Evaluation of the economic and environmental sustainability of high pressure processing of foods

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Abstract

A comparative evaluation of the environmental/economic performance of High Pressure Processing (HPP) technology for food processing is made using Life Cycle Costing (LCC) and Life Cycle Assessment (LCA) methodologies. Thermal pasteurization (TP), in the form of indirect system (with energy recovery) and of retort process, and modified atmosphere packaging (MAP), are taken as benchmark during the evaluation, as traditional food processing technologies typically used to process orange juice (TP) and sliced Parma ham (MAP). Primary data on costs and consumption of HPP, TP and MAP plants were obtained from companies. Secondary data for LCA analysis was retrieved from the Ecoinvent 3.4 database and from available scientific literature. As a result of the assessment, HPP appears as more expensive than both TP processes, but turns out to have a lower environmental impact in almost all impact categories. Compared to MAP, HPP is less expensive and also has a lower impact in most of the impact categories, as MAP requires a significant amount of packaging materials and food gases.

Keywords	life cycle assessment; life cycle costing; high pressure processing; thermal pasteurization; modified atmosphere packaging; environmental assessment

Corresponding Author	Giuseppe Vignali
Order of Authors	Federica Cacace, Eleonora Bottani, Antonio Rizzi, Giuseppe Vignali

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Supplementary_LCC HPP, TP, MAP calculation_2019_12_19.xlsx [Data in Brief]

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Research Data Related to this Submission

Data set	https://data.mendeley.com/datasets/xb63v23fn2/draft?a=8d7f47c7-e618-4e82-9158-5b1da22ae693

Data for: EVALUATION OF THE ECONOMIC AND ENVIRONMENTAL SUSTAINABILITY OF HIGH PRESSURE PROCESSING OF FOODS

Supplementary materials LCC calculation

UNIVERSITÀ DI PARMA
DEPARTMENT OF ENGINEERING AND ARCHITECTURE
Viale delle Scienze 181/A, 43124 Parma (Italy)

The Editor-in-Chief of
Innovative Food Science and Emerging Technologies
Prof. D. Knorr
Dept. of Food Technology and Food Process Engineering, Technische Universität Berlin (TUB),
Königin-Luise-Str. 22, 14195, Berlin, Germany

Parma, ITALY, Thursday, 19 December 2019

Dear Prof. Knorr,

Please find enclosed an electronic copy of the revised (third revision) manuscript entitled:

"EVALUATION OF THE ECONOMIC AND ENVIRONMENTAL SUSTAINABILITY OF HIGH PRESSURE PROCESSING OF FOODS"

The paper has been significantly revised in contents and editing according to the comments of the two reviewers. We hope that our efforts are sufficient to have the paper published on "Innovative Food Science and Emerging Technologies".

We checked all the data again in order to eliminate possible mistakes and following the suggestions of one of the two reviewer we controlled the consumption of the MAP equipment. LCC and LCA analyses of these processes (100g and 200g) were repeated and inserted in the manuscript.

We wish to take this opportunity to send to You our best regards.

Looking forward to hearing from You soon,

Yours sincerely

Giuseppe Vignali

Giuseppe VIGNALI,
Eng, Ph.D., Associate Professor
Department of Engineering and Architecture
University of Parma, viale delle Scienze 181/A, 43124 Parma (Italy)
phone +39 0521 906061
email: giuseppe.vignali@unipr.it

Comments from the editors and reviewers:

- Reviewer 1

No further comments. Accept.

- Reviewer 2

The authors did changes on their manuscript after the revision procedure and the document is improved, however I still have some comments.

1) Information on the electricity demands about the TP-indirect was changed in this version of the manuscript but the results on Table 5 and Figure 6 are the same with the previous version. Can you validate that those are the correct LCA results?

Our reply: actually, this part of the paper has been simplified in its structure, but not significantly changed and in particular, no changes were made to the numerical values. To be more precise, because we have now provided the MS Excel file with the detailed calculation of all the cost components, describing them in detail in the text is no longer required. This is why you have found this part of the paper blue highlighted. And this is also why the results in Tables 5 and 6 have not changed compared with the previous version of the paper.

