Life cycle assessment (LCA) of bio-based 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 bioplastic 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 L of ESL milk and to guarantee a shelf life of 30 days”. Two sensitivity analyses are also performed in order to assess the influence of the end-of-life stage on the total impact. The results show that, in accordance with the assumptions of an ideal scenario, bioplastic system has a better performance than fossil-based systems and multilayer carton in the categories of climate change, ozone depletion, human toxicity, freshwater eutrophication, particular matter, and land use. The recycling scenario strongly changes the impact of the glass packaging system in the considered categories.

Keywords Bioplastic · Life cycle assessment · Packaging · Environmental impact

Introduction

The dairy 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 polylactic acid (PLA) is at least as effective as HDPE and PS packaging material in protecting fresh, unpasteurized 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 perception of the product (Kim et al. 2013). Also, the material the package is made of may induce emotional responses in the potential consumers (Clark et al. 2021) and

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influence their buying. A new awareness towards the ecological problem is growing in different segments including foods and drugs; thus, the way users assess environment friendliness of products can also be a factor of differentiation (Novelli et al. 2017). 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 et al. 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 dairy 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 et al. 2010). In the dairy sector, Jungbluth et al. (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 dairy 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 improper 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, and stakeholders should value this aspect (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 milk packaging, antimicrobial coatings can be used to reduce 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 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.

Disposable bottles are one of the litter items that are most found on beach shores (European Parliament and of the Council 2019). Replacing fossil-based plastics with bio-based solutions is one of the strategies to preserve land and sea environmental quality in Europe. The market for bio-based and biodegradable plastics is supposed to grow, also thanks to the European Policy priorities: the global bioplastic production capacity is set to increase from around 2.11 million tonnes in 2019 to approximately 2.43 million tonnes

in 2024 (Bio-Plastics Europe Project 2020). Therefore, further studies on these materials are necessary.

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. The result obtained was 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. 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.

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

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, and the label and the cap are mainly made of polylactic 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 13,432 (CEN 2000).

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

Functional unit

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

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 life cycle phases of the analysis as no detailed information was available. In the PLA ecoprofile, transport of corn to the corn processing wet mill is considered (Vink et al. 2007). Transport related to distribution is not considered. 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.

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).

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). The weights of the elements of 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 1 Impact categories and their units

Impact category	Units
Global warming potential	kg CO ₂ 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
Water resource depletion	m ³ water eq
Land use	kg C deficit
Particulate matter	kg PM _{2.5} eq

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

Material	Bottle		Cap		Label		Stretch film		2°/3° Packaging	
PET	PET	25.2 g	HDPE	3.5 g	PVC	4.75 g	LLDPE	0.42 g	PE	0.24 g
HDPE	HDPE	31.6 g	PP	3.5 g	PVC	0.8 g	LLDPE	0.42 g	Wood	6.94 g
	TiO ₂	0.63 g							PE	0.24 g
Multilayer carton	LDPE	6.8 g	HDPE	4.3 g			LLDPE	0.33 g	Wood	6.94 g
	Carton	25.5 g							Box	7.34 g
	Ink	0.08 g							Wood	5.56 g
Glass	Glass	400 g	Steel	3.43 g	LDPE	0.8 g	PE	0.93 g	Box	7.34 g
									Wood	25 g
Bioplastic	PLA	25.2 g	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						

For the modelling of the materials, SimaPro 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 polylactic 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.

Results and discussion

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

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
TiO ₂	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

category, all the systems are normalized to the impact of the glass bottle 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

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 CO ₂ eq	10,147	8,393	7,264	41,956	4,265
Ozone depletion	10^{-9} kg CFC-11 eq	4,449	1,150	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	3,440	2,874	18,515	3,065
Acidification	10^{-4} molc H + eq	4,615	3,503	3,454	38,334	3,180
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	3,170	20,400	93,205	3,364
Water resource depletion	10^{-5} m ³ water eq	84,530	-3,255	-25,435	-119,074	43,896
Land use	10^{-2} kg C deficit	6,556	12,697	28,003	119,773	5,778
Particulate matter	10^{-5} kg PM _{2.5} eq	4,032	6,412	6,084	60,492	2,064

Fig. 1 Environmental impact according to the ILCD 2011 method

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

bottles in every considered environmental impact category. The higher impact of glass over PET in the category of particulate matter is also confirmed in Ferrara et al. (2021).

