Packaging Technology and Science
An International Journal

PACKAGING TECHNOLOGY AND SCIENCE
Packag. Technol. Sci. 2016; **29**: 525–546
Published online 16 August 2016 in Wiley Online Library (wileyonlinelibrary.com) DOI: 10.1002/pts.2235

Comparative Life Cycle Assessment of Packaging Systems for Extended Shelf Life Milk

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The aim of this study is to carry out a comparative analysis of the environmental impact of different packaging systems used for extended shelf life milk. The analysis, carried out exploiting the life cycle assessment approach, takes into account the packaging manufacturing process, the food packaging process, the transport phases and the end-of-life management of the different packaging systems. The packaging end-of-life is modelled by considering three possible options, such as recycling, thermo-valorization with energy recovery and landfill. One litre of extended shelf life milk is used as the reference unit, while multilayer cartons, polyethylene terephthalate bottles labelled with shrink sleeve film and high-density polyethylene bottles are analysed as the packaging types.

The key characteristics of each component of the three packaging systems were either provided by packaging manufacturers or derived from data available in literature. The evaluation of the end-of-life impact was performed considering the Italian scenario, exploiting, in particular, the data provided by specific Italian consortia. Other data for the inventory analysis phase were extrapolated from the SimaPro databases (e.g. Ecoinvent or Plastic Europe Database). Cumulative energy demand and CML2001 were adopted as the impact assessment methods.

The results obtained show that the multilayer carton system is the less environmentally impactful option for almost all the considered impact categories and that its environmental impacts are, on average, more than 12% lower than high-density polyethylene system and more than 34% lower than polyethylene terephthalate with shrink sleeve label.

Received 30 March 2015; Revised 20 May 2016; Accepted 16 July 2016

KEY WORDS: food packaging; life cycle assessment; ESL milk; food production; environmental assessment

INTRODUCTION

In today's society, packaging has a key role for sustainability: it is no longer possible that people involved in the design, development, production or use of packaging do not consider the environmental consequences of their work.[1]

The packaging sector generates about 2% of the gross national product in developed countries, and about half of this packaging is used for food.[2] On average, in 2012, every European citizen (Eu-28) generated 156.8 kg of packaging waste, 40% of which consists in paper and board, 20% in glass, 19% in plastic, 15% in wood and 6% in metals.[3] Overall, the packaging life cycle generates significant environmental impacts; indeed, its production exploits natural resources and energy and causes environmental emissions.[4] Moreover, packaging waste generates increasing disposal issues, being the second largest fraction of municipal waste after the organic fraction.[5] In developed counties, modern end-of-life management systems can partially decrease the environmental impacts of packaging; however,

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in many underdeveloped countries, or in developing ones, waste management systems are almost rudimental,[6,7] and the adoption of recycling and energy recovery are still limited and not effective.

In order to measure the environmental performance of a product or system, it is essential to assess its impacts and resources utilization, using quantitative and objective methodologies, which consider its entire life cycle. Life cycle assessment (LCA), regulated by ISO 14040 International Series of Standards,[8] is a very useful methodology to assess the environmental impact of a product throughout its lifetime. This methodology allows quantifying the level of greenhouse gas emissions, the amount of energy consumed and the level of hazardous substances emitted by a product throughout its life cycle.

In recent years, various LCA studies related to packaging were carried out, with a lot of them focusing on the food sector. In this field, most of the studies about LCA of packaging examined the impact of the packaging material and its disposal.[9] Only in recent works, the phases of packaging production and use have been included in the analysis,[10] sometimes also to evaluate the food losses generated as a consequence of the packaging characteristics and use.[11–13] Depending on the type of food, the environmental impact of the packaging, compared with that of the contained food, may vary, reaching, for example, a high percentage for beverages or vegetables foods.[14,15] Aware of these issues, some studies tried to define frameworks or guidelines to develop environmental sustainable packaging, focusing not only on the impact of the packaging materials but also on the preservation of its performance and on the impact of packaging technologies.[10,13,16–18]

Among the papers discussing the environmental impact of food packaging, several works focus on the use of LCA for packaging of milk products and its derivatives. Starting from the milk production, the LCA studies evaluated the impact of delivery, processing, packaging, distribution and consumption of the packaged milk products.[19–21] Some of the published papers expressively analysed the impact of the packaging materials, considering different possibilities in primary and secondary packaging offered by the market or by the research studies.[22,23] The study by Meneses *et al.*[24] assessed the environmental impact of packaged milk using the most common packaging options available on the Spanish market. The same study also evaluated (from the point of view of global warming and acidification) the production of the various packaging materials and sizes, as well as their final disposal. This work, however, examined only some possible solutions of packaged milk, comparing packaging materials, which are adopted for different kinds of products, and evaluated the disposal of the product assuming, alternatively, landfill, incineration or recycling; no mention has been made of the specific characteristic of extended shelf life (ESL) milk and of the packaging equipment. Xie *et al.*,[25] instead, analysed the Chinese situation of milk packaging, comparing multilayer carton (paper–Al–PE) with high-density polyethylene (HDPE) bottles. They found a lower impact of this latter packaging type, which was mainly due, however, to the fact that recycling of multilayer carton in the targeted country was not a well-established practice. Singh *et al.*[23] analysed three types of HDPE packaging for milk, which differ in their size and the possibility to be palletized with or without secondary packaging. Results, however, showed only that the adoption of reusable plastic crates for controlled environment distribution reduced the material requirements of the primary packaging and therefore decreased the overall environmental impacts of this HDPE packaging. Further information about the life cycle of food packaging materials, although not expressively focused on milk packaging, can be retrieved from Madival *et al.*[26] and Pasqualino *et al.*[27] The former authors compared different materials, such as polylactic acid, polyethylene terephthalate (PET) and polystyrene, for the production of thermoformed clamshell, while Pasqualino *et al.*[27] analysed the environmental impact of the most common packaging options in the Spanish market for juice, beer and water. All the studies found in literature also point out that the scenario where the analysis is carried out (i.e. the selected country) has a relevant impact on the life cycle analysis, because it affects the raw material, transports and the final disposal of the packaging. Overall, only some of the studies reviewed have analysed the environmental performance of the packaging equipment for pasteurized fresh milk.[19,28] The attention towards fresh milk and the environmental impact of the dairy industry reflects the fact that milk is one of the most important food products in European countries as it is considered a prescription for good health and an important ingredient for a nutrient-rich diet.[24] Nevertheless, none of the studies reviewed analyses expressively the technological requirements of a packaging system for ESL milk. The progresses made in the ESL milk production process in the last decade currently allow a shelf life up to 30 days to be reached, which requires,

DOI: 10.1002/pts

however, better performance of the packaging materials and technology compared with the traditional pasteurized milk, which can be conserved in the same refrigerated ambient only for a few days.[29,30]

On the basis of these latter considerations, the aim of the present study is to carry out a comparative LCA analysis of different types of packaging systems adopted expressively for ESL milk, which represents the most common product in the field of ESL beverages. In particular, to preserve the quality of the processed milk for ESL option, the packaging materials analysed are (a) multilayer cartons, (b) PET bottles labelled with shrink sleeve film and (c) HDPE bottles with TiO_2 insertion. All of them are able to preserve the milk from light and oxygen for the defined shelf life of 30 days. To carry out an appropriate evaluation of the Italian disposal options of these packaging materials, the more recent guidelines of the paper and plastics Italian associations have been consulted.[31,32]

The remainder of the paper is organized as follows. In the next section, we describe the main features of the different packaging systems for the ESL food products. Then, the main steps of the LCA approach are reported. The results of the analysis and of a subsequent sensitivity analysis are detailed in Results and Discussion and Sensitivity Analysis sections. Finally, the Conclusions section summarizes the main findings on the work, the related limitations and implications and outlines future research directions.

