multilayer and monolayer pigmented HDPE bottles provide the best overall protection to pasteurized milk (Moyssiadi et al. 2003; Zygoura et al. 2003). However, Bio-based materials can be as performant in preserving food. (Haugaard et al. 2002) demonstrated that a rigid packaging material based on Poly lactic acid (PLA) is at least as effective as HDPE and PS packaging material in protecting fresh, unpasteurised orange juice against quality changes.

Beyond food protection, the tasks that milk packaging, and food packaging in general, must fulfil are numerous and involve different aspects. Since no differentiation in product can be obtained, in the market of commodities other aspects must be used in order to catch clients’ attention. Packaging can be an important lever, as it can differentiate the product on the shelf. The pieces of information conveyed and highlighted on labels, along with the brand name, can influence consumer’s perception of the product (Kim, Lopetcharat, and Drake 2013). Also, the material the package is made of may induce emotional responses in the potential consumers (Clark et al. 2021) and influence their buying. A new awareness towards the ecological problem is growing, thus the way users assess environment-friendliness of products can also be a factor of differentiation. The perception of environmental sustainability by the consumers is strongly related to the material of the packages and to what they can personally do at the disposal stage (Boesen, Bey, and Niero 2019).

Packaging is a powerful means from a commercial point of view and its importance in worldwide economy is undeniable. Milk packaging specifically contributes to over one third of the global diary packaging demand. At the moment, HDPE bottles cover more than 70% of fresh milk packaging (Mordor Intelligence 2020) but a new awareness toward eco-friendly materials could change this trend.

The environmental impact of packaging on the whole food chain is relevant. It was assessed that in the life cycle of beer, the impact of packaging is similar to the impact of beer production. For water and juice, packaging has the highest environmental impact in the life cycles (Pasqualino, Meneses, and Castells 2010). In the dairy sector, (Jungbluth, Keller, and Meili 2018) assessed that consumer packaging has the second biggest impact in various environmental categories, after milk production itself. However, its environmental burden can also depend on the diary factory considered (Djekic et al. 2014). Not only the production phase but also the household waste is relevant in determining the total impact of packaging (Sonesson and Berlin 2003). The amount of food waste directly linked to packaging is another aspect that can influence the environmental performance of these items. In fact, packaging design has the potentiality of reducing food waste and the linked environmental burdens (Wikström et al. 2013). However, it may be necessary to increase the environmental impact of the packaging in order to reduce the impact due to the food loss (Williams and Wikström 2010). For

duce food waste by increasing the shelf life. (M. Manfredi et al. 2015) showed

that environmental benefits linked to milk savings are higher than the impacts associated with coating's life cycle. Also PLA packages can be used to enhance the shelf life of products, as demonstrated for blueberry (Almenar et al. 2010). The introduction of bio-compostable materials can also be a powerful means to create a circular economy and to reduce the marine litter. In fact, disposable bottles are one of the litter items that are most found on beach shores (European Parliament and of the Council 2019).

The huge dimension of the milk packaging sector and the strong impact of packaging on food chains justify an attentive analysis specifically on milk packaging materials from an environmental point of view. Several studies were made using the Life Cycle Assessment method. (Stefanini et al. 2020) compared PET bottles and glass bottles, both returnable and non-returnable. It was shown that PET bottles have the lowest impact in all the selected categories. Non-returnable glass bottles have the highest impact. The reuse of these bottles can improve the performance of the glass packaging system but, even considering 30 cycles of reuses before disposal, its impact is not comparable to the PET bottle one's. (Bertolini et al. 2016) evaluated the impact of PET bottles, HDPE bottles and multilayer carton. The paper pointed out that the impact of multilayer carton is, on average, 12% lower than HDPE bottle and 34% lower than PET bottle. (Xie et al. 2011) compared PA-PE-Al laminate and polyethylene milk packaging, showing that the composite packaging has a slightly higher impact than the plastic one. Furthermore, they demonstrated that raw material extraction and the disposal phase are the most impactful stages in the life cycle. In this paper, we wanted to focus on the neglected topic of the bio-compostable plastic bottles in milk packaging from an environmental point of view. Using the LCA methodology, we wanted to assess the impact of bioplastic items compared to other solutions currently in use.