2) Line 649. The primary packaging is indicated (also in line 623) as 0.018 kg per 100 g of product. So for 1 kg which is the functional unit (line 721) that should be 0.180 kg. However, on Table 10, that is not the case. Can you indicate what is the functional unit on which the data are corresponding in Table 10 (and Table 11)?

Our reply: this was simply a transcription error. Indeed, in SIMA PRO we have inserted the data relating to one tray of product (i.e. 0.018 kg for the primary packaging), because these data are directly available, but we have multiplied by 10 to reproduce the functional unit (1 kg of finished product). The same applies to other unitary values. Therefore, we can confirm that the analyses have been performed correctly. What we forgot was to indicate the correct value in Table 10. We have now fixed and you will see that Table 10 reports the data relating to the functional unit. In checking this table, we have also amended the input data relating to the Manufacturing stage; once again, this was simply a transcription error when copying data from SIMA PRO, but did not affect the correctness of the analyses. Thank you anyway for highlighting this point.

Table 11 does not appear to be affected by errors. The detailed calculation of the input data required for the LCA analysis is reported in the supplementary material, where the "input of LCA analysis" are all highlighted.

3) In Table 10, you indicate that the preservation treatment consumes 13.36 Wh while for the HPP that is approximately 173 Wh (if we take the data provided for the orange juice). Compared to literature data cited by Pardo and Zufía 2012, the values for the electricity demand for MAP are quite small. Why is that? Can you indicate the values for 1 kg which is the functional unit?

Our reply: thank you for highlighting this point. The electric consumption of the preservation treatment for MAP was checked once again on the basis of the technical details of the machine taken as an example for the process (it is mentioned in a footnote in the description of the process). As a result, the numerical values have changed (see Table 10); consequently, the LCA analyses were run once again and the LCC analysis was *updated with the new value. We confirm that all the data inserted in Table 10 are now consistent and refer to 1 kg of finished product.*

4) Can you confirm also in Tables 12, 13 and 14 (and corresponding figures) that the functional unit for these results is 1 kg of product?

Our reply: As mentioned in our reply to your previous comment, all the LCA analyses related to MAP have been run once again to take into account the updated electric consumption. You will see that this part of the paper has been modified accordingly. We confirm that all the results presented are consistent and refer to 1 kg of finished product.

5) Especially for Table 14 make clear that the titles of the columns 100 g and 200 g are not the functional units but the 2 scenarios considered for the sensitivity analysis.

Our reply: This has been modified according to your comment. We appreciate the precision of the reviewer in indicating this point.

6) Why is there so much difference between the scenarios of 100 g and 200 g especially in the categories of mineral resource scarcity and water consumption?

Our reply: the behavior observed for the categories "mineral resource scarcity" and "water consumption" was due to the fact that one process had a negative impact. In the 100 g scenario, this negative impact was compensated by the positive impact of other processes and resulted in a positive impact. In the 200 g scenario, instead, the higher negative contribution of the process leads to a negative total impact.

Having said that, however, we also have to observe that this behavior no longer applies. As the LCA analyses of the MAP process were modified to take into account the updated energy consumption, at present there are NO impact categories with turn out to be positive in one scenario and negative in the other one. Please see the updated figures and tables referring to the comparison of MAP – 100g and MAP – 200 g. We hope that this answers your comment.

7) In the answers to the reviewers, you indicate that you assume that the quality of the products is the same after treated with the different method. However, since you do not know the optimum conditions, can you perform a sensitivity analysis to show what the effect on the environmental footprint can be at slight change of processing conditions?

Our reply: we thank the reviewer for your suggestion. In reading your comment, we are afraid that probably, we have not correctly written our previous response to the reviewers. In fact, in our study it is actually impossible to compare the quality of products treated in different way, and this has not been done. What we meant is that the aim of the study is to compare the technical features of real treatments carried out on products typically sold on the market. This has been clearly reported in the text (p.5 and conclusion), where we state that "as far as the comparability of the quality and shelf-life of the tested products is concerned, it has to be observed that the aim of this article is to compare possible treatments and packaging solutions generating products, which can be bought by consumers, without analyzing in details the quality or the shelf-life of these products".

If we change now the process conditions (for example the time and pressure of HPP or the temperature and time of TP-retort or TP-indirect), we will not obtain the same F-value of sold products, and we probably also change their real shelf life.