PACKAGING SYSTEMS FOR ESL MILK

Overview of the ESL milk production

In many markets, ESL has become the logical next step beyond pasteurization for chilled dairy and beverage products, extending their shelf life up to 30 days in Asia or Europe, even 60 or 90 days in North America.[2,33,34] Several products have been manufactured and sold using this technology, including white milk, flavoured milk, enriched/fortified products, fermented products, creams, dairy desserts, soy beverages and juices. There are three main processing technologies, different from those used for traditional pasteurized products, that can be used to obtain ESL products, i.e. pasteurization combined with bactofugation, pasteurization combined with microfiltration and high heat treatment.[29] However, not all these technologies can be applied to all products. On milk, which is frequently commercialized as an ESL product, several studies have been performed with the aim of demonstrating the performance of the different ESL treatments.[34–36] Nevertheless, a preferred milk treatment for industrial applications does not actually exist, because its choice depends on the shelf life a company wants to guarantee to the final customer.[29]

Apart from the process technology, the packaging technology used plays an important role in the production of ESL milk.[37] Indeed, both the filling technology and the packaging itself should meet strict hygienic requirements, as even the slightest defect in the packaging will dramatically reduce the shelf life of the product. For ESL products, at least an ultra-clean packaging technology is required for shelf life longer than 21 days.[29] Compared with the traditional systems, the ultra-clean technology needs some sterilization procedures on the packaging materials and the environment. The levels of microbiological reduction for the packaging sterilization, as well as the levels of environmental microbiological contamination, are lower than those of the aseptic filling: 3Log of microbial reductions instead of 5Log for the aseptic packaging and an environmental class ISO 7 instead of ISO 5.[38] Nonetheless, the technologies adopted are quite similar. If considering ESL milk with a shelf life of at least 30 days, different packaging equipment for flexible or semi-rigid containers can be adopted:

1. a Form Fill Seal (FFS) technology for flexible containers (e.g. Tetra Brik®) or a filling technology for preformed flexible containers (e.g. combibloc or Tetra Top®) using an ultra-clean packaging environment; or
2. an ultra-clean technology for rigid (e.g. glass) and semi-rigid (e.g. PET and HDPE) packaging materials.[39]

Both systems exploit a clean room and the same phases of packaging decontamination, packaging drying, product filling and capping. However, in the FFS case, all these operations are performed in a single room following a vertical flow; conversely, in the remaining cases, linear systems (for small

DOI: 10.1002/pts

capacity and preformed flexible container) or rotary carousels (for high capacity and PET or HDPE containers) are used to move the bottles through sterilization, drying, filling and capping.

For the reference product of 1 l of ESL milk, a decontamination treatment with hydrogen peroxide (liquid and vapourized) is considered in this work for both FFS and preformed containers filling, as suggested by many food equipment manufacturers and the literature.[29,40] Packaging materials and filling technology are assessed taking into account the most widespread solutions for the ESL milk Italian market.[41]

Description of the packaging materials

The packaging materials most widely used to guarantee a shelf life longer than 30 days for ESL milk are PET with a shrink sleeve label, HDPE and multilayer cartons.[2]

PET. PET is a recyclable material that is cheap, light, easy to mould and able to limit losses of carbonation and flavour.[42] The raw material compounds for the commercial production of PET are ethylene and p-Xylene for the production of ethylene glycol and acetic acid and p-Xylene for the production of purified terephthalic acid. The purified terephthalic acid is then reacted with ethylene glycol to produce bis-hydroxyethyl terephthalate, with water as a by-product. The monomer is then polymerized in the liquid phase to produce amorphous PET. A second polymerization is then carried out to increase the molecular weight of the polymer and to produce a partially crystalline resin. This resin (granulate) can be used to create preforms via injection moulding, which are subsequently converted into bottles exploiting a stretch blow moulding process. The detailed production process shown in Figure 1 is taken into account in our analysis.

PET bottles can be blow moulded *in situ*, e.g. inside a food company, starting from bottle preforms, which are usually sent by some preform producers. Stretch blow moulding machines could be directly

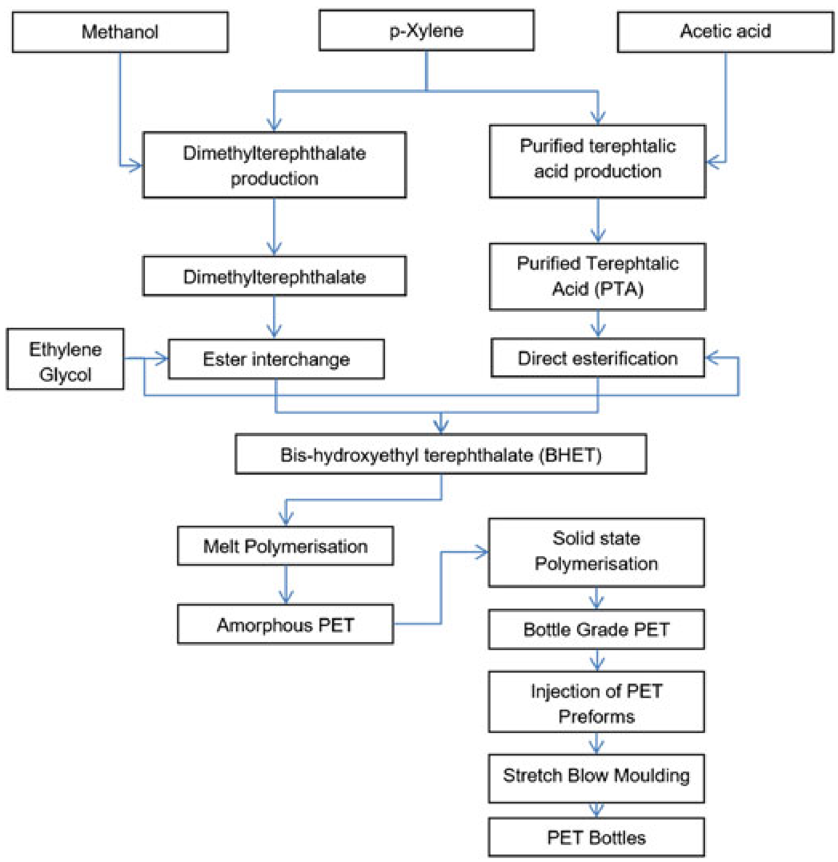

Figure 1. Scheme of the production process of PET bottles.

DOI: 10.1002/pts

connected to the filling equipment without the use of expensive conveyors. Moreover, transporting preforms instead of blown bottles helps reduce the cost and the environmental impact of this packaging, because of the higher number of packaging materials that can be transported for each shipment, compared with blown bottles. Some big companies are also carrying out the injection of PET preforms *in situ*, thus receiving the PET granulate directly from chemical companies. As this alternative process is still limited, its implementation will be discussed only in Sensitivity Analysis section.

HDPE. HDPE is a polyolefin composed of several thousands of bound ethylene units. There are two main techniques used for HDPE production: (a) the slurry polymerization, where the polymer is produced at relatively low temperature (70–110°C) and low pressure (1–5 MPa) in a saturated hydrocarbon medium; and (b) the gas-phase polymerization that exploits a gas-phase reactor in a fluidized bed of dry polymer particles (at temperature of 70–110°C and pressure of 2 MPa). The powder obtained is mixed with stabilizers and generally extruded into pellets. As far as the ESL milk packaging is concerned, very often a pigmented monolayer (HDPE + 2% TiO_2) is used, to ensure higher protection against the light and a better gas barrier compared with the simple monolayer, at the same time avoiding the complex structure of a multilayer packaging (e.g. HDPE + 2% TiO_2/HDPE + 4% carbon black/HDPE + 2% TiO_2).[43] The titanium dioxide production process includes the relative impacts of mineral extraction, transport, production of liquid oxygen and chlorine treatment, as well as the related energy consumption.[44] The blow moulding machine operates combining reciprocating-screw blow moulding technology with sterile blow air in enclosed, pressurized clamp area. A laminar airflow system delivers dry, HEPA-filtered air to the clamp interior. This study considers the blow moulding of the HDPE bottles starting from the polymer granules at the milk packaging site; indeed, it is nowadays uncommon to transport the empty HDPE blow moulded bottles from an external producer.[2] The detailed production process shown in Figure 2 is taken into account in the analysis.

Multilayer carton. The multilayer carton used for ESL milk consists of an external layer of low-density polyethylene (LDPE), a cardboard and a further internal layer of LDPE. Overall, the cardboard and LDPE account for 79% and 21% of the total weight of the carton, respectively. The cardboard is used as support, while the internal LDPE layer is in direct contact with the food[46] and the external one avoids the adsorption of moisture. All the layers are then laminated together. Printing on the paper, with specific inks, is made just before lamination. The manufacturing process described previously is shown schematically in Figure 3.

