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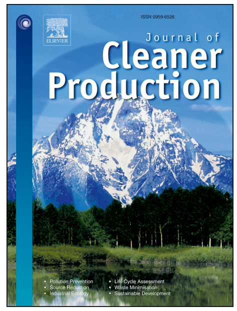

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Abstract

Antimicrobial coatings are being increasingly used as a means to extend the shelf life of food products. This extension helps consumers cut down on the food waste generated at household level, while at the same time reducing the impact, which these products' life cycle has on the environment. The aim of this Life Cycle Assessment study is thus to assess the consequences on the environment arising from the application of an antimicrobial coating onto the packaging of a fresh milk product, while also taking into account the reduction in milk waste.

The antimicrobial coating considered is a synthetic derivative of lauric acid. The application of the coating involves additional environmental impacts caused by all the inputs and outputs which occur during its life cycle. At the same time, however, the use of this coating allows to extend the fresh milk's shelf life with a consequent reduction in food waste.

The data related to the production and application of the coating were provided by the packaging laboratory of the Institute of Agrochemistry and Food Technology (Valencia) and by manufacturing companies. The data related to food waste, milk processing, refrigeration transports, storage, and end of life of both product and packaging were obtained from previous studies, institutional reports and Ecoinvent database v2.2. The Midpoint Impact 2002 method was used to assess impacts.

The results show how the reduction in milk waste achievable by using the coating generates higher environmental benefits than the impacts caused by the coating's life cycle due to milk saving. Furthermore this study demonstrates the importance of including food waste in Life Cycle Assessment studies of packaging systems. The connection between packaging design and food waste is a decisive aspect in the evaluation of actual environmental sustainability and should thus be considered in all assessments of packaging solutions.

Key words: *Life Cycle Assessment; Sustainable food production; Antimicrobial coating; Reduction in Food waste, Milk*

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1 Introduction

About one-third of the food produced for human consumption is either lost or wasted, and this figure amounts to about 1.3 billion tons per year (FAO, 2011). On the one hand, this represents a serious issue from a social and ethical point of view, since the number of chronically undernourished people in the world remains unacceptably high (FAO, 2014). On the other, it also involves consequences on the environment since the manufacture of products which are subsequently disposed of both requires resources and causes emissions into air, water and soil in the phases of production and supply chain. This is confirmed by the global Carbon Footprint generated by food waste, which has been estimated as equivalent to 3.3 Gtonnes of CO_2 (FAO, 2013).

Reducing the amount of food waste is important for all food categories, and in particular for food products having high environmental impacts such as fish, meat and dairy products (Verghese et al., 2013). Most of the food waste can be avoided by acting, first of all, on the products' shelf life, since most of it is caused by food not being used before its expiry date, and this occurs particularly in the case of perishable products (WRAP, 2008). Fresh milk is one of the most highly consumed perishable products, and its shelf life is generally no longer than 7-9 days (Rysstad and Kolstad, 2006). Moreover, once the package has been opened, the product is to be consumed within 2 days. For these reasons, milk waste is generally high in the phases of both supply chain and final consumption (FAO, 2011; WRAP, 2013).

The production and packaging processes play a central role in determining a product's shelf life. In the specific case of fresh milk, the technological optimization of the manufacturing process could extend the product's shelf life (Rysstad and Kolstad, 2006; Craven et al., 2008), but it cannot increase the number of days available for consumption once the package has been opened, as this indeed involves microbial contamination of the product which cannot be contrasted by the manufacturing process or the type of packaging materials.

The most novel alternative for extending the life of the product after opening is associated with the use of active packaging, in particular antimicrobial packaging (Mastromatteo et al., 2011). This is a technology which inhibits or retards the proliferation of microorganisms in foods which is a consequence of food/packaging interactions (Appendini and Hotchkiss, 2002). The incorporation of an antimicrobial agent into a packaging film able to release it through the coating surface into the food in a controlled way provides a continuous antimicrobial effect on the food during the product's shelf life (Muriel-Galet et al., 2014). A coating based on an ethylene-vinyl alcohol (EVOH) copolymer having LAE (lauramide arginine ethyl ester) as antimicrobial compound has recently been developed (Muriel-Galet et al., 2012). The preparation and application of LAE are described in several patents and papers (Urgell Beltran and Seguer Bonaventura, 2003; Rodriguez, 2004); it is one of the most powerful food antimicrobial agents, with a broad spectrum of antimicrobial activity. This coating can be applied to packaging film by using a gravure printing technique and its addition to a packaging structure significantly extends the shelf-life of liquid products such as fresh milk, as further described below, thus reducing food waste, although the introduction of this additional step to the normal packaging production phase involves a source of additional environmental impacts. In order to assess the actual environmental sustainability of this innovative technology, these impacts need to be compared with the environmental benefits brought by the reduction in food waste.

The adoption of scientific reliable tools is essential to assess the real environmental sustainability of a product or a system. Life Cycle Assessment (LCA) is a standardised method (ISO, 2006a, b) which assesses potential environmental impacts associated with a product, process, or service throughout its life cycle, and is internationally recognised as the best tool to evaluate the environmental performance of products or systems (EC, 2003, EC, 2013a,b; EC, 2008). In recent years this method has been widely used to investigate the sustainability of the manufacture and packaging of food products (Meneses et al., 2012; Manfredi and Vignali, 2014). These studies have generally been carried out by considering one unit of purchased or delivered food product as a functional unit, i.e. as the reference unit of the analysis. In other cases, comparative analyses of packaging solutions have been performed without considering the environmental impact of food production, mainly by taking into account the impact of packaging materials (Kang et al., 2013; Papong et al., 2014) or adding the packaging processing (Toniolo et al, 2013; Cleary, 2013, Manfredi and Vignali, 2015). Both these approaches can be misleading, especially for comparative analysis between different packaging solutions in which the packaging properties could affect the amount of waste throughout the supply chain. In fact, in some cases changes to the packaging material which may lengthen the shelf life have a greater environmental impact. However, the modified material is able to reduce food waste as the food lasts longer (Williams and Wikström, 2011). The connection between packaging design and food waste should therefore be acknowledged and included in the analysis, as packaging designed as environmentally friendly but ineffective in protecting food may otherwise appear to be a better environmental alternative than packaging which helps reduce food losses (Williams et al., 2012).