This is why, if you agree with us (also because of the need not burden the paper length), we would like not to perform such kind of sensitivity analysis, leaving only that already performed on the size of the MAP trays.

High pressure processing (HPP) is a well-known non-thermal technology, which since its introduction has had limited use, mainly due to the high cost of the electricity required for the process. Nowadays, however, new technologies in the food processing and new food product applications could make it more widely used. To correctly evaluate whether HPP technology is actually cost-effective and has low impact on the environment, detailed economic and environmental analyses have been carried out in this paper. Results are expected to enhance the use of HPP technology in industry.

- HPP technology is evaluated in environmental/economic terms for two food products
- The evaluation methodologies are Life Cycle Costing and Life Cycle Assessment
- Thermal pasteurization and modified atmosphere packaging are compared with HPP
- HPP is more expensive than TP for orange juice and cheaper than MAP for Parma ham
- HPP is on average less environmental impactful than TP and MAP for the two products

EVALUATION OF THE ECONOMIC AND ENVIRONMENTAL SUSTAINABILITY OF HIGH PRESSURE PROCESSING OF FOODS

Authors:

Federica Cacace[(a)], Eleonora Bottani[(b)], Antonio Rizzi[(c)], Giuseppe Vignali[(d)]

Affiliation:

[(a, b, c, d)] Department of Engineering and Architecture, University of Parma, Parco Area delle Scienze 181/A, 43124 Parma (Italy)

Email contacts:

[(a)]federica.cacace@studenti.unipr.it, [(b)]eleonora.bottani@unipr.it, [(c)]antonio.rizzi@unipr.it

[(d)]giuseppe.vignali@unipr.it

Corresponding author:

Giuseppe Vignali; giuseppe.vignali@unipr.it

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ABSTRACT

A comparative evaluation of the environmental/economic performance of High Pressure Processing (HPP) technology for food processing is made using Life Cycle Costing (LCC) and Life Cycle Assessment (LCA) methodologies. Thermal pasteurization (TP), in the form of indirect system (with energy recovery) and of retort process, and modified atmosphere packaging (MAP), are taken as benchmark during the evaluation, as traditional food processing technologies typically used to process orange juice (TP) and sliced Parma ham (MAP). Primary data on costs and consumption of HPP, TP and MAP plants were obtained from companies. Secondary data for LCA analysis was retrieved from the Ecoinvent 3.4 database and from available scientific literature.

As a result of the assessment, HPP appears as more expensive than both TP processes, but turns out to have a lower environmental impact in almost all impact categories. Compared to MAP, HPP is less expensive and also has a lower impact in most of the impact categories, as MAP requires a significant amount of packaging materials and food gases.

Keywords: *life cycle assessment; life cycle costing; high pressure processing; thermal pasteurization; modified atmosphere packaging; environmental assessment.*

INDUSTRIAL RELEVANCE

High pressure processing (HPP) is a well-known non-thermal technology, which since its introduction has had limited use, mainly due to the high cost of the electricity required for the process. Nowadays, however, new technologies in the food processing and new food product applications could make it more widely used. To correctly evaluate whether HPP technology is actually cost-effective and has low impact on the environment, detailed economic and environmental analyses have been carried out in this paper. Results are expected to enhance the use of HPP technology in industry.

1 INTRODUCTION

In the food industry, cost reduction and environmental impact reduction are key issues on which to base of a new technology. The assessment of economic sustainability is a key prerequisite for business activities, while assessing the environmental sustainability can be a strategic tool for increasing the product value and structuring green marketing strategies (Stillitano et al. 2017). This is why an integrated sustainability assessment, combining the life cycle costing (LCC) and life cycle assessment (LCA) methodologies, can be an effective tool for both public and private decision-makers, as well as for scientists, professionals and society in general, to achieve eco-compatible strategies (De Luca et al. 2014).

High pressure processing (HPP) is a well-known non-thermal technology, which since its introduction, has had limited use, mainly due to the high cost of the electricity required for the process (Sampedro et al. 2013, 2014; Mujica-Paz et al. 2011). Nowadays, however, new technologies in the food processing and new food product applications could make it more widely used (Milani et al. 2016). Nonetheless, to correctly evaluate whether HPP technology is actually cost-effective and has low impact on the environment, detailed economic and environmental analyses need to be carried out.