2. Methodology And Data

The present analysis is made following the Life Cycle Assessment Methodology. The software SimaPro 9 (PRé Consultants 2019) was used to perform the calculation. As prescribed by the ISO 14040 series (International Organization for Standardization 2006a; 2006b) the following phases are presented:

- Goal and scope definition
- Life cycle inventory
- Life cycle assessment
- Life cycle interpretation

2.1. Goal and scope definition

The aim of this analysis is to perform a Life Cycle Assessment of different packaging systems used for Extended shelf-life (ESL) milk. All the items are modelled through the main materials they are made of. In detail, the following packaging systems are considered.

- The *PET bottle* system. The bottle is made of polyethylene terephthalate (PET), the cap is made of High-density polyethylene (HDPE) and the label is made of polyvinyl chloride (PVC).
- The *HDPE bottle* system. The bottle is made of High-density polyethylene (HDPE), the cap is made of Polypropylene (PP) and the label is made of polyvinyl chloride (PVC).
- The *Multilayer carton* system. Beyond the multilayer aseptic carton, a cap made of High-density polyethylene (HDPE) is included in this system. No label is included.
- The *Glass bottle* system. The bottle is made of Glass, the cap is made of Steel and the label is made of Low-density polyethylene (LDPE).
- The *Bioplastic bottle* system. The bottle is made of PLA, the label and the cap are mainly made of Poly lactic acid (PLA) and poly butylene succinate (PBS). The items made of PLA and PBS are compostable. Biodegradability under composting conditions is determined by applying the standard EN 13432 (CEN 2000).

In all the systems, secondary and tertiary packaging is also included.

2.2. Functional unit

The functional unit chosen is "the packaging needed to contain 1 litre of ESL milk and to guarantee a shelf life of 30 days" (Bertolini et al. 2016).

2.3. System boundaries and assumption

The analysis is made on “cradle to grave” systems. For each packaging system, the phases of extraction and production of materials for primary, secondary and tertiary packaging are considered. No transportation is included in the analysis as no detailed information was available. However, (Eide 2002) found that transport does not have a major influence on the milk food chain, so its exclusion does not lead to consistent alterations in the results. The production of milk is not included, as its impact is the same for all the considered packaging systems. The end of life of the materials is included in the analysis. It is assumed that all the items are sent to landfill. This choice allows to focus on the impact of the packaging production. A sensitivity analysis is then performed in paragraph 3.2 in order to understand how the end of life influences the outcome. The considered systems are a simplification of the real ones thus the results should be interpreted in this perspective.

2.4. Impact categories

The Impact Assessment Method selected to perform this analysis is the ILCD 2011 (‘European Commission Service Site’ 2016). The impact categories analysed are chosen among the PEF suggested ones (S. Manfredi et al. 2012) and are presented in Table 1 with their units. A complementary analysis is performed using the Cumulative Energy Demand (CED) method, as it allows to express and compare the energy consumption of the processes. Characterization factors for energy resources are divided into five impact categories:

1. Non renewable, fossil.
2. Non renewable, nuclear.
3. Renewable, biomass.
4. Renewable, wind, solar, geothermal.
5. Renewable, water.

A cumulative energy demand index is obtained by a weighted average of the previous factors, giving each category the weighting factor 1 (PRé Sustainability 2020).

Table 1
Impact categories and their units

Impact category	Units
Global Warming Potential	kg CO2 eq.
Ozone Depletion Potential	kg CFC-11 eq.
Human toxicity, cancer effects	CTUh
Photochemical ozone formation	kg NMVOC eq
Acidification	molc H + eq
Terrestrial eutrophication	molc N eq
Freshwater eutrophication	kg P eq

2.5. Inventory

The data used in life cycle inventory are gathered from different and various sources.

For PET, HDPE and Multilayer carton systems, data of primary, secondary and tertiary packaging were obtained from (Bertolini et al. 2016). Data for the bioplastic packaging system were provided by the company (‘BioWare S.R.L.’ 2020). The weights of the bottle, the cap and the label of the glass bottle were taken from (Stefanini et al. 2020). Data about secondary and tertiary packaging were assumed considering the shape and the weight of the glass bottles. All quantities referred to the functional unit are presented in Table 2. All the compositions provided should be considered as indicative.

Table 2
Average weights of the items referred to the functional unit.