Wikström et al. (2014) have recently demonstrated via six packaging scenarios how the inclusion of the function "avoiding food waste" in an LCA study is necessary to evaluate the real sustainability of a packaging system. Moreover, Silvenius et al. (2014) evaluated the environmental impacts resulting from food waste generated by consumers as a function of the packaging properties, revealing that packaging solutions which minimize food waste generation lead to the lowest environmental impacts of the entire product-packaging chain. No LCA study has so far been performed on packaging systems with an active antimicrobial coating, which however it would be important to assess if the reduction in food losses increased the environmental sustainability of the entire milk-packaging system.

The main purpose of this paper is to show the influence of the package on the amount of food waste by comparing the environmental profile of a traditional packaging system with the profile of a packaging coated with an active layer for fresh milk packaged in Tetra Top® beverage containers. This comparison is performed by applying LCA method to both types of packaging. The study also includes a sensitivity analysis in order to understand how the variation in food waste might affect the total environmental sustainability of a packaging system.

The remainder of the article is organized as follows: section 2 contains a description of the coating production and application as well as an estimate of the milk waste reduction from applying the coating; section 3 reports the characteristics of the LCA study, while the main results of the analysis and a further sensitivity analysis are explained in section 4; a Conclusions section summarizes the main results, highlights the limitations of the study and makes some suggestions for future research.

2 Description of the system analysed

The aim of the present study is to assess the environmental performance of a specific antimicrobial coating applied to fresh milk Tetra Top® packaging by using the LCA method. This coating is able to extend the product's shelf life, thereby reducing the amount of product waste. The production of fresh milk is a standardized process whose phases are well explained in literature (Fantin et al., 2012). The data about the milk processing and packaging used as a starting point for our analysis have been taken from the study by Fantin et al. (2012).

The properties of the antimicrobial coating added to the traditional system and the evaluation of the potential benefits in terms of reduced waste in the consumption phase are explained in this section.

2.1 LAE Coating

LAE (ethyl-Nα-dodecanoyl-L-arginate hydrochloride), a synthetic derivative of lauric acid, L-arginine and ethanol (Gavara et al., 2013; Higueras et al., 2013; Muriel-Galet et al., 2012 and 2014), is one of the most innovative antimicrobial agents and is noted for its antimicrobial effectiveness, which derives from its chemical structure and surfactant properties. Its antimicrobial properties are due to its action as cationic surfactant on the cytoplasmic membrane and the outer membrane of Gram-negative, and the cell membrane and cytoplasm of Gram-positive denaturation proteins. These changes produce disturbance in the membrane potential, resulting in cell growth inhibition and loss of viability (Rodriguez, 2004).

LAE can be applied onto packaging film or carton as the active component of an EVOH coating. In the previously mentioned reports (Muriel-Galet et al., 2012 and 2014) the coating matrix was based on two EVOH copolymers with 29 and 44 mol % ethylene contents (EVOH-29 and EVOH-44). LAE was incorporated at 0.25%, 1%, 5%, and 10% of EVOH weight. The results showed that the antimicrobial efficiency increased with the concentration of LAE. Films containing 5% and 10% LAE produced total growth inhibition, whilst viable counts decreased with 0.25% and 1% LAE. Films were tested *in vivo* by applying them to infant formula milk inoculated with L. monocytogenes and S. enterica and stored for 6 days at 4 °C. According to the report the film formed by 5% LAE and 95% EVOH is the most promising. This solution can be applied onto the packaging surface by rotogravure technique using tap water and 1-propanol in a 1:1 ratio as solvent (Cerisuelo et al., 2014). Previous studies of LAE coating applied onto fresh milk packages demonstrated that it can extend shelf life from 2 to 9 days after the package has been opened (Muriel-Galet et al., 2012).

2.2 Quantification of milk waste and potential reduction

The FAO Report on Global Food Losses and Food Waste (2011) highlights the losses occurring along the entire food chain of many different products and assesses their magnitude. The report states that the consumption level for milk and dairy products is approximately 40-65% of total waste in the most industrialized world regions. In particular, the overall amount of dairy product waste in Europe is 13% of the total and the fraction due to the consumption phase represents 7%. These values are an average of all the dairy products, considering both fresh and non-fresh products. The percentages of fresh products wasted, such as fresh milk, may be even higher due to the shorter shelf life. Indeed, the most important reason for milk waste is attributed to exceeding the expiration date (Wrap, 2009). It has been estimated that by extending the fresh milk's shelf life from 7 to 10 days the amount of wasted milk could decrease from 8.1% to 1.6% (Wrap, 2013), which demonstrates how a small increase in shelf life may lead to considerable reductions in food losses. Other studies (Abeliotis et al., 2014; Farr-Wharton et al., 2014) have focused on consumer behaviour at household level and shown to what extent it can affect the amount of food wastage. Abeliotis et al. (2014) showed how understanding the date labels is a key aspect in reducing food waste, while Farr-Wharton et al. (2014) identified three main behaviours which can lead to food waste: (i) supply knowledge – i.e. does a consumer know what food is available; (ii) location knowledge – i.e. does a consumer know where to locate food items; and (iii) food literacy – i.e. to what extent do past experience and acquired knowledge impact on a consumer's food consumption and wastage practices. However, only the work by Wrap (2013) (limited to the United Kingdom) tried to quantify the impact of food durability after opening on food waste production at household level on the basis of consumer behaviour. In a specific section this research investigated the effect of milk durability on milk waste once the packaging has been opened; if the durability indicated on the label increases from 2 to 5 days, the amount of milk purchased that is wasted is reduced by about 60% (Wrap, 2013).

The introduction of an antimicrobial coating which extends the life of opened fresh milk can therefore allow a reduction in wasted milk. Although the exact value of savings cannot be determined, some estimates can be made. Starting from the results contained in Wrap (2013), a conservative approach was adopted in this study, assuming that the extension of shelf life from 2 to 9 days could lead to an average 33% reduction in milk waste considering the European situation. Since this is a crucial aspect of the study which could strongly affect the LCA results, a sensitivity analysis regarding the amount of possible losses saved will subsequently be carried out.

3 Life Cycle Assessment

Life Cycle Assessment (LCA) is a standardised method to evaluate the potential environmental impacts of a product or system throughout its life cycle, and can therefore help identify the opportunities to obtain environmental advantages as well (ISO, 2006a).

The main steps of an LCA study are: definition of goal and scope, inventory analysis, impact assessment and interpretation (ISO, 2006b).