The focus of the study is an economic and environmental evaluation of the HPP conservation process for two types of food, i.e. orange juice and sliced Parma ham. These two food products require specific treatments to achieve an adequate shelf-life for sale. Orange juice is often treated with thermal pasteurization (TP) and then transferred to aseptic polymeric bottles able to withstand chemical decontamination agents (e.g. Hydrogen peroxide) or to specific hot-filling machines (Manfredi and Vignali 2015). Alternatively, orange juice can be thermally treated in a non-aseptic packaging using some polymeric thermally resistant packaging materials (Pardo and Zufía 2012; Aganovic et al. 2017; DTS[1]). Parma ham can be sold either sliced or as whole ham. Sliced Parma ham is typically packaged in modified atmosphere packaging (MAP), as are many other hams (Cilla et al. 2006; Parra et al. 2010; Bak et al. 2013). HPP technology allows the way these food products are produced and sold to be changed; orange juice in particular can undergo filling and packaging at ambient conditions and then can be treated at high pressure to ensure an adequate shelf-life. In the case of Parma ham, the whole product, once packaged, can be sold worldwide if treated with HPP, as this treatment reduces the risk of *Listeria monocytogenes* contamination (Koutchma 2014; Rastogi 2013) and ensures a sufficient shelf-life of the finished product in the case of similar dry-cured ham (Martínez-Onandi et al., 2018; Pérez-Santaescolástica et al., 2019). For this type of products, other preservation techniques such as the use of antimicrobial coating on packaging are not suggested and applied (Manfredi et al. 2015).

[1] Available at: http://www.dtszb.cn/autoclave-series/rotary-retort/sterilizer.html

The methodologies used to support the economic and environmental evaluation of HPP are life cycle costing (LCC) and life cycle assessment (LCA). LCC is used in industrial systems as a tool to support business decisions, as it considers the whole cost a company will incur throughout a product/asset life cycle, besides the initial investment (Dhillon 2010). LCC analysis is typically carried out before the investment decision is made, to evaluate the potential profit but most importantly to quantify all costs that arise after the asset is purchased (i.e. during use and at disposal), and then to eventually decide whether to purchase it (Ristimäki et al. 2013).

LCA determines and quantifies the actual and potential energy and environmental loads at the various stages of the production and life cycle, using appropriate impact indicators and returns as output related impact on the environment. The LCA definition of the Society of Environmental Toxicology and Chemistry (SETAC, 1993) is the first to introduce the concept of "life cycle", i.e. a "cradle-to-grave" analysis, ranging from the extraction of raw materials to the final disposal of an asset. However, other approaches to LCA can be used; for instance, the "cradle-to-gate" approach excludes the system phases after the product exits from the production site. In the "gate-to-gate" approach, instead, the analysis covers the processes inside the production plant only. The application of the LCA methodology is regulated by UNI EN ISO 14040:2006 and UNI EN ISO 14044:2006 and supported by technical standards (e.g. ISO/TR 14047:2003; ISO/TR 14049:2000; ISO/TS 14048:2002).

The remainder of the paper is organized as follows. Section 2 reviews the state-of-the-art studies about LCC and LCA for HPP, MAP and TP processes. In section 3, the HPP process is described, together with its main cost data. Sections 4 and 5 describe the comparison of HPP with TP for orange juice processing and with MAP for Parma ham processing respectively, covering both the economic and environmental aspects. For the sake of brevity, as the computational procedure followed to determine the cost components (as well as to derive some of the LCA data) is similar across the three technologies evaluated, it is detailed in the text only for the HPP technology; for the remaining technologies it is omitted, while only the main input data are provided. The full details of the computational procedure and related outcomes are provided in the Supplementary material of this paper (Excel spreadsheet). Finally, Section 6 discusses the main findings of the work, highlights the contribution and limitations and introduces possible future research activities.

2 LCC AND LCA STUDIES ON NON-THERMAL FOOD PROCESSING TECHNOLOGIES

LCA and LCC have been applied in several industrial contexts, including food processing. However, comparative studies of food preservation treatments are limited: only one study has been found to deal with a cost analysis of different food processing technologies, while two studies have made an environmental evaluation.