Material	***Bottle***		***Cap***		***Label***		***Stretch film***		***2°/3° Packaging***	
PET	PET	25,2g	HDPE	3,5 g	PVC	4,75 g	LLDPE	0,42 g	PE	0,24 g
									Wood	6,94 g
HDPE	HDPE	31,6 g	PP	3,5 g	PVC	0,8 g	LLDPE	0,42 g	PE	0,24 g
	TiO2	0,63 g							Wood	6,94 g
Multilayer	LDPE	6,8 g	HDPE	4,3 g			LLDPE	0,33 g	Box	7,34 g
carton	Carton	25,5 g							Wood	5,56 g
	Ink	0,08 g								
Glass	Glass	400g	Steel	3,43g	LDPE	0,8g	PE	0,93 g	Box	7,34 g
									Wood	25g
Bioplastic	PLA	25,2g	PLA	1,6 g	PLA	4 g	PBS	0,5 g	PBS	0,25 g
			PBS	0,4 g	PBS	1 g			Wood	6,94 g
			Talc	1 g						

Table 3
Ecoinvent traces used in the modelling process.

Material	**Ecoinvent traces**
PET	*Polyethylene terephthalate, granulate, amorphous {GLO}| market for*
HDPE	*Polyethylene, high density, granulate {GLO}| market for*
PVC	*Polyvinylchloride, bulk polymerised {GLO}| market for*
LLDPE	*Polyethylene, linear low density, granulate {GLO}| market for*
PE	*Packaging film, low density polyethylene {GLO}| market for*
Wood	*Wood pellet, measured as dry mass {RER}| market for wood pellet*
LDPE	*Polyethylene, low density, granulate {GLO}| market for*
Carton	*Kraft paper, bleached {GLO}| market for*
Ink	*Printing ink, offset, without solvent, in 47.5% solution state {RER}| market for*
Box	*Corrugated board box {RER}| market for corrugated board box*
TiO2	*Titanium dioxide, chloride and sulphate processes, production mix, at plant GLO*
PP	*Polypropylene, granulate {GLO}| market for*
Glass	*Packaging glass, white {GLO}| market for*
Steel	*Steel, unalloyed {GLO}| market for*
Talc	*Feldspar {GLO}| market for*

For the modelling of the materials, SimaPro's databases and literature research were combined. As talc is not present in any of the provided libraries, Feldspar is used instead as approximation (Hill and Norton 2018). To model Poly-lactic acid (PLA), the ecoprofile provided by NatureWorks is used, referring to 2006 production (Vink et al. 2007). The modelling of PBS is based on the production process of hybrid poly butylene succinate (Moussa 2014). The PBS synthesis is achieved from 1,4-butanedion and succinic acid (Cok et al. 2014).

The landfill scenario is modelled as *Municipal solid waste (waste scenario) {CH}| Treatment of municipal solid waste, landfill*, using the Ecoinvent library (Wernet et al. 2016).

All the other materials were modelled using the Ecoinvent library (Wernet et al. 2016), as reported in Table 3.

3. Results And Discussion

3.1. Impact assessment results

The environmental impact of the systems according to the ILCD method is represented in Table 4. In Fig. 1, a contribution analysis is provided in order to better understand the role of the main elements of each system. The label "Bottle + Cap + Label" represents the production of the materials of the primary packaging for each system. The label "2/3 packaging" represents the impact of the production of the materials of secondary and tertiary packaging. The label "End of life" represents the impact of the end of life of all the materials of the considered system. For greater usability, the results are shown in terms of percentage values. For each category, all the systems are normalized to the impact of the glass bottle's primary packaging.

The environmental impact of the systems according to the CED method for this baseline scenario is presented in Table 5. In the same table, the CED index associated to raw material production is also provided.

The glass bottle has the highest values in all the considered categories, mainly due to the production of the primary packaging materials. The same result was obtained by (Stefanini et al. 2020) in the comparison of glass and PET production for primary packaging. (Dhaliwal et al. 2014) confirmed that glass bottles are outperformed by polymer bottles in every considered environmental impact category.

Table 4 Environmental impact according to the ILCD method for the baseline scenario.