3.1 Goal and scope of the study

The goal of this study is to perform a comparative analysis of the environmental profiles of the life cycle of Tetra Top® packaging both in the standard case and with the addition of antimicrobial coating. In the present paper the former case will be defined “Milk without coating”, while the latter case will be defined “Milk with coating”. The production and management of milk waste and the packaging’s life cycle are included in the evaluation of the consumed milk chain. In particular, the amount of wasted milk in the case of “Milk without coating” is estimated to be 7% (FAO, 2011), while this amount is assumed to decrease by 33% in the case of “Milk with coating”.

3.1.1 Functional unit

The purpose of the functional unit is to provide a reference unit upon which the inventory data are normalized (ISO, 2006a). The system's function and functional unit are central elements of an LCA which enable a meaningful and valid comparison of products (European Commission's Joint Research Centre, 2010).

The functional unit adopted in this study considers the delivery of *eaten* food as suggested by Wikström et al. (2014). As regards the case study, the functional unit is 1 L of consumed milk considering the whole life cycle of the milk-package system, from raw milk production to potential milk waste and the packaging's life cycle. The milk waste's life cycle is included to understand the impact of food waste and assess whether its inclusion changes the milk's environmental profile.

3.1.2 The calculation of reference flows

The reference flows are calculated by using the percentages of milk losses and waste provided in the FAO (2011) report.

Starting from the same reference unit of 1 L, Table 1 reports the amount of milk to be produced, processed, transported to the supermarket and purchased by customers per each litre of consumed milk, taking into account the percentage of waste and losses in each step. The reference flows are calculated starting from the equations of Wikström et al. (2014).

As shown in Table 1, per each consumed litre of "Milk without coating" 0.1455 L are lost or wasted in the supply chain and consumption phases, whereas in the case of "Milk with coating" the calculated amount of milk losses or waste in the same phases is 0.1159. The latter value was obtained by considering a reduction in milk waste by 33% (from 7% to 4.7%) during the consumption phase.

Here Table 1

3.1.3 System boundaries

The system boundaries need to be determined to quantify the environmental impacts of the product analysed. The system boundaries include the production of the packaging, its end-of-life scenario, the production and supply chain of fresh milk including transportation and refrigerated storage, and the life cycle of milk waste.

The system boundaries of the two cases are reported in Fig. 1.

Here Fig. 1

The process of coating production and application occurs only if LAE coating is introduced. All the other phases are common to the two systems analysed but the necessary reference flows are different because they depend on the different amount of milk waste that occurs during the consumption phase reported in Table 1.

3.1.4 Cut-off criteria

Cut-off criteria are used to define the number of flows that can be ignored because they are not considered relevant (European Commission's Joint Research Centre, 2010). In this paper a 1% cut-off level has been applied related to mass and energy.

3.2 Life cycle inventory

The life cycle inventory analysis quantifies the use of resources and energy, and the releases into the environment associated with the system being evaluated (ISO, 2006a).
Primary data were used in this study for coating production and application. The data related to packaging and milk production were taken from Fantin et al. (2012). The percentage of milk waste was obtained from the FAO Report "Global Food Losses and Food Waste" (FAO, 2011), while the amount of "food saved" was estimated from WRAP reports (WRAP, 2009 and 2013). Ecoinvent database v2.2 (Swiss Centre for Life Cycle Inventories, 2010) was used for background data.
The packaging system analysed is the Tetra Top® flexible packaging, whose cradle-to-gate inventory data were taken from Fantin et al. (2012), who performed an LCA study of an Italian brand of high quality milk packaged in Tetra Top®., All the inventory data in that study referred to the Italian situation by using national datasets (i.e. electricity production mix). In the present study, instead, the Inventory data of the packaging's life cycle were adapted to the European situation by using European Datasets (Swiss Centre for Life Cycle Inventories, 2010). Tetra Top® components and weight are summarized in Table 2.

Here Table 2

The end of life of the Tetra Top® packaging materials was considered. The Western Europe end of life scenario was used considering the percentage of recycling, incineration and landfill obtained from the IFEU Final Report (2012) and reported in Table 3. Doka (2009) and the SimaPro 7.3.3 software guidelines were followed to assess the impact of the treatment used.

Here Table 3

In the case of LAE coating on the inner layer of the packaging, production and application must be considered. The amount of LAE coating to be applied onto each package is 0.3 grams. The composition of the coating is 5% LAE and 95% EVOH, thus the final amount of the two substances is 0.0143 g and

0.2857 g respectively. The coating is applied by rotogravure technique with tap water and 1-propanol used as solvent in a 1:1 ratio. This solvent constitutes 87% by weight of the final solution. The amount of each component for the reference unit is reported in Table 4.

Here Table 4

Inventories of the ingredients for the production of LAE are not currently available, so the inventory of a generic inorganic chemical component taken from Althaus et al. (2007) was used. This approximation was validated through a sensitivity analysis using the consideration adopted by Humbert et al. (2009) too: instead of the generic inorganic chemical component, the chemical component with the highest impacts available in Ecoinvent was used and the result showed that the changes are well below the cut-off applied. This result was predictable since the weight of this material is very low, less than the 0.05% of the total weight of primary packaging.

Ethylene vinyl alcohol (EVOH) is a copolymer of ethylene and vinyl alcohol. Since the latter monomer mainly exists as its tautomer acetaldehyde, the copolymer is prepared by polymerization of ethylene and vinyl acetate to yield the ethylene vinyl acetate (EVA) copolymer followed by hydrolysis. EVOH copolymer is defined by the mole % ethylene content: lower ethylene content grades have higher barrier properties; higher ethylene content grades have lower temperatures for extrusion.

No inventory on EVOH life cycle is available in literature. In this study EVA was used as an approximation for EVOH according to Humbert et al. (2009), who state that this is a suitable choice because changes in impact evaluation are minimal and under cut-off rules, being EVOH prepared by polymerization of ethylene and vinyl acetate to yield the ethylene vinyl acetate (EVA) copolymer followed by hydrolysis. The study by Hischier (2007) was the source of data for the EVA inventory that includes raw materials and chemicals used for production, transport of materials to manufacturing plant, estimated emissions into air, water from production, estimation of energy demand and infrastructure of the plant.

The Inventory was changed, since the EVOH used in this application has different percentages of vinyl acetate and ethylene compared to the one of the reference. In particular EVOH 29 is composed by 71% vinyl acetate and 29% ethylene.