An alternative production process would exploit a preformed multilayer carton, such as Tetra Top®, made of paperboard with an injection moulded plastic top and internally coated.[20] This carton is formed and sealed in its bottom part by the end-user company and then filled with milk, capped, packed in cardboard boxes, palletized and wrapped with stretch polyethylene films. This process is

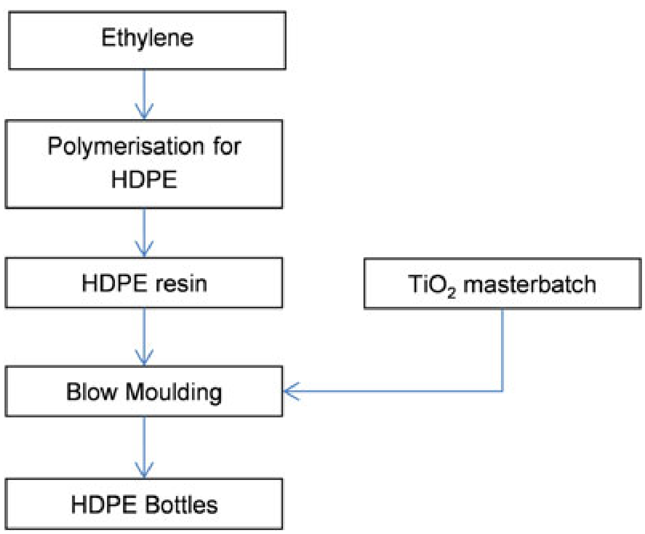

Figure 2. Scheme of the production process of HDPE bottles.

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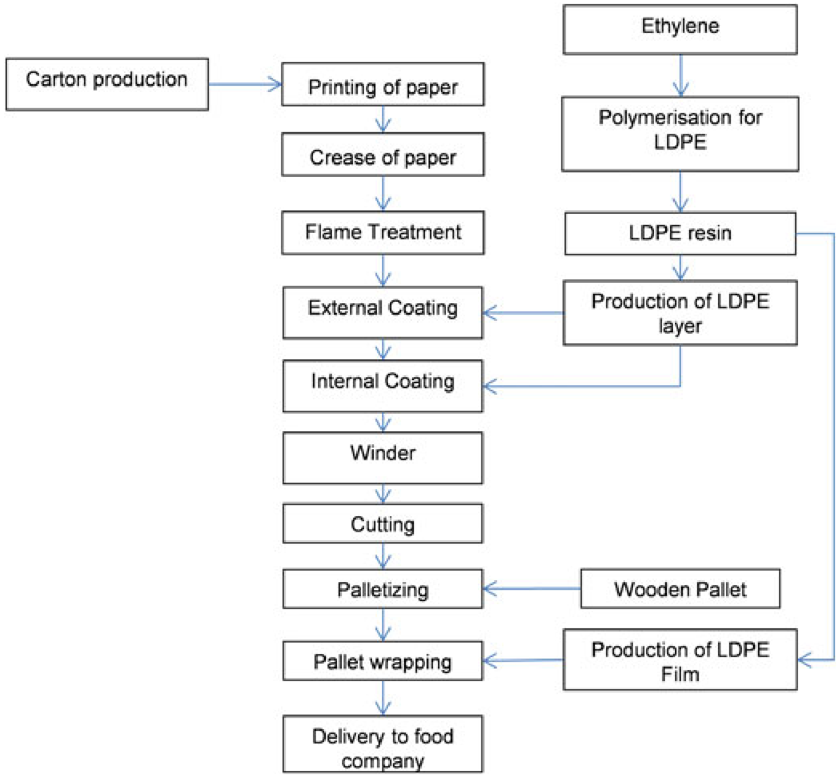

Figure 3. Scheme of the production process of multilayer cartons.

thus similar in almost all phases to that depicted in Figure 3; compared with that, we must add forming and longitudinal sealing of the final packaging, which are carried out before the inlet into the milk filler.

Caps and other packaging materials. Figure 4 shows the processes considered for complementary packaging materials, as well as for secondary and tertiary packaging of ESL milk. The packaging caps are made of HDPE for PET bottles and PP for HDPE bottles and cartons. Both kinds of caps are obtained by injection moulding. Moreover, both PET and HDPE bottles have a PVC label, usually

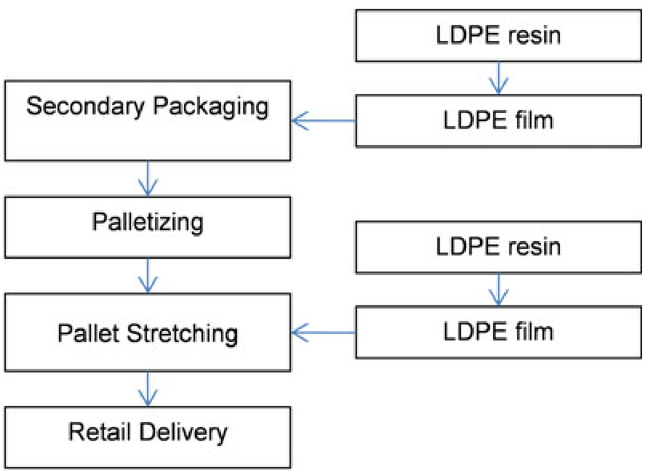

Figure 4. Secondary and tertiary packaging for packaged ESL milk.

printed by rotogravure technique; for PET, this label covers all the area of the bottle ('shrink sleeve' label), to shield the content from the light.[45]

Once filled, all the containers are packed with secondary and tertiary packaging to be shipped to the retailers. Regardless of the milk packaging type, secondary and tertiary packaging consists of boxes of corrugated cartons, LDPE films and pallets.

LIFE CYCLE ASSESSMENT

The LCA methodology consists of four main steps: (a) goal and scope definition; (b) inventory analysis; (c) impact assessment; and (d) interpretation.[47]

Goal and scope definition

The primary goal of this study is to compare the environmental impact of adopting three different packaging systems (i.e. using PET bottles with shrink sleeve label, HDPE bottles and multilayer carton containers), to package 1 l of ESL milk. A second objective is to analyse how some technological innovations could reduce the environmental burdens of these packaging systems. This point will be addressed by means of an appropriate sensitivity analysis (cf. Sensitivity Analysis section).

Functional unit. The functional unit (FU) is intended as a reference unit for which the inventory data are normalized.[8] The FU adopted in this analysis is the packaging required to contain 1 l of ESL milk and guarantee a shelf life of 30 days.

System boundaries. The processes considered for each packaging system are the extraction of the packaging raw material, the resin production, the container formation (taking into account the different processing phases), the filling of ESL milk and, finally, the end-of-life of packaging materials. Transport activities required at the different levels of the life cycle are also taken into account in the analysis.

With respect to the PET and HDPE bottles, data related to the process prior to the formation of the bottles granulate were taken from the Plastic Europe Database (http://www.plasticseurope.org/plastics-sustainability-14017/eco-profiles.aspx1Accessed May 2016.). Conversely, data about the injection moulding (for PET), extrusion (for HDPE) and blow moulding (for both PET and HDPE) processes were directly retrieved from manufacturers. For multilayer cartons, data have been taken from previously published studies.[48,49]

The analysis carried out in this study covers also the remaining packaging components, namely, caps, labels and secondary packaging, such as film and boxes. Moreover, all the processes related to the primary, secondary and tertiary packaging, as well as the transport of the packaged products from the food company to a retail store, have been taken into account. In this context, the fill rates have been assumed to not influence the results, having evaluated the impact of the different processes per single packaged product. Finally, the materials end-of-life is also assessed, considering the Italian scenario as the reference, in terms of the percentage of raw materials recycled, incinerated and disposed to landfill. A scheme of the system boundaries and of the processes considered in the analysis is reported in Figure 5. Conversely, the environmental impact of the milk production has not been evaluated in this work, because this phase is always the same regardless of the types of packaging; a similar consideration holds true for the storage of the packaged product at the different levels of the supply chain.