Category	Unit	PET bottle	HDPE bottle	Multilayer carton	Glass Bottle	Bioplastic Bottle
Climate change	10^{-2} kg CO2 eq	10,147	8,393	7,264	41,956	4,265
Ozone depletion	10^{-9} kg CFC-11 eq	4,449	1,15	4,569	48,628	1,013
Human toxicity, cancer effects	10^{-9} CTUh	5,869	2,851	3,863	19,501	1,277
Photochemical ozone formation	10^{-4} kg NMVOC eq	3,434	3,44	2,874	18,515	3,065
Acidification	10^{-4} molc H+ eq	4,615	3,503	3,454	38,334	3,18
Terrestrial eutrophication	10^{-4} molc N eq	9,221	6,845	8,212	69,316	11,162
Freshwater eutrophication	10^{-6} kg P eq	23,501	3,17	20,4	93,205	3,364

Table 5
Cumulative energy demand index expressed in MJ for the baseline scenario and for material production.

Scenario	PET bottle	HDPE bottle	Multilayer carton	Glass bottle	Bioplastic bottle
Baseline	0,462	0,504	0,493	1,267	0,331
Material Production	0,46	0,502	0,49	1,254	0,329

Bioplastic bottle has a good performance in all the presented categories. In Terrestrial Eutrophication its impact is higher than the multilayer carton, PET bottle and HDPE bottle. This is due to the necessary steps to grow the sugar cane or the other raw materials needed for the fabrication of bioplastics. In particular, the use of pesticides and fertilizer in the fields leads to higher eutrophication potential (Changwichan, Silalertruksa, and Gheewala 2018). The small impact in terms of CO2 Eq. of Bioplastic bottles with respect to PET bottles is also confirmed by (Gironi and Piemonte 2011). In the category of Ozone Depletion, the primary packaging material of this system has low values in terms of CFC-11 Eq. due to the small impact of bio-compostable resin production. This result was confirmed by (Madival et al. 2009) in the comparison of PET clamshell with PLA clamshell. In the category of Acidification, bioplastic bottle has lower impact than fossil-based systems, as also showed by (IFEU Heidelberg 2006) for PLA and PET clamshells. (Tabone et al. 2010) found a different trend of PLA in the latter two categories. The impact of PLA depends on the considered production technology (IFEU Heidelberg 2006; Vink et al. 2007), and this may lead to different outcomes in the comparisons.

The performance of multilayer carton is worse than the bioplastic bottle's in most categories. Only in Photochemical Ozone Formation multilayer carton assumes the lowest value, thanks to the small contribution of primary packaging production. In Climate change it is less impactful than HDPE and PET bottles, as also confirmed by (Meneses, Pasqualino, and Castells 2012). Multilayer carton presents high values in the categories of Terrestrial Eutrophication and Freshwater Eutrophication. In Acidification, the impact of multilayer carton is

lower than the ones of fossil-based systems. In this category, the same trend was found for recycled paper egg packaging over PS egg packaging (Zabaniotou and Kassidi 2003).

The performance of HDPE bottle strongly depends on the considered category. In Ozone depletion, Terrestrial Eutrophication and Freshwater Eutrophication this system assumes very low values, thanks to the limited impact of primary packaging production. In fact, in these categories HDPE production is less impactful than PET production or PLA production, as also assessed by (Tabone et al. 2010).

PET bottle does not assume the lowest value in any of the considered categories. This is mainly due to the high impact of primary packaging production. However, the total performance of this system is sensibly better than the one of the glass bottle, as also assessed for the Palestinian market (Saleh 2016).

The Cumulative Energy Demand Index confirms that the Bioplastic bottle is the most convenient solution whereas the glass bottle the least. The good performance of bioplastics is linked to its lower use of non-renewable energy than fossil based polymers (Groot and Borén 2010). The energy efficiency of PLA over fossil-based polymers was also demonstrated by (Bohlmann 2004), who studied PLA over PP cups. The Energy demand of the glass bottle is about four times bioplastic bottle's one. According to this index, PET bottle is more convenient than HDPE bottle and Multilayer carton.