The inventory data on Propanol production were obtained by using information from Sutter (2007), who assessed the production of 1-propanol 100% by means of the hydrogenation process, including transportation and consumption of raw materials, energy, infrastructure and land use as well as the generation of emissions into air.

As regards coating preparation, only energy consumption was taken into account. In the industrial project the coating preparation occurs in a 200 L heated tank with a mixer. The energy consumption is due to the mixer engine and to the tank heater, equal to 0.17 kWh in both cases. Accordingly, the amount of electricity which is consumed by this equipment is 3.7E-06 kWh per packaging.

Rotogravure is the most suitable technique for coating application onto the packaging film. The inventory data of coating application were provided by Bobst Group Italia S.p.A. The gravure system is composed of an application apparatus, where the coating is laid on by means of engraved rollers which collect the product from a coating tray, and by a drying station, where the solvent is evaporated by means of hot air flow. Finally the propanol, which is dispersed into the hot air, is combusted by a burner. Natural gas is used to heat the air and fuel the burner. The energy consumption and emissions occurring during the phases of coating production and application are reported in Table 5.

Here Table 5

Milk waste was also included in the system boundaries, considering all the inputs and outputs of its life cycle. The data related to the milk's life cycle up to the transportation to the distribution centres were taken from Fantin et al. (2012). In particular, the data related to the following phases were taken from this study: (i) raw milk production on farm and transport to dairies; (ii) pasteurization; filling and packaging; (iii) delivery to distribution centres. As before, inventory data were adapted to the European situation by using European datasets instead of national ones.

All the inputs and outputs of the phases occurring after the delivery to the distribution centres were estimated. The energy consumption required to store cold products in the distribution centres is between 30 and 50 kWh/m^3/year (Duiven and Binard, 2002). One-day average storage for fresh milk with an average consumption of 40 kWh/m^3/year was used in this assessment.

An average distance of 50 km was considered for the transportation of milk between the Distribution Centre and the supermarket. Since no datasets are available for refrigerated transports in LCA commercial databases, the Ecoinvent dataset "16-32 tons truck EURO4" was used (Spielmann et al., 2007); the truck's diesel consumption reported in the dataset was changed too by using primary data related to a refrigerated truck provided by a transportation company.

The energy consumption related to the milk storage in the market racks was taken into account by adopting the hypotheses put forward by LCA Food (2002), and considering 4 days as average storage time.

Class A+ refrigerator was selected as average class to estimate the energy required for domestic storage. Ten class A+ refrigerators were selected from the market and the average of their technical characteristics led to 292 kWh annual consumption and an internal volume of 298 L. The volume available for storage was considered as half of the overall capacity. Based on these considerations the average daily consumption per litre of product which is potentially storable in the refrigerator turns out to be 0.0054 kWh; 3 days of average permanence were assumed.

It was assumed that the milk wasted by consumers is poured down the sink and the packaging disposed of according to the European end-of-life scenario. Milk disposed of down the sink is usually subjected to wastewater treatment (WRAP, 2009). About 80% of the population in the OECD area is connected to a municipal waste water treatment plant (EPOC, 2012). The calculation tool for municipal wastewater treatment plants designed by Doka (2009) was used to evaluate the impact of these plants. The remaining 20% of milk was considered as being directly emitted into water. The physical parameters of milk, in particular COD, BOD, metals, nitrogen and phosphorous concentrations were obtained from literature (Mawson, 1994; Enb et al., 2009; Beach et al., 1941; Lenstrup, 1926), and used to evaluate the impact of the municipal wastewater treatment and of the emissions into water.

3.3 Impact assessment

The data collected in the Inventory analysis are the basis for the Impact Assessment phase, which aims to evaluate the system's potential environmental impacts (ISO, 2006a) caused by releases into the environment and consumption of resources.

The Impact 2002 + method (Jolliet et al., 2003) was adopted in this study. This method includes 14 midpoint categories: (i) Human Toxicity carcinogens and non-carcinogens, (ii) Respiratory inorganics, (iii) Respiratory organics, (iv) Ionizing radiations, (v) Ozone layer depletion, (vi) Aquatic eco-toxicity, (vii) Terrestrial eco-toxicity, (viii) Terrestrial acidification, (ix) Aquatic acidification, (x) Aquatic eutrophication, (xi) Land occupation, (xii) Global warming, (xiii) Non-renewable energy and (xiv) Mineral extraction.

In addition, normalization was applied in order to better understand the relative significance of impact category results. The normalized factors of midpoint impact were taken from Humbert et al. (2012).

4 Results and Discussion

The variation in the environmental sustainability of the product-packaging system due to the introduction of the antimicrobial coating for fresh milk packaging is evaluated in the present section. In order to assess the environmental profile of the two different packaging solutions, the impact of the milk's life cycle is included in the boundaries of the analysis, considering the different amount of food waste generated, as suggested by Wikström et al. (2014).

In this section the impacts are explained considering the following sub-voices:

- Milk consumed: it includes all the inputs and outputs related to the life cycle of the consumed milk, which in both cases is 1 L per FU;

- Milk waste: it includes all the inputs and outputs related to the life cycle of the wasted milk, whose amount differs depending on the scenario analysed, as shown in Table 1;
- Packaging: it includes all the inputs and outputs related to the packaging's life cycle, for both consumed milk and milk waste;
- Coating: it includes all the inputs and outputs related to the coating's life cycle.

Table 6 shows the results of the impact assessment for the midpoint categories considered. The results show that "Milk with coating" has lower environmental impacts in all the categories apart from the Mineral extraction category.

Here Table 6

Fig. 2 reports the relative contribution of each aspect to the whole product-packaging system for milk packaged without antimicrobial coating (a) and with antimicrobial coating (b).

The life cycle of consumed milk is, as expected, the main cause of impacts, representing 60-87% of the total environmental burdens in the case of "Milk without coating", and 64-89% in the case of "Milk with coating".

The impacts of the milk waste's life cycle is on average the second source of impact and it contributes by 8-37% in the case of "Milk without coating" and 6-28% when antimicrobial coating is applied. This confirms what stated by Wikström et al. (2014) and Silvenius et al. (2014), i.e. a crucial issue in developing sustainable packaging is to reduce food waste. The increase in the food products' life which can be obtained by using novel environmentally-friendly technologies is therefore particularly important for the sustainability of the entire food supply chain.