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 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 et al. 2018). In the category of water resource depletion, this system has a very high impact due to the amount of water needed throughout its production steps. In particular, raw material cultivation gives a large contribution on water depletion, particulate matter, and land use (Morão and de Bie 2019). The production of process heat and electricity needed for fermentation, purification, and polymerization is largely responsible for the impact in the categories of particulate matter and climate change (Moretti et al. 2021). 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. Beyond the processing technologies, also the crop type, climate, and geography contribute to the differences in the results. The differences in performances in the various categories highlight significant trade-offs (Vendries et al. 2020), which must be carefully evaluated.

The performance of multilayer carton is worse than the bioplastic bottle 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 et al. (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). Low values for HDPE bottle are also obtained in the categories of land use and particulate matter.

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 has the lowest impact whereas the glass bottle the highest. 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 one. According to this index, PET bottle is more impactful than HDPE bottle and multilayer carton.

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. 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. It is important that the input

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%

of the composting process has limited contamination from non-compostable materials (Vendries et al. 2020). Furthermore, it must be pointed out that not all the compost plant accept compostable packaging, as they can increase the production costs of composting and may hurt resale quality (Composters Serving Oregon n.d.). In particular, the treatment of technical materials through industrial composting can be a conflict of interest for composters, as they do not see themselves as a waste disposal company. Their business is focused on selling compost in productive soil operations for conventional or organic farming and, also, for sanitation. Polymer processing is therefore a good outlet for polymer producers, not necessarily for industrial composters who are in business for different purposes. Furthermore, the nutrient value of compost produced from packaging waste can be insignificant (Vendries et al. 2020). All these aspects are likely to introduce uncertainty in the results. 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.

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 Figs. 2 and 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 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 categories, thanks to the contribution of the end-of-life stage. 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, land use, 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 et al. (2019). The use of glass as packaging material

Fig. 2 Environmental impact and contribution analysis according to the ILCD method based on the 2019 rates of recycling

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 CO ₂ 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
Water resource depletion	10^{-5} m ³ water eq	67,144	-35,841	-51,462	-197,200	32,678
Land use	10^{-2} kg C deficit	5,173	8,346	24,637	30,832	4,152
Particulate matter	10^{-5} kg PM _{2.5} eq	3,150	4,186	5,160	3,200	1,804

Fig. 3 Environmental impact and contribution analysis according to the ILCD method based on the 2030 rates of recycling

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 particulate matter, land use, 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

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 CO ₂ 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
Water resource depletion	10 ⁻⁵ m ³ water eq	71,768	− 34,391	− 47,894	− 176,108	38,588
Land use	10 ⁻² kg C deficit	6,052	8,605	25,209	36,140	4,980
Particulate matter	10 ⁻⁵ kg PM _{2.5} eq	3,212	3,967	5,237	5,458	1,995

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

performance of PLA-based products in their lifecycle (Maga et al. 2019); thus, further improvements could be reached for this system. Recycling and incineration with energy recovery can lead to the great reductions of environmental impacts for bio-based packaging (Vendries et al. 2020). One of the main problems of recycling is the difficulty of distinguishing with high certainty between compatible bio-sourced polymers and fossil plastics. Beltrán et al. (2021) highlighted for PLA 3D printing wastes that the heterogeneity of the wastes plays a fundamental role on the final properties of the recycled materials. This technical barrier could be mitigated by adopting distributed recycling, since it allows to recycle carefully selected waste streams. For lightweight polymers, distributed recycling can reduce the inefficiency of collection and transfer of large volumes of materials such as ABS and PLA (Lee et al. 2018). This study does not consider the environmental impact of food waste, but it must be pointed out that composting has the potential of enabling higher levels of food waste recovery, with resulting environmental benefits (Vendries et al. 2020).

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). The increase of the recycling ratio leads to a consistent reduction in impact in the category of particulate matter.

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 one of the most impactful in the categories of freshwater eutrophication and particulate matter. 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 CO₂ 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.

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.

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.

Under the assumptions made, bio-compostable packaging system proved to be the best alternative in the baseline scenario, assuming high values only in the category of terrestrial eutrophication and water resource depletion. 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, human 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. In the composting process, the possibility of contamination with non-compostable materials was not taken into account, so the results obtained are referred to an ideal situation.

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Author contribution All authors read and approved the final manuscript. Prof. Barletta contributed in conceptualization, funding acquisition, investigation, methodology, project administration, resources, supervision, and writing – review and editing. Dr. Aversa contributed in writing – review and editing. Ing. Cappiello and Mrs. Genovesi contributed in data curation, formal analysis, investigation, software, validation, visualization, and writing – original draft.

Data availability The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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