3.2. Sensitivity analysis. Rate of recycling

Two sensitivity analyses are performed in order to assess the impact of different end of life scenarios. The first sensitivity analysis is made using the recycling rates of Italy in 2019 whereas the second analysis is made using the targeted Italian rates of recycling for 2030 (CONAI 2021). The percentages used are reported in Table 6. It can be observed that the target for year 2030 is substantially achieved at national level, except for paper and plastic packaging waste. Further improvements in the recycling rates could be reached in the future, therefore the results obtained in these analyses should be considered conservative. As no percentage was provided for the bio-compostable items, it is assumed that the PLA-based and PBS-based items are sent to a compost plant in the same proportion as the plastic items are recycled in each scenario. Thus, in the 2019 recycling scenario 45,5% of bioplastics is sent to a compost plant, and in the 2030 recycling scenario 55% of bioplastics is sent to a compost plant. The composting process is represented as *Biowaste {CH}| market for*, using the Ecoinvent library (Wernet et al. 2016). All the recycling processes were modelled using the Ecoinvent library (Wernet et al. 2016). The recycling process of wood is assumed equal to the recycling process of paper. The remaining items are sent to landfill. All the other data and assumptions made for the systems are unchanged.

Table 6
Rate of recycling used in the sensitivity analysis (CONAI 2021).

Material	2019	2030 (target)
Steel	82,2%	80,0%
Aluminium	70,0%	60,0%
Cardboard	80,8%	85,0%
Wood	63,1%	30,0%
Plastic	45,5%	55,0%
Glass	77,3%	75,0%
Total	70,0%	70,0%

The results of the sensitivity analysis with the 2019 recycling scenario are represented in Fig. 2 and Table 7. In Fig. 3 and in Table 8 the results for the 2030 targeted recycling scenario are shown. In Fig. 2 and Fig. 3, a contribution analysis is also provided. As previously assumed, the label "Bottle + Cap + Label" represents the production of the materials of the primary packaging for each system. The label "2/3 packaging" represents the impact of the production of the materials of secondary and tertiary packaging. The label "End of life" represents the impact of the end of life of all the materials of the considered system. For greater usability, the results are shown in terms of percentage values. For each category, all the systems are normalized to the impact of the glass bottle's primary packaging.

In Table 9 the CED index for the 2019 recycling scenario and the 2030 recycling scenario is provided.

The recycling process strongly influences the performances of the Glass Bottle. Its impact is sensibly reduced in all the considered

ge. In the categories of Climate Change and Acidification the total impact of the

Glass Bottle system is the lowest. In Freshwater Eutrophication, Glass is the system which undergoes the strongest variation in outcome. In the categories of Ozone Depletion, Human Toxicity and Photochemical Ozone Formation, glass still has a much higher impact than all the other considered systems, for both the recycling scenarios. In the 2030 recycling scenario, Glass bottle is the most impactful system also in the category of Terrestrial Eutrophication. Further benefits could be obtained by considering the possibility of cleaning and reusing glass bottles, as demonstrated for an Italian wine consortium by (Landi, Germani, and Marconi 2019). The use of glass as packaging material becomes convenient only when appropriate waste infrastructure and management practice exist. Otherwise, substituting commonly used bottles with glass bottles could lead to a significant increase in impact, as demonstrated for the category of Global Warming Potential by (Kouloumpis et al. 2020).

Bioplastic bottle is still the less impactful in the categories of Ozone depletion and Human Toxicity, in both the recycling scenarios. The end-of-life stage for bioplastic undergoes a strong decrease in Human Toxicity, thanks to the small impact of the composting process. In the category of Terrestrial Eutrophication and Acidification, Bioplastic is the most impactful solution due to the large contribution given by feedstock production (Morão and de Bie 2019). In Climate Change, the bioplastic bottle showed lower values than PET bottle, multilayer carton and HDPE bottle in all the considered scenarios. This is also due to the low emissions of PLA production in terms of GHG compared to fossil-based polymers, as also showed by (Groot and Borén 2010). The introduction of bio-compost as end of life leads to an increased impact in the category of Terrestrial Eutrophication. An effective end of life for Bioplastics is also mechanical recycling, whose impact is lower than composting (De Andrade et al. 2016; Piemonte 2011). The introduction of recycling can lead to a better environmental performance of PLA-based products in their lifecycle (Maga, Hiebel, and Thonemann 2019), thus further improvements could be reached for this system.

The performance of the PET bottle system strongly changes when compared to the baseline scenario whereas it is substantially the same in the two recycling scenarios. In Climate Change, PET bottle has the highest impact. The introduction of the recycling process decreases the impact of Human Toxicity of almost a half, but it is still higher compared to the one of the Bioplastic bottle, as also confirmed by (Papong et al. 2014). In the category of Photochemical Ozone Formation, this system assumes the lowest value. Further improvements for this system could be obtained by including the incineration process as end-of-life stage (Foolmaun and Ramjeawon 2008).