As far as the packaging materials are concerned, in the case of traditional milk they contribute in a range of 0-12% except for the Carcinogens category, for which they contribute by 28%. In the case of "Milk with coating", their impacts are slightly higher compared to the traditional case. The Mineral extraction category represents the only category in which the contribution of the coating's life cycle is really important, as shown in Fig. 2 (b), this being due to the production of compressed air in particular. The environmental impacts of packaging are on average lower than the impact of milk waste by about 60% in the case of milk without coating and about 30% in the case of milk with coating. This is in agreement with the study by Silvenius et al. (2014), according to which the environmental burden of packaging is always lower than the impact of food waste.

Here Fig. 2

The impacts of the consumed milk's life cycle in absolute value are the same in both cases since they are expressed for the same FU, i.e. 1 L (see also Table 1), and therefore they can be excluded from a comparative analysis between the packaging solutions with and without antimicrobial coating. On the basis of this exclusion, the proportion of the impacts between the packaging's and the milk waste's life cycles can be analysed more carefully. This analysis also helps to understand the actual impact of the packaging system, since it can influence the impacts of food waste but it cannot help to reduce the impacts of eaten food.

Fig. 3 (a) and table 7 show the comparison of impacts of "Milk packaging without coating" and "Milk packaging with coating" by excluding the contributions of the consumed milk's life cycle; Fig. 3 (b) shows the same impacts after normalization. Considering the normalized impacts, the respective share of each impact is compared to the overall damage by applying normalization factors in order to facilitate the interpretation.

The average impact reduction across the various categories is about 14%, apart from the Mineral extraction category where the impact of traditional milk is about 40% lower.

The normalization phase highlights the categories which appear to be the most critical ones for the product analysed, and shows that the Terrestrial acidification category appears to be the most critical, followed by Human toxicity carcinogens, Aquatic acidification and Land occupation. The Mineral extraction category is the only one which resulted higher in the case of "Milk packaging with coating", but its significance after the normalization phase is rather low.

Here Table 7

Here Fig. 3

Finally, it is important to point out the current difficulty in accurately estimating the influence of durability of packaged food products once they have been opened on the amount of food waste generated, because they depend on various factors that often cannot be determined beforehand. In this study a conservative approach (i.e. 33% of waste reduction during the consumption phase) was considered in the case of coating application. Different rates of food waste reduction can significantly affect the LCA results; a sensitivity analysis was then carried out to evaluate the variability of the results.

4.1 Sensitivity analysis

As mentioned in Section 2, the assessment of the potential waste reduction in the case of coating application was based on a literature analysis and personal considerations. This hypothesis has a high degree of uncertainty due to multiple reasons (consumer behaviour, country, culture, etc…), therefore, a sensitivity analysis was conducted in this study to verify the influence of waste saving percentage on LCA results.

Indeed, an LCA analysis needs to investigate all the parameters that can strongly influence the final results (ISO 2006a). Sensitivity Analysis is "a systematic procedure to estimate the effects of the choice made regarding methods and data on the outcome of a study" (ISO 2006b).

A 33% reduction in wastage resulting from the application of the antimicrobial coating was assumed in the initial analysis. In this sensitivity analysis two additional scenarios were evaluated by considering 20% and 50% respectively as percentages of waste reduction, while the impacts of consumed milk were not taken into consideration, as before.

Here Fig. 4

The results of the sensitivity analysis for all the impact categories considered are shown in Fig. 4. If the amount of food saved during the consumption phase were 20%, the impacts of the coated packaging would be higher in three impact categories (Mineral extraction, Human toxicity and Photochemical oxidation), mainly due to the consumption of natural gas for the solvent evaporation and compressed air, equal in Non-renewable energy, and lower in all the other categories compared to traditional packaging. With 50% waste reduction the coating application would reduce the environmental impacts in all the categories considered apart from Mineral extraction. Shifting from 20% to 50% waste reduction, the environmental profile of the system "packaging + food waste" improves by 13% on average for the impact categories considered, demonstrating the system's great sensitivity to the amount of reducible waste.

It is essential to emphasize that these values were calculated considering 7% waste occurring during the consumption phase, which is probably an underestimated value for fresh milk, since this is the average value for dairy products (FAO, 2011). If the amount of waste were greater, the environmental benefits would obviously grow proportionally.

5 Conclusions

The application of an antimicrobial coating on Tetra Top® packaging for fresh milk was analysed from the environmental point of view via LCA method. The coating considered, one of the most innovative antimicrobial agents, is a synthetic derivative of lauric acid. Its application can significantly extend the shelf life of an opened package, thereby avoiding a great amount of food waste.

As derived from literature, 7% of milk was considered as wasted during the consumption phase and it was assumed that this value could be reduced by 33% by applying the antimicrobial coating. As regards the case study, the functional unit was 1 L of consumed milk, considering the entire life cycle of the milk-packaging system, from milk production to potential milk waste. Food waste was in fact included in the system boundaries and its environmental impacts resulted to be on average higher than the impacts of the packaging's life cycle, thus confirming the importance of including them in the system boundaries.

The results have shown that the application of the antimicrobial coating would reduce the impacts in all the impact categories considered (apart from Mineral extraction) and this is even more evident when the impact of the consumed milk's life cycle, whose amount is equal for both the systems, is excluded.

Food waste reduction cannot be estimated precisely, due to a large variability of different cultural, geographical and technical factors, so a sensitivity analysis was carried out by testing a percentage of food reduction ranging between 20% and 50%. Even when considering a reduction by 20%, the overall environmental impact of coated packaging appeared to be lower in most of the categories considered. When shifting from 20% to 50% waste reduction, the environmental profile of the system improved by 13% on average.

This study demonstrates the importance of including food waste in LCAs of packaging systems, especially when packaging attributes significantly affect the amount of food waste that can be generated. In fact, a packaging system able to reduce food waste could be a better solution from the environmental point of view despite its higher potential environmental impacts throughout the life cycle. Therefore, future research should focus on further innovative technologies which may help reduce food waste, in order to improve the environmental sustainability of the whole food sector. Moreover, further research activities should aim to apply the LCA method to other applications of antimicrobial coatings on food packaging systems, in order to assess if the application of these coatings can always be promising for the environment. It would then be very important to better understand the impact of the extension in food life (before and after the package opening) on reducing food waste for several food products.