Among these studies, Pardo and Zufía (2012) applied a cradle-to-grave LCA analysis to compare four thermal and non-thermal technologies (i.e. retort processes, microwaving, hydrostatic pasteurization and MAP) for the conservation of fish and vegetables, and evaluated the environmental impact associated with each technology using the ReCiPe Midpoint method. Emerging technologies (hydrostatic pasteurization and MAP) turned out to have a lower environmental impact in terms of energy demand and CO_2 emissions compared to conventional pasteurization (autoclaving). Moreover, lower water requirements were observed for non-thermal technologies (HPP and MAP) compared to thermal processes. MAP was found to be the most sustainable option for products that need fewer than 30 days' shelf life. The LCA analysis showed that the main environmental burdens are caused by the conservation treatment, probably because of the significant levels of energy and water required. Aganovic et al. (2017) evaluated the energy balance and LCA of conventional (thermal), alternative conservation technology (pulsed electrical fields, PEF) and HPP treatments for tomato and watermelon juice. The comparison was made at a fixed level of microbial inactivation and considering the same production capacity. Two main systems were identified for the LCA: the first considers the juice processing process only ("gate-to-gate"), while the second extends the system boundaries to include the agricultural production and waste treatment phases during the preparation and processing of juice ("farm-to-gate"). The results showed no major differences in the environmental impact of the three technologies, although a slightly higher impact was observed for HPP, followed by PEF and finally heat treatment. Some details about the energy consumption of HPP treatment have been reported by Atuonwu and Tassou (2018). They considered different sizes of HPP Avure models and measured the energy consumption at differ levels of MPa treatments, however without performing a complete LCA.

As far as the economic analysis is concerned, Sampedro et al. (2014) estimated the cost of HPP, PEF and TP for orange juice processing in the US. They found that the total cost of producing 1 liter of orange juice by TP accounts for 1.5 ¢/l, while by HPP it accounts for 10.7 ¢/l (i.e. 7 times more). For the PEF system, the overall cost was estimated to be 3.7 ¢/l (2.5-fold higher than TP). In the same study, the authors also quantified the CO_2 eq. emission of the three technologies to be 90,000 kg for TP, 700,000 for PEF and 773,000 kg for HPP.

The above review shows that to date, very few energetic or environmental evaluations on HPP vs. thermal food processing technologies have been performed, while integrated LCC and LCA analyses on the HPP treatment of food products lack almost completely. This paper aims to fill this gap using updated data for the HPP technology.

To this end a comparison of several treatments have been performed, considering real processes applied on the same food substrates. As far as the comparability of the quality and shelf-life of the tested products is concerned, it has to be observed that the aim of this article is to compare possible treatments and packaging solutions generating products, which can be bought by consumers, without analyzing in details the quality or the shelf-life of these products. The choice of orange juice or dry-cured ham has in fact many implications from a social, economic and environmental point of view, being important, particularly in this period, to pay attention to the environmental impact and to the cost of food treated in different ways. Despite this, in the case of juice (e.g. cloudy apple) some authors demonstrated the possibility to compare the quality of the products resulting from the treatments analyzed in this article (Wibowo et al., 2019), as well as the possibility to use HPP on several food substrates (Oey et al., 2008).

3 HPP PROCESS

3.1 SYSTEM DESCRIPTION

The HPP system for Parma ham and orange juice processing is the high pressure *Avure QuintusFoodPress (QFP350L)*[2] (Avure Technologies Inc., US) plant located at HPP-Italia S.r.l. (Parma, Italy). The plant consists of a high-pressure vessel (weighing 46,000 kg) capable of reaching 600 MPa, with a maximum volume of 350 liters; on average, the system can process up to 270 kg of packaged product per cycle. For orange juice (density=1.08 kg/l), this corresponds to approximately 250 liters (i.e. bottles); for whole ham, approximately 27 hams each weighting an average of 10 kg can be processed per cycle.

A processing cycle's loading and unloading operations, and pressurization and depressurization last about 5 min, whilst treatment time can vary from 5 to 7 min. Overall, a processing cycle requires 10-12 minutes.