Table 7 Environmental impact according to the ILCD method based on the 2019 rates of recycling.

Category	Unit	PET bottle	HDPE bottle	Multilayer carton	Glass bottle	Bioplastic bottle
Climate change	10^{-2} kg CO2 eq	6,003	5,435	4,663	0,348	3,38
Ozone depletion	10^{-9} kg CFC-11 eq	2,778	1,243	4,257	10,991	0,866
Human toxicity	10^{-9} CTUh	3,069	1,697	2,771	4,066	0,636
Photochemical ozone formation	10^{-4} kg NMVOC eq	2,069	2,224	2,165	3,179	2,915
Acidification	10^{-4} molc H+ eq	2,657	2,408	2,483	0,254	2,993
Terrestrial eutrophication	10^{-4} molc N eq	5,815	4,763	6,526	9,052	11,242
Freshwater eutrophication	10^{-6} kg P eq	13,598	3,739	16,065	-0,21	1,601

The introduction of the recycling rates leads to an improvement of Multilayer Carton performances but not as strong as for the other systems. This packaging solution becomes the most impactful in the category of Freshwater Eutrophication. This is due not only to the limited reduction introduced by the end-of-life stage but also to the contribution given by the secondary and tertiary packaging production. A strong decrease in impact can be found for the Climate Change category, as also confirmed by (Mourad et al. 2008). However, the emissions in terms of CO_2 are still higher than the one of bioplastics and glass. The impact of the raw material production is very small for this system in most categories, as also assessed by (Bertolini et al. 2016). The introduction of recycling reduces the value of the CED index, compared to the Baseline case. For this system, the differences in performance between the 2019 recycling scenario and the 2030 recycling scenario are limited. (Villanueva and Wenzel 2007) confirmed that paper recycling can be a better option than landfill and even than incineration, since it leads to an improvement in most environmental categories.

Table 8 Environmental impact according to the ILCD method based on the 2030 rates of recycling.

Impact category	Unit	PET bottle	HDPE bottle	Multilayer carton	Glass bottle	Bioplastic bottle
Climate change	10^{-2} kg CO2 eq	5,527	5,207	4,642	2,4	3,585
Ozone depletion	10^{-9} kg CFC-11 eq	2,569	1,401	4,343	12,43	0,974
Human toxicity	10^{-9}CTUh	2,817	1,788	2,887	5,285	0,834
Photochemical Ozone formation	10^{-4} kg NMVOC eq	1,892	2,079	2,139	3,872	2,992
Acidification	10^{-4} molc H+ eq	2,484	2,416	2,539	1,918	3,19
Terrestrial eutrophication	10^{-4} molc N eq	5,493	4,718	6,601	11,717	11,649
Freshwater eutrophication	10^{-6} kg P eq	13,383	5,71	17,175	6,818	3,085

Table 9
Cumulative energy demand index expressed in MJ for the scenarios considered in the sensitivity analysis.

Scenario	PET bottle	HDPE bottle	Multilayer carton	Glass bottle	Bioplastic bottle
2019 recycling rate	0,227	0,273	0,314	0,014	0,277
2030 recycling rate	0,218	0,265	0,32	0,141	0,306

The recycling scenarios affect the performance of HDPE bottle differently in each category. In Ozone Depletion, HDPE bottle has a good performance, even if its value is higher than in the baseline scenario. It happens because the impact of the end-of-life stage increases with the rate of recycling. In fact, for some items, increasing the recycling rates over a certain level leads to higher impacts due to the environmental loads associated with transport, sorting and packaging (Romero-Hernández et al. 2009). It can be observed a strong reduction in CO_2 Eq. emissions, but this system is still one of the most impactful in the Climate Change category. Limited to this category, further improvements could be obtained in terms of GHG by substituting fossil-based HDPE with bio-based HDPE (Belboom and Léonard 2016). In Terrestrial Eutrophication, the HDPE bottle keeps on having the best performance, thanks to the small impact of raw material production.

4. Conclusions

This study compared the environmental burden of different bottles used for milk packaging. The focus was on the role of bioplastics and on the improvements that can derive from its use in the packaging sector.