Acknowledgments

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Tables captions

Table 1: Percentages and amount of the milk wasted in supply chain phases in Europe per each litre of consumed milk in the case of traditional packaging and coated packaging (T.P. – Traditional Packaging; C.P. – Coated Packaging).

Table 2: Inventory data for Tetra Top® related to 1l of beverage (extracted from Fantin et al. (2012)).

Table 3: End of life scenario for packaging materials.

Table 4: Amount of coating component for each package.

Table 5: Consumption and emissions in the production and application phases of coating.

Table 6: Total environmental impacts of "Milk without coating" and "Milk with coating" for 1 litre of milk including food waste.

Table 7: Environmental impacts of traditional packaging and coated packaging for 1 litre of milk excluding consumed milk

Table 1

Milk reference flow in the different life cycle phase	Current average waste T.P.	Milk without coating [L]	Current average waste C.P.	Milk with coating [L]
Consumed milk		1.0000		1.0000
Household milk waste	7% of purchased milk	*0.0753*	4.7% of purchased milk	*0.0492*
Milk purchased to consume 1L of milk at home		1.0753		1.0492
Supermarket milk waste	0.5% of milk stored at supermarket	*0.0058*	0.5% of milk stored at supermarket	*0.0055*
Milk stored at supermarket to consume 1L of milk at home		1.0811		1.0547
Processing milk waste	1.2% of milk processed	*0.0142*	1.2% of milk processed	*0.0135*
Milk purchased at supermarket to consume 1L of milk		1.0953		1.0683
Milk production losses	4% of milk produced	*0.0502*	4% of milk produced	*0.0477*
Total milk produced to consume 1L of milk including wasted and lost milk		1.1455		1.1159

Table 2

Component	Weight [g]
PE external layer	0.81
Paperboard	22.16
PE inner layer	3.18
HDPE Cap	2.50
Ink	0.55
PE Tape	0.14

Table 3

Component	End of life scenario	Percentage	Weight [g]
PE	Landfill	55.5%	3.68
	Incineration	44.5%	2.95
	Recycling	-	-
Paperboard	Landfill	35.1%	7.79
	Incineration	28.2%	6.24
	Recycling	36.7%	8.13

Table 4

Component	Amount [g]
LAE	0.0143
EVOH	0.2857
Tap Water	0.9489
Propanol	0.9489

Table 5

Input	Unit	Hour consumption	Single pack consumption
Electricity - coating production	kWh	2	1.1E-06
Electricity - application	kWh	148	3.704E-04
Electricity - solvent combustion	kWh	60	1.502E-04
Methane - coating drying	kWh	250	6.26E-04
Methane - solvent combustion	kWh	900	2.252E-03
Compressed air	Nm^3	13500	3.379E-02
Combustion emissions	**Unit**	**Hour emissions**	**Single pack emissions**
CO_2	g	258846	0.6478
No_x	g	1350000	3.379
CO	g	1350000	3.379
Propanol	mg	338062	0.8461

Table 6

Impact category	Unit	Milk Without Coating	Milk With Coating
Human toxicity (carcinogens)	kg C_2H_3Cl eq.	9.74E-03	9.73E-03
Human toxicity (non carcinogens)	kg C_2H_3Cl eq.	3.90E-02	3.83E-02
Respiratory (inorganics)	kg PM2.5 eq.	2.49E-03	2.44E-03
Ionizing radiations	Bq C-14 eq.	1.17E+01	1.16E+01
Ozone layer depletion	kg CFC-11 eq.	7.76E-08	7.61E-08
Photochemical oxidation	kg C_2H_4 eq.	4.99E-04	4.95E-04
Aquatic ecotoxicity	kg TEG water	9.88E+01	9.16E+01
Terrestrial ecotoxicity	kg TEG soil	7.61E+01	7.33E+01
Terrestrial acidification	kg SO_2 eq.	2.19E-01	2.14E-01
Land occupation	m^2org.arable	1.23E+00	1.20E+00
Aquatic acidification	kg SO_2 eq.	2.88E-02	2.81E-02
Aquatic eutrophication	kg PO_4 P-lim	6.96E-04	6.23E-04
Global warming	kg CO_2 eq	9.71E-01	9.55E-01
Non-renewable energy	MJ primary	1.14E+01	1.12E+01
Mineral extraction	MJ surplus	1.07E-02	1.20E-02

Table 7

Impact category	Unit	Milk packaging without coating			Milk packaging with coating			
		Total	Packaging	Milk waste life cycle	Total	Packaging	Milk waste life cycle	Coating
Human toxicity (carcinogens)	kg C_2H_3Cl eq.	3.49E-03	2.70E-03	7.89E-04	3.48E-03	2.64E-03	5.93E-04	2.47E-04
Human toxicity (non carcinogens)	kg C_2H_3Cl eq.	7.21E-03	2.23E-03	4.98E-03	6.48E-03	2.18E-03	3.86E-03	4.40E-04
Respiratory (inorganics)	kg PM2.5 eq.	3.56E-04	5.43E-05	3.02E-04	3.01E-04	5.30E-05	2.39E-04	9.64E-06
Ionizing radiations	Bq C-14 eq.	2.59E+00	1.29E+00	1.30E+00	2.39E+00	1.26E+00	9.93E-01	1.45E-01
Ozone layer depletion	kg CFC-11 eq.	1.27E-08	4.20E-09	8.48E-09	1.12E-08	4.10E-09	6.48E-09	6.49E-10
Photochemical oxidation	kg C_2H_4 eq.	9.35E-05	4.02E-05	5.33E-05	8.96E-05	3.92E-05	4.15E-05	8.92E-06
Aquatic ecotoxicity	kg TEG water	3.09E+01	3.55E+00	2.73E+01	2.37E+01	3.46E+00	1.89E+01	1.31E+00
Terrestrial ecotoxicity	kg TEG soil	1.41E+01	1.19E+00	1.29E+01	1.13E+01	1.16E+00	9.62E+00	4.95E-01
Terrestrial acidification	kg SO_2 eq.	2.87E-02	1.08E-03	2.76E-02	2.31E-02	1.06E-03	2.19E-02	1.55E-04
Land occupation	m^2org.arable	1.67E-01	1.38E-02	1.53E-01	1.35E-01	1.34E-02	1.22E-01	3.23E-05
Aquatic acidification	kg SO_2 eq.	3.87E-03	2.79E-04	3.59E-03	3.18E-03	2.73E-04	2.85E-03	5.08E-05
Aquatic eutrophication	kg PO_4 P-lim	2.80E-04	2.02E-05	2.60E-04	2.07E-04	1.97E-05	1.77E-04	9.91E-06
Global warming	kg CO_2 eq.	1.73E-01	6.71E-02	1.06E-01	1.58E-01	6.54E-02	8.27E-02	9.57E-03
Non-renewable energy	MJ primary	2.47E+00	1.35E+00	1.12E+00	2.34E+00	1.32E+00	8.56E-01	1.69E-01
Mineral extraction	MJ surplus	1.88E-03	6.38E-04	1.24E-03	3.21E-03	6.22E-04	9.65E-04	1.62E-03