Inventory analysis and data quality

The life cycle inventory analysis quantifies the resources usage, energy usage and environmental releases associated with the system under examination, by means of a mass and energy balance of each FU.[8] Four different companies were contacted to obtain the data related to the weight of all packaging, with the purpose of retrieving representative values for the Italian packaging market. A cut-off of 1% was set, meaning that inventory data that are expected to contribute to the overall life cycle by less than this percentage are neglected in the analysis.[50]

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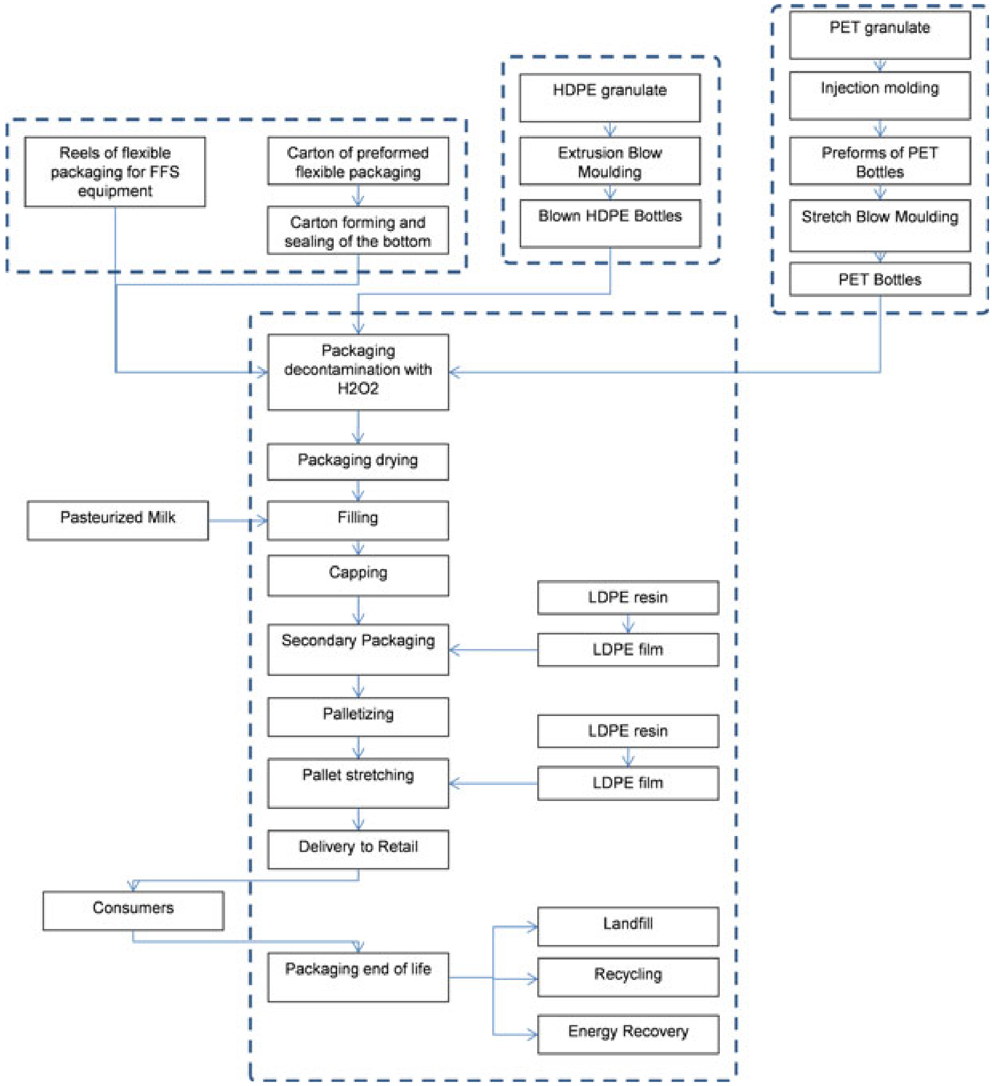

Figure 5. System boundaries for PET, HDPE and multilayer paperboard packaging (preformed or obtained by FFS equipment) for ESL milk.

Packaging materials. The average weights of the packaging materials were obtained by directly weighting the empty containers supplied by the different contacted companies. As far as the secondary and tertiary packaging is concerned, 12 PET and HDPE bottles are contained in each shrink-wrapped pack, reaching a total amount of 600 bottles per pallet (considering five layers with 10 packs per layer). Conversely, multilayer cartons are contained in a corrugated paperboard (box) in groups of 10, allowing each pallet to transport 750 packs (five layers with 15 boxes per layer). Table 1 reports the weights of the packaging materials considered in the analysis, referred to one FU. A cautionary average duration of six cycles has been assumed for pallets.[51]

Packaging equipment. Data related to the energy and resources consumption of primary packaging equipment (including packaging decontamination, filling and capping) are reported in Table 2. This table lists the inventory data for the most relevant substances used in each packaging process and of the energy required.

With respect to the material and energy consumption, the filling process is similar for beverage cartons and bottles. The data for this study were provided distinguishing between the consumption of electric energy and steam, as well as of water and compressed air. A cross-check has been conducted

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Table 1. Weight of packaging materials for 1 FU.

PET with shrink sleeve label			HDPE			Multilayer carton		
Part	Material	Mass (g)	Part	Material	Mass (g)	Part	Material	Mass (g)
Bottle	PET	25.2	Bottle	HDPE	31.6	Laminated Carton	LDPE	6.8
				TiO_2	0.63		Paperboard	25.5
Cap	HDPE	3.5	Cap	PP	3.5		Water-based inks	0.08
Shrink sleeve label	PVC	4.75	Label	PVC	0.8	Cap	HDPE	4.3
Shrink wrap film	PE	0.24	Shrink wrap film	PE	0.24	Box	Paper	7.34
Pallet	Wood	6.94	Pallet	Wood	6.94	Pallet	Wood	5.56
Stretch film	LLDPE[1]	0.42	Stretch film	LLDPE	0.42	Stretch film	LLDPE	0.33
Total		41.05	Total		44.13	Total		49.91

[1]Linear low-density polyethylene.

Table 2. Consumptions of primary packaging systems for 1 FU.

	TT/3 filling machine	Ultra clean filler for HDPE and PET
Electricity	0.0039429 kWh	0.02847 kWh
Compressed air	0.0040286 Nm^3	0.01076 Nm^3
Water	0.53071431	0.07061
Vapour (steam)	0.001343 kg	0.02701 kg
Hydrogen peroxide (35%)	0.000251	0.00027211
Lubricants	1.78571E−061	—
Detergents	7.14286E−061	1.389E−051

exploiting pieces of information collected from three companies manufacturing fillers and four users of these filling machines. Tetra Top® packaging system has been considered for multilayer cartons, following the data provided by Università degli Studi di Padova.[49] Primary data have been obtained for the ultra-clean system able to package in the same way HDPE and PET bottles.

According to the cut-off set, consumption data related to the preliminary treatments on water (e.g. extraction, sterilization or desalination) have been neglected in this study, as well as the manufacturing of the packaging equipment according to IFEU.[40] We assumed the consumption of secondary and tertiary packaging machines to account for 0.0079 kWh per FU, in line with that calculated for packaging machines of jars of tomato puree in a recent study.[15]

End-of-life of packaging. Data related to the packaging end-of-life scenario, such as the percentage of packaging recycled, incinerated or disposed in landfill, were obtained from specific Italian consortia and from Tetrapak documents, as shown in Table 3.

For each of the packaging materials and processes (recycle, energy recovery and landfill) mentioned previously, data about the impact generated were obtained from European EU-27 database (ELCD[54] for landfill and energy recovery and US LCI Database[55] for plastic recycling process). The dataset

Table 3. Italian end-of-life scenario for packaging materials.

Packaging materials	Recycle (%)	Energy recovery (%)	Landfill (%)	Source
Paper	79.53	8.63	11.85	32
Plastic	37.9	44.5	17.5	33
Carton beverage, paperboard	19	22	59	52
Carton beverage, other materials	0	25	75	52

DOI: 10.1002/pts

in the ELCD database includes the emissions and resource consumption for the thermal treatment of waste. The behaviour of bottom ash and air pollution control residues on a landfill were considered. All credits for the electricity and steam export as well as recovered metals were included.

Regarding the laminated multilayer materials, paperboard fibre recycling solution has been considered: the paper in the packages is used to produce pulp as material for new paper products.[53] The recycling processes of PET and HDPE reflect those described by the US LCI Database[55] and by Rigamonti *et al.*,[56] which detailed also some percentage of efficiency for each process (75.5% for PET, 90% for PE and 61.4% for Plasmix). The framework and the efficiency of the paper/cardboard recycling process for the secondary packaging were retrieved from Wang *et al.*[57] and account for 70%. The efficiency of paperboard recycling from carton multilayer process was derived from Xie *et al.*[58] and set at 60%.

Transports. In line with the life cycles previously described, the transport activities consist typically in the shipping of

1 the *raw materials*, from the material supplier to the packaging manufacturer;
2 the *packaging materials*, from the packaging manufacturer to the milk producer; and
3 the *packaged products*, from the milk producers to the retailers.