Bio-compostable packaging system proved to be the best alternative in the baseline scenario, assuming high values only in the category of Terrestrial Eutrophication. Glass had the worst result in all the considered categories due to the high impact of raw material production. Multilayer carton presented intermediate values between fossil-based items and bioplastic bottles, assuming higher values only in the category of Ozone Depletion and presenting the best performance in Photochemical Ozone Formation.

Introducing Recycling as end-of-life scenario improves the performance of all the systems, especially of Glass. Bioplastic bottle presents a good performance in the categories of Climate Change, Ozone Depletion, Hyman toxicity and Freshwater Eutrophication. Multilayer carton still shows intermediate values between the fossil-based systems and the Bioplastic ones. Waste management is a fundamental stage, as it can deeply change the ranking of the items in many categories. The introduction of recycling as end-of-life scenario for PLA-based products could lead to further improvements for the bio-compostable system.

Declarations

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Consent for publication: not applicable

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Figures

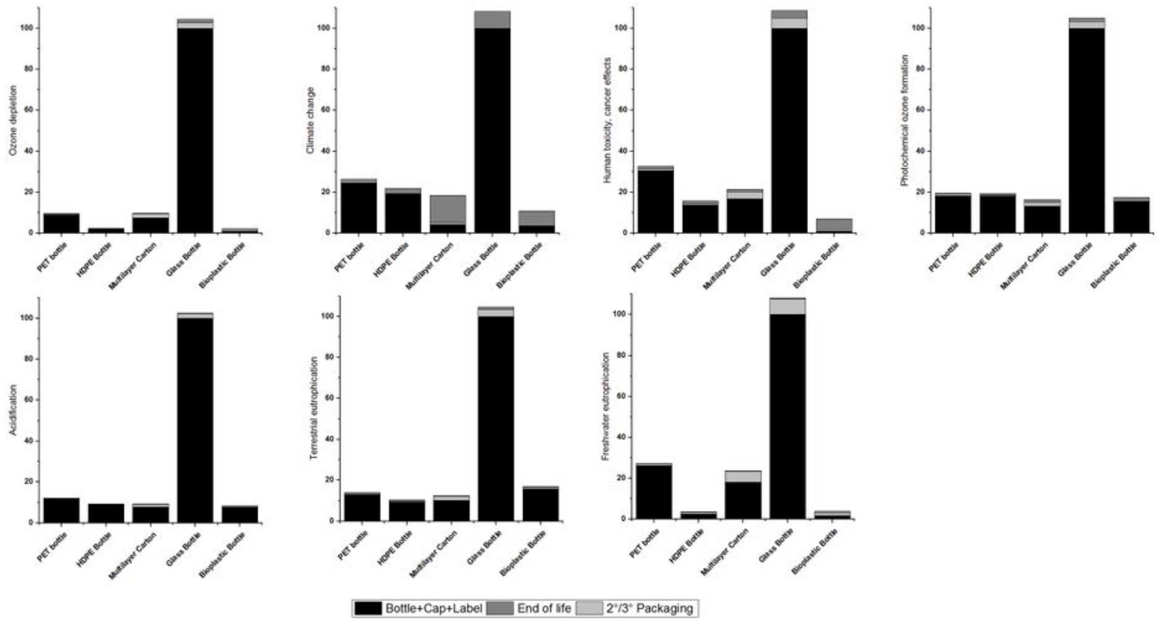

Figure 1

Environmental impact according to the ILCD 2011 method.