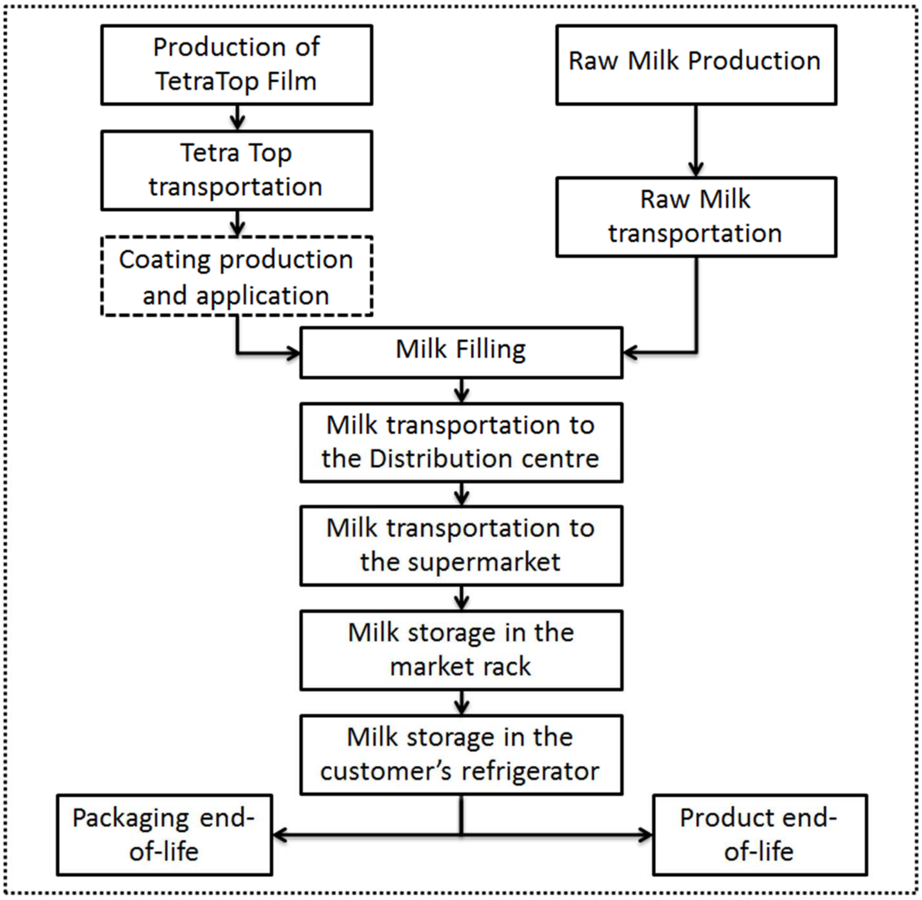
Figure captions

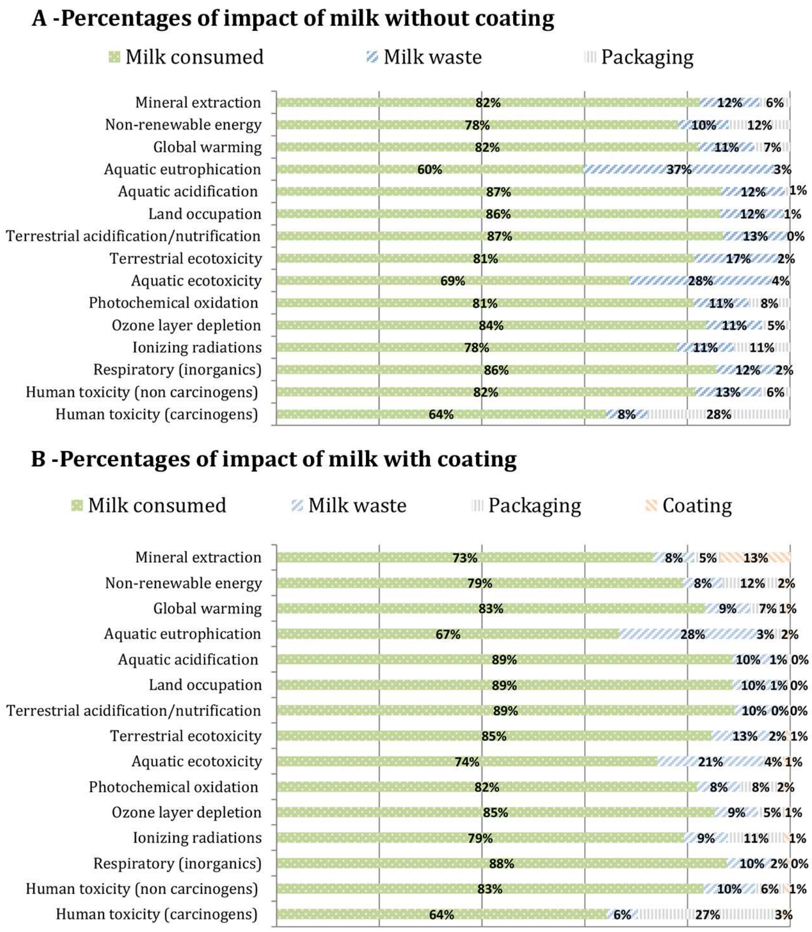
Fig. 1: System boundaries of the two possible configurations (the process "coating production and application" occurs only in the case of coated packaging).

Fig. 2: Environmental impacts of milk packaged without antimicrobial coating (a) and with antimicrobial coating (b), which are divided into production of consumed milk's life cycle, milk waste's life cycle, packaging and coating (only in the latter case).