In the case of the road transport, goods (either raw material or finished products) with a low density are expected not to fully saturate the load capacity of the vehicle. Under that circumstance, the truck will transport a lower weight with respect to its maximum capacity, resulting in a load factor lower than 100%. Infras[59] estimates the fuel consumption and CO_2 emission of an empty truck (gross weight: 24–40 tons) to account for approx. 61% of those of a full load truck. A similar ratio is assumed to hold true for the remaining categories of environmental impacts. Whenever the load factor of the truck is intermediate between 0% and 100%, the overall impact of the truck can be estimated starting from the following equation:

$$LF * IFLT + (1 - LF) * 0.61 * IFLT$$

where LF denotes the load factor of the truck, expressed in percentage, and IFLT indicates the impacts of a full load truck.

According to the foregoing equation, the environmental impact of a truck whose load factor is 50% will account for 80.5% the impact of a full load truck. However, although the impact of this truck is lower, each kilogram of product carried by the truck will have higher environmental impact. Indeed, the impacts of a kilogram of product will be computed as the ratio between the impacts of the truck and the overall weight of the product transported. Therefore, in the case of a half-loaded truck, the impact of each kilogram of product carried will be 1.61 (i.e. 0.805/0.5) times the impact of a corresponding kilogram of product carried by a full load truck.

When carried by truck, raw materials and goods are generally palletized. Taking into account the gross weight limitations for trucks in Europe and the corresponding load capacity, it can be estimated that the lowest average weight of a pallet that allows saturating the weight of a truck accounts for 848 kg approximately. This value results as the ratio between the truck net weights (28 tons) and the maximum number of pallets that can be loaded on the same truck (i.e. 33 pallets, avoiding pallet overlapping). Hence, pallets whose weight is lower than 848 kg would not completely saturate the truck weight; in line with the considerations made previously, this will cause a higher environmental impact for each kilogram of product transported. In the case pallets overlap is allowed, the lowest weight of the pallet that allows complete saturation of the truck load capacity is approximately halved (i.e. 424 kg).

As regards the multilayer carton, the transport of the packaging raw materials was evaluated assuming that paper materials (i.e. paper and inks) and HDPE caps to come from Sweden (1560 km, covered by truck), LDPE granulate from Belgium (1000 km, by truck), while packaging materials (pallets, LDPE wrap and stretch film, and paper trays) from Italy (100 km, by truck). The transport distance from the laminated packaging manufacturer to the milk producer was calculated assuming an average trip of 500 km, using 28 ton lorries. Because of the relevant weight of a pallet of multilayer carton

DOI: 10.1002/pts

(about 8000 packs per reel, with six reels per pallet), full truck load shipment is ensured for the transport of packaging material. Similar considerations hold true for the transport of raw materials.

With respect to the HDPE bottles, the distance from the resin supplier to the manufacturing, filling and distribution centre should be first determined.[23] Italian milk producers can buy the HDPE granulate from Belgium: the transport (1000 km) will be covered by truck as already reported. As mentioned, modern dairy companies blow mould the HDPE bottles *in situ* starting from the polymer granules; therefore, the second transport activity listed previously can be skipped for HDPE bottles. As per the previous case, the density of the HDPE granulate is quite high (approximately 960 kg/m^3, according to Robertson[2]); therefore, full truck load shipment can be assumed for the transport of the packaging material from the resin supplier to the manufacturer. With respect to the remaining packaging materials, moulded PP caps are assumed to come from Belgium, together with the HDPE granulate, while labels from Germany (830 km, by truck). Finally, as for multilayer carton, pallets and LDPE wrap and stretch films for the finished product are assumed to come from Italy (100 km). Full truck load shipment is assumed for the transport of those complementary packaging materials.

With respect to the PET bottles, two different options are available: (a) companies can buy preforms from local producers (Plasco or Retal in Italy), or (b) they can buy PET granulate from chemical industries located in the middle East (http://www.octal.com/index.aspx) or also in Europe (Mossi & Ghisolfi – Italy, http://www.gruppomg.com/en; Indorama, site of Ottana – Italy http://www.indoramaventures.com/EN/ourBusinesses/ourBusiness_PET_Facilities_de09.php). At the state of the art, most companies purchase preforms, so the transport of granules from chemical companies with internal production of preforms in the milk company will be only discussed in Sensitivity Analysis section.

As far as the case of preforms purchase is concerned, preforms are typically packaged in specific boxes, called 'octabins' because of their shape of a prism with octagonal base (see, e.g. http://www2.dssmithpackagingeurope.com/en/industrial/products/Octabin). Octabins are available in different sizes; however, the biggest ones are 1120 mm (length) × 1120 mm (width) × 1150 (height) wide, with a tare of approx. 25 kg. The capacity of this kind of octabin is approximately 1020 l. According to the pieces of information retrieved from an Italian milk producer and from a preforms supplier (http://www.retal.biz/en/index.php), each octabin contains about 9000 preforms. Starting from the net weight of the preforms and adding the tare of the octabin and of the pallet, the gross weight of the stock keeping unit is estimated to account for approximately 265 kg. Anglo-Saxon pallets (1000 × 1200 mm) are typically used for transport of octabins; therefore, the number of pallets that can be loaded on a 28 ton truck is 52 (13 × 2 × 2, allowing two overlapping levels of stock keeping units). This results in a gross weight of the truck of 13.78 ton and in a load saturation of only 49.21% in weight. A transport distance of 510 km, covered by 16–32 ton lorries EURO4RER, has been assumed. With respect to the remaining packaging materials, moulded HDPE caps are expected, once again, to come from Belgium, while labels from Germany (830 km). As per the remaining packaging systems, pallets and LDPE wrap and stretch films for the finished product come from Italy (100 km). In line with the assumption made for complementary packaging materials in the remaining scenarios, full truck load shipments are hypothesized also for these packaging materials.

As far as the transport of finished products is concerned, regardless of the packaging type, we assume a distance of 300 km from the production site of packaged milk to the retailers, covered by means of 28 ton lorries with full truck load shipments.[60]

Data quality. A check on the data quality was carried out with the purpose of ensuring that the input data describe the current packaging production of Italy as accurately as possible. To this extent,

- data for the resin production, including all processes from cradle to gate, were retrieved from the Plastics Europe Database (http://www.plasticseurope.org/plasticssustainability/eco-profiles.aspx/);
- the LCI dataset published by Alliance for Beverage Cartons and the Environment[48] was used for the carton converting process;
- data to evaluate the materials end-of-life were retrieved by the ELCD database 2.0[54] (for landfill and energy recovery), by Wang *et al*.[57] (for paper recycling process) and by the US LCI Database[50] (for plastic recycling process);
- the Ecoinvent database v2.2[61] was used for the remaining processes, namely, plastic injection and extrusion, aluminium production and transports; and

DOI: 10.1002/pts

- finally, according to the description in Packaging Equipment section, primary data have been obtained for the ultra-clean system able to package in the same way ESL milk in HDPE and PET bottles, while data for packaging process of ESL milk in multilayer materials have been taken from the report of the Università degli Studi di Padova.[49]

Because this study targets the Italian scenario, the data used were referred to this specific context (if possible), or, alternatively, to the European one. In line with the cut-off set, this study takes into account input data that cumulatively contribute more than 99% to the mass and energy consumption of the system.

Impact assessment method

SimaPro version 7.3.3 software was used for the analysis of the environmental burdens. CML2001[62] and cumulative energy demand (CED)[63] have been adopted as the impact assessment methods. The CML2001 is a mid-point method, which was adopted to assess Global Warming Potential for a time horizon of 100 years (GWP100), Photochemical Ozone Creation Potential (POCP), stratospheric Ozone Depletion Potential (ODP), Human Toxicity Potential (HTP), Acidification Potential (AP) and Eutrophication Potential (EP). Global energy requirement was instead evaluated according to the CED method.

RESULTS AND DISCUSSION

The total impacts associated with the three different packaging systems are discussed in the following subsections, together with the contribution of each phase of the whole life cycle. A comparison between the impacts generated by three solutions is proposed in Comparison of the Packaging Systems section, to highlight the main differences among the packaging types.