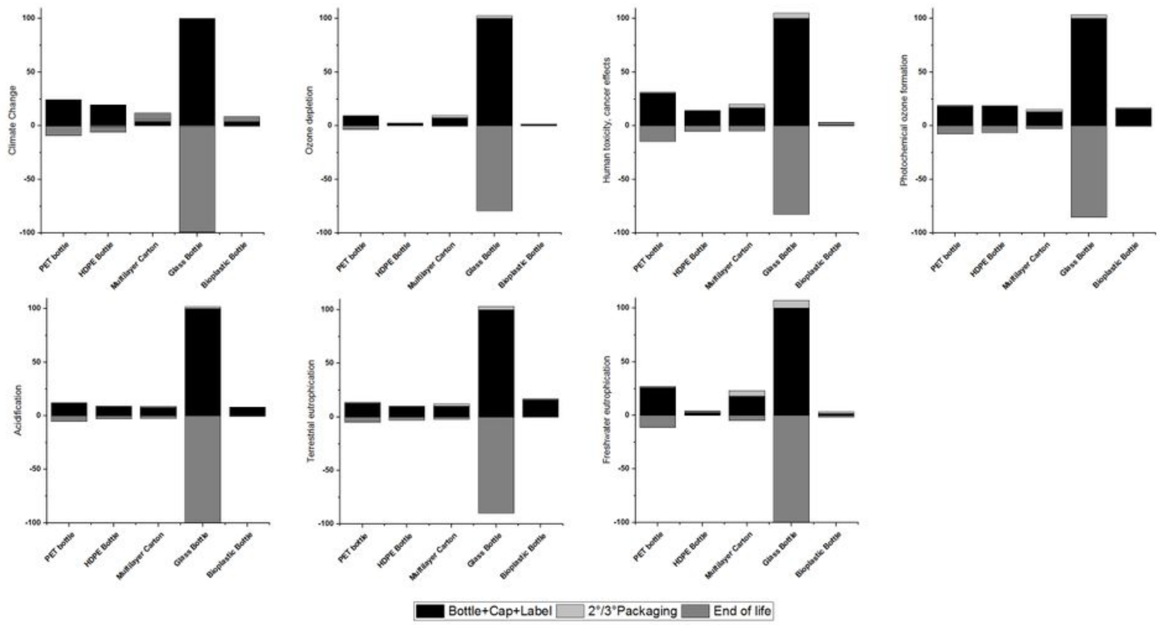

Figure 2

Environmental impact and contribution analysis according to the ILCD method based on the 2019 rates of recycling.

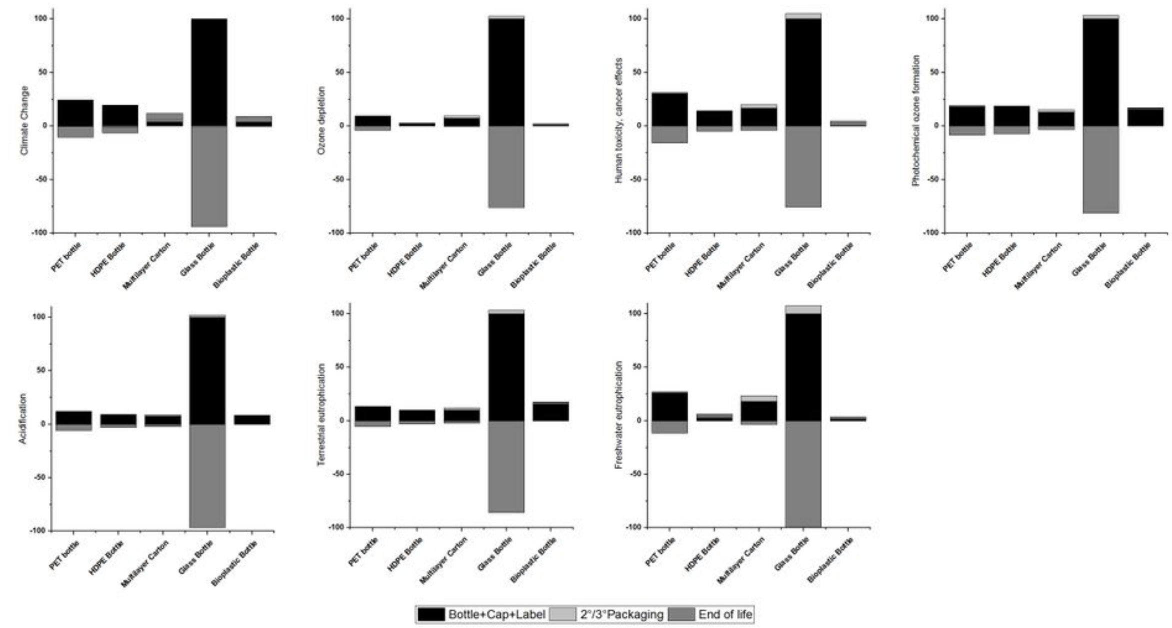

Figure 3

Environmental impact and contribution analysis according to the ILCD method based on the 2030 rates of recycling.