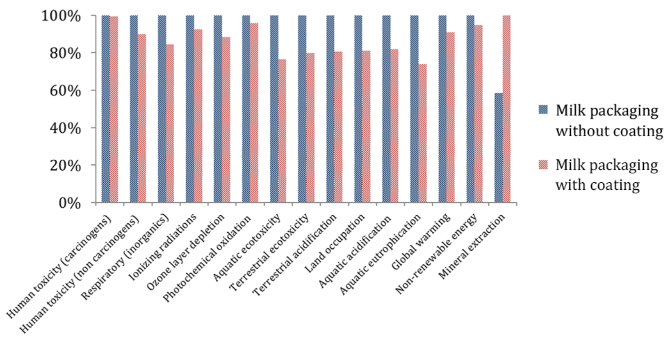
Fig. 3: Comparison of total impacts (a) and comparison of normalized results (b) of milk packaging without coating and milk packaging with coating, without considering the consumed milk's life cycle.

Fig. 4: Percentage variation of the impacts in the different categories for each scenario.

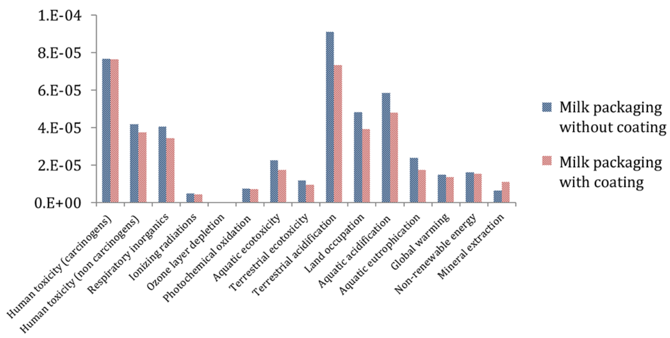

Production of TetraTop Film
Tetra Top transportation
Coating production and application
Raw Milk Production
Raw Milk transportation
Milk Filling
Milk transportation to the Distribution centre
Milk transportation to the supermarket
Milk storage in the market rack
Milk storage in the customer's refrigerator
Packaging end-of-life
Product end-of-life

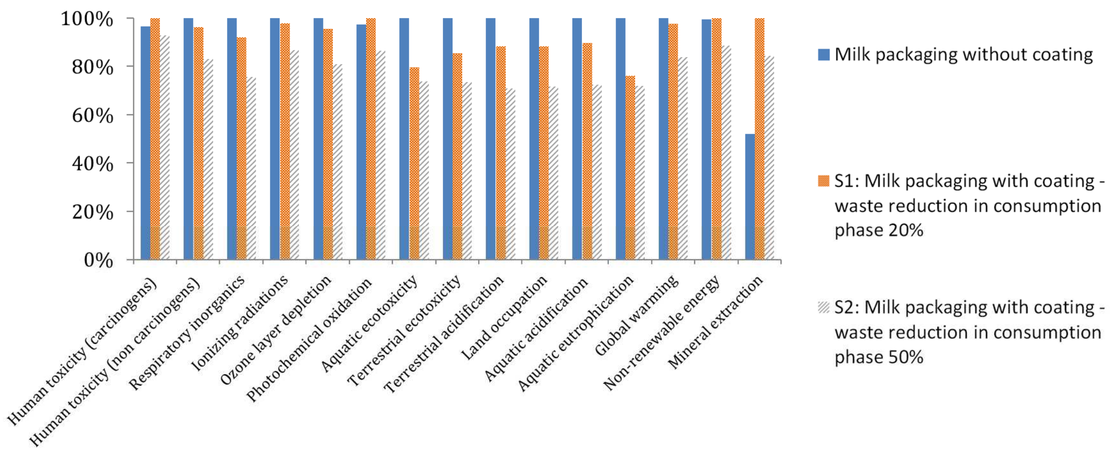

A -Percentages of impact of milk without coating
Milk consumed
Milk waste
Packaging
Mineral extraction 82% 12% 6%
Non-renewable energy 78% 10% 12%
Global warming 82% 11% 7%
Aquatic eutrophication 60% 37% 3%
Aquatic acidification 87% 12% 1%
Land occupation 86% 12% 1%
Terrestrial acidification/nutrification 87% 13% 0%
Terrestrial ecotoxicity 81% 17% 2%
Aquatic ecotoxicity 69% 28% 4%
Photochemical oxidation 81% 11% 8%
Ozone layer depletion 84% 11% 5%
Ionizing radiations 78% 11% 11%
Respiratory (inorganics) 86% 12% 2%
Human toxicity (non carcinogens) 82% 13% 6%
Human toxicity (carcinogens) 64% 8% 28%
B -Percentages of impact of milk with coating
Milk consumed
Milk waste
Packaging
Coating
Mineral extraction 73% 8% 5% 13%
Non-renewable energy 79% 8% 12% 2%
Global warming 83% 9% 7% 1%
Aquatic eutrophication 67% 28% 3% 2%
Aquatic acidification 89% 10% 1% 0%
Land occupation 89% 10% 1% 0%
Terrestrial acidification/nutrification 89% 10% 0% 0%
Terrestrial ecotoxicity 85% 13% 2% 1%
Aquatic ecotoxicity 74% 21% 4% 1%
Photochemical oxidation 82% 8% 8% 2%
Ozone layer depletion 85% 9% 5% 1%
Ionizing radiations 79% 9% 11% 1%
Respiratory (inorganics) 88% 10% 2% 0%
Human toxicity (non carcinogens) 83% 10% 6% 1%
Human toxicity (carcinogens) 64% 6% 27% 3%

(a) – Comparison of total impacts



(b) – Comparison of normalized results




100%
80%
60%
40%
20%
0%
Human toxicity (carcinogens)
Human toxicity (non carcinogens)
Respiratory inorganics
Ionizing radiations
Ozone layer depletion
Photochemical oxidation
Aquatic ecotoxicity
Terrestrial ecotoxicity
Terrestrial acidification
Land occupation
Aquatic acidification
Aquatic eutrophication
Global warming
Non-renewable energy
Mineral extraction
Milk packaging without coating
S1: Milk packaging with coating - waste reduction in consumption phase 20%
S2: Milk packaging with coating - waste reduction in consumption phase 50%

Highlights

- Life Cycle Assessment of an antimicrobial coating applied to packaged fresh milk
- The antimicrobial coating considered is a synthetic derivative of lauric acid
- The application of the antimicrobial coating would reduce the environmental impacts
- This study demonstrates the importance of food waste in LCAs of packaging systems