PET packaging system

The overall impact generated by the use of PET with shrink sleeve label for ESL milk is reported in the first column of Table 4. The same table and Figure 6 show also the specific value of the different phases and their relative impact (on a 100% scale) for each impact category, respectively. As can be seen from Table 4 and Figure 6, the bottle production always provides the highest contribution to the considered impact categories. It contributes for 69% to CED and between 52% and 79% to the remaining categories. The impact of cap and label is significant as well, ranging, overall, between 11% and 38% in all the considered impact categories. In the considered case of PET preforms transport from Italian internal producer, the overall transportation of packaging materials (PET preforms, caps, etc.) by means of truck load shipments is a risible source of impact, which contribute, overall, between 1% and 4% for all the considered impact categories. Similarly, the overall transport of raw materials (where the PET granulate is shipped from Italian producers to the previously cited Italian preforms manufacturer) contributes only for 1% to 3% to all the considered impact categories. Conversely, the contribution of the filling process is lower, ranging from 5% to 10% for all the considered impact categories. Interestingly, the evaluation of the end-of-life in the Italian context for the packaging materials used in this system contributes to decrease the impact for almost all the considered categories (with the only exception of the EP); the decrease is maximum (33%) for HTP.

HDPE packaging system

The overall impact of the ESL packaging system using HDPE bottles is shown in Table 5. As can be seen from Figure 7, and similarly to the case of PET, even in this case the impacts of bottle materials and production vary from 34% in ODP to a maximum of 80% in POCP. The cap contributes from 3% to 26% to all the considered impact categories, while the label contribution ranges from 1% to 10%. The contribution of the ultra-clean filling system (similar to that observed for the PET system) to the different impact categories varies between 7% and 14%. Low impact is ascribed to the packaging transport activities, which, in the case of HDPE packaging system, contribute from 1% to 3% to all the

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Table 4. Environmental impact of each phase for the PET packaging system.

Impact category	Unit	Total	PET bottle	HDPE cap	Shrink sleeve label	Shrink wrap film	Pallet	Stretch film	Packaging equipment	Raw materials transport	Packaging materials transport	Finished products transport	End-of-life phase
CED	MJ	3.16E+00	2.77E+00	3.73E−01	3.39E−01	2.17E−02	4.80E−05	3.56E−02	3.18E−01	5.35E−02	6.55E−02	6.28E−02	−8.77E−01
GWP100	kg CO_2 eq.	1.65E−01	1.04E−01	1.14E−02	1.51E−02	6.22E−04	4.72E−07	9.78E−04	1.60E−02	3.20E−03	3.92E−03	3.75E−03	6.40E−03
POCP	kg C_2H_4 eq.	3.21E−05	2.19E−05	3.04E−06	3.50E−06	1.22E−07	2.93E−10	1.73E−07	2.59E−06	3.91E−07	4.78E−07	4.58E−07	−5.57E−07
ODP	kg CFC-11 eq.	2.27E−08	1.89E−08	2.18E−09	2.04E−11	6.51E−12	3.19E−14	1.13E−11	1.20E−09	5.05E−10	6.19E−10	5.93E−10	−1.36E−09
HTP	kg 1.4-DB eq.	5.52E−02	4.32E−02	1.41E−03	3.07E−02	4.76E−05	7.68E−07	7.41E−05	5.22E−03	5.88E−04	7.20E−04	6.89E−04	−2.75E−02
AP	kg SO_2 eq.	4.95E−04	3.88E−04	4.11E−05	7.01E−05	2.43E−06	2.16E−09	3.27E−06	6.02E−05	1.23E−05	1.51E−05	1.44E−05	−1.12E−04
EP	kg PO_4 eq.	8.23E−05	4.44E−05	3.64E−06	5.90E−06	1.80E−07	3.73E−10	2.68E−07	6.61E−06	2.48E−06	3.03E−06	2.91E−06	1.29E−05

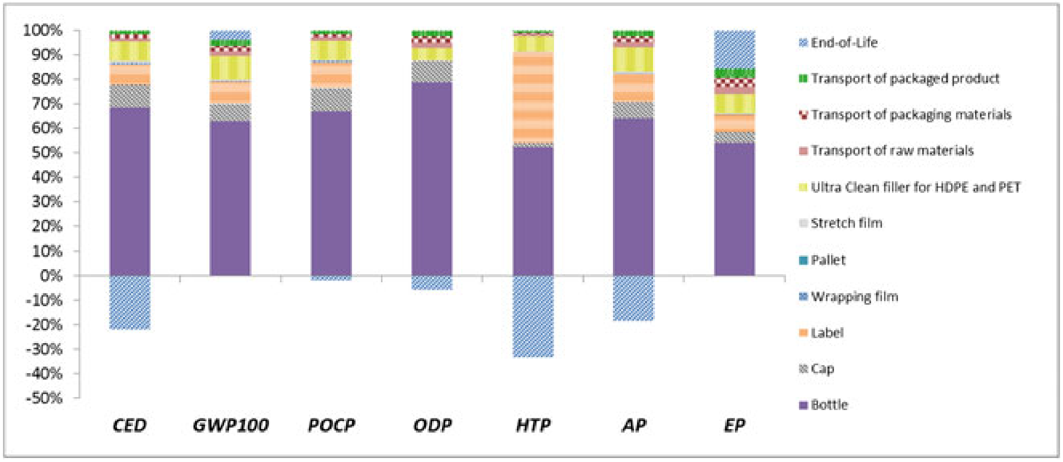

Figure 6. Relative impact of each phase involving PET packaging system for each impact category.

considered impact categories. Conversely, the impact of raw materials transport activities is more relevant, contributing from 3% to 14% to all the considered impact categories. This is due to the fact that, in the case under examination, the main packaging component (HDPE polymer of the bottle) comes in granules from Belgium. End-of-life of packaging materials adopted in this configuration contributes to reduce the impact in almost all categories (except in GWP) with a peak of 39% reduction in ODP and 27% in AP and 31% in CED.

Multilayer carton packaging system

The overall impact of the ESL packaging system using multilayer carton is shown in Table 6, while the relative impact of each phase is proposed in Figure 8. As can be seen from Figure 8, primary packaging materials (i.e. printed paperboard and PE layers), together with the beverage carton converting, contribute for more than 23% to all impact categories (up to a maximum of 63% in CED). For this packaging system, a significant impact is due to the cap and the considered portion of the box, which together contribute from 16% to 44% to all the considered impact categories. This is due to the fact that the impact of the remaining voices of the packaging system is quite low and then the percentage of impact of these voices turns out to be quite high. For the same reason, the impact of transport of raw and packaging materials, in percentage, is higher for multilayer cartons, ranging overall from 3% (in POCP) to 24% (in ODP); the main contribution, in particular, comes from the transport of raw materials. Moreover, the contribution of the filling process is quite low, ranging from 2% to 7% for all the considered impact categories. A particular outcome is observed for the contribution of the end-of-life phase of this packaging; in this case, end-of-life causes a reduction in the overall impact only for the CED, ODP and AP categories, while it increases the impact for the remaining categories (up to 29% for GWP). This result is due to the low percentage of recycling set in our analysis; the data used reflect, in fact, the percentage of recycling in 2010 for the Italian context.

Comparison of the packaging systems

A comparison of the environmental performance described earlier (Figure 9) highlights that the multilayer carton is the less environmentally impactful solution among those analysed, for almost all the considered impact categories. The only exceptions are the ODP and EP, for which the impact of the HDPE system is slightly lower (respectively of 9% and 14%). In the remaining categories, the impacts of the carton multilayer packaging compared with the HDPE system are significantly lower, with differences that range between 16% (in AP) and 42% (in HTP). The difference between the multilayer carton system and the PET system is even wider, ranging from 4% for EP to 68% for ODP. Focusing on the ODP category, in particular, the use of solvents in the injection moulding of PET preforms contributes to more than 60% of the impact related to the PET system. Comparing PET and HDPE, it can

DOI: 10.1002/pts

Table 5. Environmental impact of each phase for the HDPE packaging system.

Impact category	Unit	Total	Bottle (HDPE + TiO_2)	PP cap	PVC label	Shrink wrap film	Pallet	Stretch film	Packaging equipment	Raw materials transport	Packaging materials transport	Finished products transport	End-of-life phase
CED	MJ	3.14E+00	3.53E+00	3.66E−01	5.82E−02	2.20E−02	4.80E−05	3.56E−02	3.18E−01	1.29E−01	2.98E−02	6.53E−02	1.41E+00
GWP100	kg CO_2 eq.	1.65E−01	1.12E−01	1.16E−02	2.58E−03	5.72E−04	4.72E−07	9.78E−04	1.60E−02	7.69E−03	1.78E−03	3.91E−03	7.37E−03
POCP	kg C_2H_4 eq.	2.96E−05	2.99E−05	2.35E−06	5.97E−07	3.39E−07	2.93E−10	1.73E−07	2.59E−06	9.39E−07	2.18E−07	4.77E−07	−7.96E−06
ODP	kg CFC-11 eq.	5.23E−09	2.88E−09	2.18E−09	6.81E−12	7.70E−11	3.19E−14	1.13E−11	1.20E−09	1.22E−09	2.82E−10	6.17E−10	−3.25E−09
HTP	kg 1.4-DB eq.	5.06E−02	3.96E−02	1.40E−03	5.19E−03	3.02E−04	7.68E−07	7.41E−05	5.22E−03	1.41E−03	3.28E−04	7.17E−04	−3.68E−03
AP	kg SO_2 eq.	4.56E−04	4.56E−04	3.99E−05	1.19E−05	1.50E−06	2.16E−09	3.27E−06	6.02E−05	2.96E−05	6.87E−06	1.50E−05	−1.69E−04
EP	kg PO_4 eq.	6.58E−05	4.41E−05	4.16E−06	1.04E−06	3.58E−07	3.73E−10	2.68E−07	6.61E−06	5.96E−06	1.38E−06	3.02E−06	−1.08E−06

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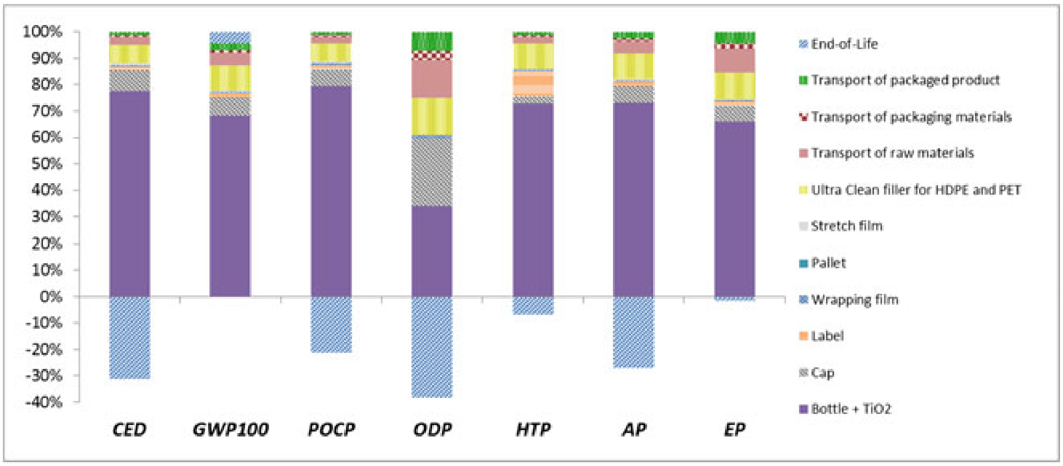

Figure 7. Relative impact of each phase involving HDPE packaging system for each impact category.

also be seen that PET has a similar impact in CED (+1%) and GWP100 (0%), while HDPE shows a better performance against POCP (−8%), ODP (−77%), HTP (−8%), AP (−8%) and EP (−20%).

Looking at PET and HDPE, in both cases, we found that the bottle is the main cause of environmental burden. In particular, its impact is generated by the raw materials (granulate) and by the high energy consumption and emissions related to its manufacturing. Comparing the bottle resins, the PET production has a higher impact in all the considered categories; such a higher impact, nonetheless, is counterbalanced by the lower weight of the PET bottle compared with the HDPE one. By comparing the outcomes of the three packaging systems, it can be appreciated that the numerical values for caps are not significantly different (e.g. CED for caps scores 3.73E−01 for PET, 3.66E−01 for HDPE and 3.55E−01 for multilayer carton). An important difference in the impact of the three packaging systems is due to the use of 4.75 g of shrink sleeve label in PVC for PET bottle. Covering completely the bottle with this label is, however, required to shield the milk from the light, being PET transparent by nature.

The better environmental profile of multilayer cartons, instead, depends mainly on the low energy consumption and emissions related to the converting phase (less than 10% in all categories) and by the use of paperboard instead of mere polymeric materials.

Finally, the contribution of the packaging and raw materials transport activities varies depending on the considered packaging type. It accounts, on average, for 5% in the case of PET, 6% in the case of HDPE and 14% in the case of cartons. The difference in the contribution of the raw materials transport should be ascribed both to the technology of packaging manufacturing and to the distance from the supplier, which, in practical cases, is typically selected on the basis of economic considerations rather than of environmental ones.

SENSITIVITY ANALYSIS

A sensitivity analysis is carried out in this section with the purpose of investigating how potential technological improvements could modify the environmental profile of the different packaging solutions. The rationale for carrying out a sensitivity analysis is that the technologies for packaging production are constantly evolving and the attention to the environmental compatibility of packaging is expected to increase in the future. Taking into account these considerations, some technological improvements that could significantly change the environmental impact of the packaging types under examination have been identified and analysed.

The first hypothesized improvement refers to the possibility of decreasing the weight of the packaging materials, by optimizing the current production technologies. Specifically, the weight of PET and HDPE bottles could be reduced up to a maximum of 10%. Conversely, for the multilayer carton, the

DOI: 10.1002/pts

Table 6. Environmental impact of each phase for the multilayer carton packaging system.

Impact category	Unit	Total	Paperboard + Ink	PE layer	Beverage carton converting	PP cap	Paper box	Pallet	Stretch film	Packaging equipment	Raw materials transport	Packaging materials transport	Finished products transport	End-of-life phase
CED	MJ	2.44E+00	1.16E+00	6.30E−01	9.28E−02	3.55E−01	2.70E−01	3.07E−05	2.85E−02	7.44E−02	1.29E−01	2.98E−02	6.44E−02	−3.93E−01
GWP100	kg CO_2 eq.	1.04E−01	1.53E−02	1.81E−02	4.22E−03	8.88E−03	9.50E−03	3.02E−07	7.82E−04	3.51E−03	7.69E−03	1.78E−03	3.85E−03	3.00E−02
POCP	kg C_2H_4 eq.	2.24E−05	3.65E−06	3.55E−06	9.14E−07	6.87E−06	1.83E−06	1.88E−10	1.38E−07	6.47E−07	9.39E−07	2.18E−07	4.70E−07	3.21E−06
ODP	kg CFC-11 eq.	7.34E−09	1.49E−09	1.89E−10	1.85E−10	2.18E−09	1.12E−09	2.04E−14	9.00E−12	1.92E−10	1.22E−09	2.82E−10	6.08E−10	−1.33E−10
HTP	kg 1.4-DB eq.	2.78E−02	7.85E−03	1.38E−03	1.14E−03	8.32E−03	3.23E−03	4.92E−07	5.93E−05	1.81E−03	1.41E−03	3.28E−04	7.07E−04	1.52E−03
AP	kg SO_2 eq.	3.75E−04	8.61E−05	7.05E−05	2.19E−05	1.37E−04	3.24E−05	1.38E−09	2.62E−06	1.54E−05	2.96E−05	6.87E−06	1.48E−05	−4.17E−05
EP	kg PO_4 eq.	7.76E−05	2.36E−05	5.24E−06	2.49E−06	3.46E−06	9.29E−06	2.39E−10	2.14E−07	1.89E−06	5.96E−06	1.38E−06	2.98E−06	2.11E−05

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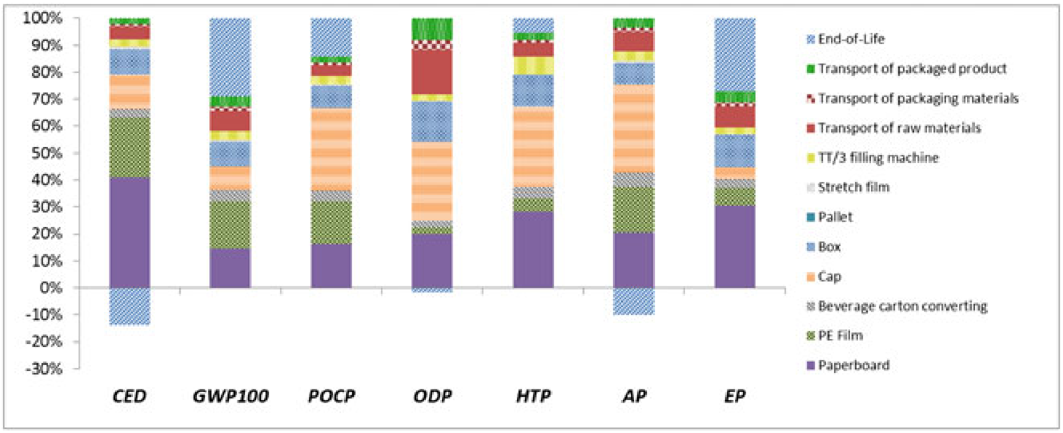

Figure 8. Relative impact of each phase involving carton multilayer packaging system for each impact category.

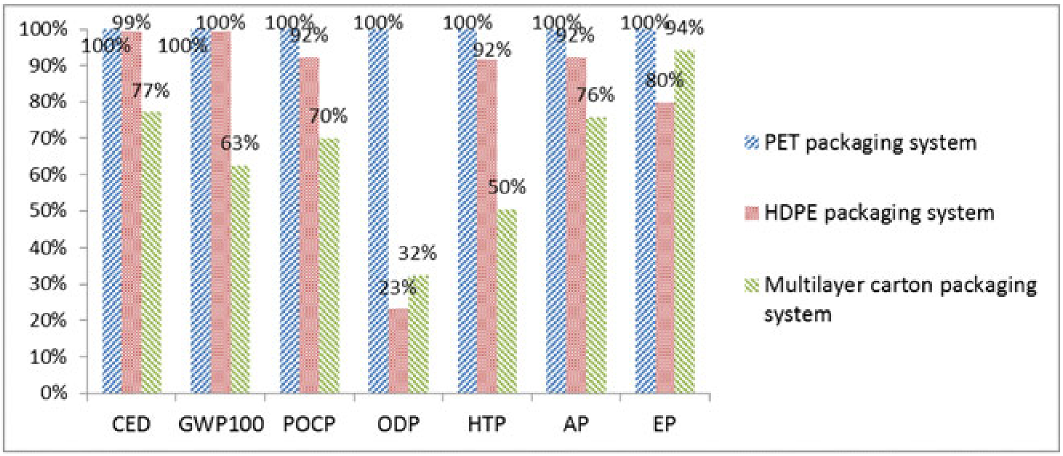

Figure 9. Comparison of the environmental impacts of the different packaging systems.

technical possibility to reduce the amount of material is lower; it has been therefore assumed a 5% decrease of the cardboard weight, being not technically feasible to lighten the PE layers further.

The second improvement refers to the possibility of reducing the weight of the PET bottle significantly, thanks to a new technology that allows decontaminating directly the preforms before their blowing.[64] To be sterilized without deformation, PET bottles need a minimum thickness, which result in a weight of 25 g. Conversely, direct decontamination of the preforms allows treating lighter preforms, as they are less sensitive to temperature deformation than bottles. This technique would replace the traditional decontamination, which consists in the sterilization of the bottles already formed. This innovation could be applied also in the ultra-clean technology, and it would allow reducing the weight of 1 l PET bottles from 25 g to approx. 16 g.

The last improvement considered concerns the possibility of purchasing PET granulate directly from chemical companies and to inject the preforms *in situ*, then moulding them. This innovation, which could be suitable for a big milk packaging site, would also decrease the transport distance for PET raw materials (from the manufacturers to the packaging producers) and avoid the transport of PET preforms (from the packaging producer to the food companies). In this regard, we assume that PET granulate can be manufactured in Italy (http://www.gruppomg.com/en) (150 km, covered by trucks). The rationale behind this assumption is to assess whether the internal production of PET preforms and consequent avoidance of their transport could make the PET packaging system comparable with the remaining ones from an environmental perspective.

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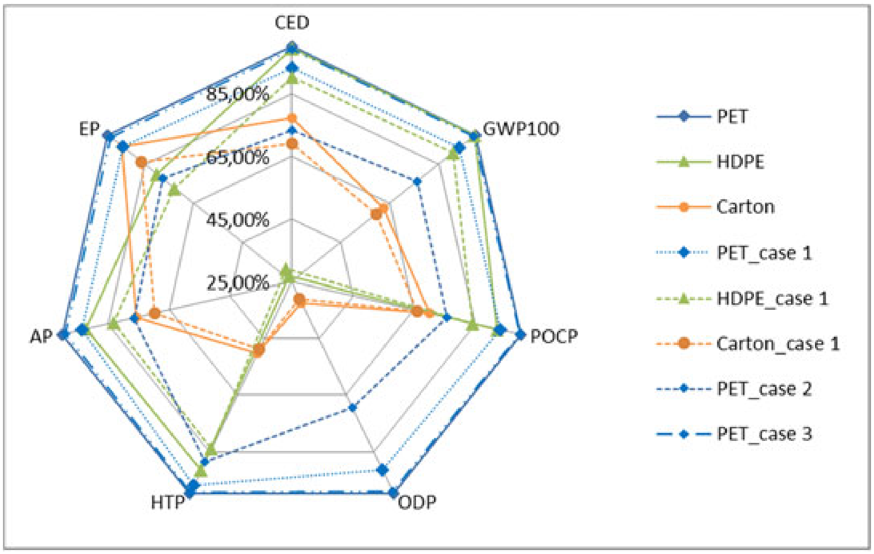

Figure 10. Percentage variations among the impacts of the technological alternatives.

Figure 10 shows the environmental profile of the different packaging solutions and their variation as a consequence of the modified scenarios described before. Case 1 (i.e. decreasing the weight of packaging materials) would lead to a decrease of the overall impact by 3.1–8.3% for PET, by 8.6–10.82% for HDPE and by 3.2–10.5% for multilayer carton in all the categories assessed. Lightening the PET bottle to 16 g (case 2) generates from 11.47% to 30.4% of reduction for the considered impact categories compared with the original PET packaging system configuration. Thanks to this innovation, PET would reach a similar impact profile than the multilayer carton for CED, with similar performance also against the remaining impacts (apart from ODP and HTP) and improved performance against EP. Finally, it is evident that the introduction of PET preforms injection inside the milk packaging company (case 3), although desirable, has no potential to radically change the impact of the whole system life cycle; such a modification, in fact, generates a variation between 0.5% and 1.4% for all the considered categories.

CONCLUSIONS

In this paper, the environmental profile of three different packaging solutions for ESL milk has been investigated *via* the LCA methodology. This study considers multiple categories of environmental impact and resource consumption. The results obtained show that the multilayer carton system is the less environmentally impactful solution for almost all the considered impact categories and that its environmental impacts are, on average, more than 12% lower than HDPE system and more than 34% lower than system using PET with shrink sleeve label. Comparing PET system and HDPE one, the HDPE system shows a better profile for all the considered impact categories, with similar results in CED and GWP (respectively −0.6% and −0.43%) but with strong differences in the remaining impact categories (up to −76.9% in ODP). A sensitivity analysis was carried out to assess how technological innovations could reduce the environmental impact of the existent packaging options.

Analysing the impacts generated by the three systems, container materials emerge as the most important source of environmental impacts, followed, in order of contribution, by the caps and, where adopted, labels and by the burdens generated by the packaging equipment. In line with this latter point, in recent years, many research activities have been made to substitute fossil packaging materials with bio-based ones, although their diffusion in the food packaging field has been limited because of their not excellent properties. Indeed, nowadays, bio-based packaging materials are primarily used to pack

DOI: 10.1002/pts

short shelf life products, like fresh fruits and vegetables, and long shelf life products, like pasta and chips, which do not need very high oxygen and/or water barrier properties.[66] Their lower environmental impact should also be verified,[65,67] taking into account the potential decrease of the shelf life of food products, which could increase the amount of food waste.[68] Based on the results obtained by the sensitivity analysis and by evaluating the impact of recycling activities, the better options to reduce the impact of ESL milk packaging solution are the reduction of container's weight and the increase in the percentage and efficiency of recycling activities.

Some limitations of the study should be mentioned. A first one is that the analysis carried out is specific to the Italian context; therefore, our results cannot be generalized to other European countries. A further limitation is due to the data used to analyse the end-of-life scenarios of the multilayer cartons, which refers to the Italian scenario in 2010. The percentage of recycling for this packaging has actually increased in subsequent years (up to 22.2% in 2013); however, more recent data could not be used in the analysis because of the lack of the corresponding percentage of 'energy recovery' and 'landfill'. This point could be taken into account in future studies, together with new updates that could be available in other databases (e.g. the Plastic Europe Database) and with the possibility to consider the carbon sequestration of some end-of-life processes, such as recycling and energy recovery.[69] Similarly, future research could be directed to the analysis of other possible innovations, beside those considered in this study, in line with the technological evolution of packaging systems. Additional future research activities could be directed towards the analysis of the impact of new materials and the associated food packaging technologies.

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