Regardless of the type of food processed, the treatment cycle involves the following steps:

1. *Load*: food packs are loaded into the perforated barrel;
2. *Closure of the vessel*;
3. *Filling*: the water supply system fills and pressurizes (1-2 bars) the chamber inside the cylinder with water. The temperature can be set to keep the difference between the product and the water temperature as low as possible;
4. *Pressure*: the YH-intensifier pump 7X increases the pressure from 1-2 bars to the value set by the operator;
5. *Processing*: during this phase, the pressure is kept constant for a set time. If the pressure decreases by 1% compared to the target value during the sealing time, the pump increases the pressure to the required level;

[2] http://www.chiefup.com.tw/data/high_pressure/qfp_350l-eu-may-2007.pdf

6. *Decompression*: the decompression valve is opened and the pressure is released through the fluid spill in a tank full of water;
7. *Opening the vessel*.

3.2 COST COMPONENTS

To carry out the LCC analysis, four cost macro-categories were considered, namely initial investment, operating cost, maintenance cost and end-of-life cost. The cost components were either obtained from quotations, estimated on the basis of the and maintenance manual of the HPP plant or derived by applying a specific computational procedure. The cost computation is detailed in the Supplementary material and explained below.

1. *Initial investment*. The initial investment in the HPP technology involves the following:

1.1. *Purchasing cost*. This includes the cost of purchasing the HPP plant and an appropriate building, and connecting it to an energy source. In the case under examination, the building was already available but originally had a different intended use; therefore, the building cost also includes adapting it to its current use. The cost of adapting the building totals €800,000, while the cost for the HPP plant and energy connection totals €1,000,000. This latter component includes the transportation of the plant from Sweden to Parma (HPP-Italy site), its installation and testing;

1.2. *Handling cost*. This component covers the cost of a special machine needed to move the HPP plant within the company building and totals €5,747.50.

2. *Operating cost*. This cost refers to the operation and usage of the HPP plant. The most significant costs are:

2.1. *Lubricant*. The pressure intensifiers need a special lubricant as a process fluid (STRUB - Food Lube 46). Based on its price and the amount required, the cost of this lubricant can be estimated at 5,800 €/year;

2.2. *Energy*. The HPP plant consists of two chillers, a cold room, four engines and one machine. Their average energy consumption was derived from the technical details of the plant and consists of the following components:

- general electric machine consumption: 11.7 kWh per cycle;
- chiller consumption: 27.70 kWh;
- cold room consumption: 21 kWh;
- engines consumption (for high pressure production): 56 kWh.

Taking into account the average duration of a cycle and the work schedule (one 8-hour shift), it is easy to calculate that the plant will carry out approximately 40 cycles/day, i.e. 10,000 cycles/year assuming 250 working days/year. Taking into account the machine consumption and the number of cycles completed in one year, it can be estimated that the machine consumption is 117,000 kWh for a year of functioning. The annual cost of energy consumption can be finally obtained by applying the energy cost (of Italy) of 0.175 €/kWh (GSE, 2010), and stands at 20,475 €/year. The energy consumption of chiller and engines was obtained following the same procedure and totals 55,400 kWh and 112,000 kWh respectively (167,400 kWh overall); the corresponding annual cost totals 29,295 €/year. The cold room works 24 hours/day for 365 days/year; therefore, it consumes 183,960 kWh over one year. The corresponding energy cost totals 32,193 €/year. Overall, the energy cost of the HPP plant totals 81,963 €/year.

2.3. *Water consumption*. The HPP plant requires approx. 61.5 l/cycle of water (≈0.227 l per kg of product processed). To calculate its annual cost, a unitary cost of 2.150107 €/m^3 can be applied (Ireti, 2016); this value reflects the cost of water for industrial use in the Emilia-Romagna region of Italy for a consumption greater than 180 m^3/year.

2.4. *Manpower*. For the plant to function, two operators are required. Their annual cost was estimated to be 70,483.56 €/year according to Italian regulations (Contratto collettivo nazionale del lavoro per i lavoratori dell'industria alimentare, 2015).

2.5. *Safety*. This cost depends on the characteristics of the working environment and on the relating risks. In this study, non-negligible risks include biological (presence of microorganisms) and chemical risks. Conversely, noise and electric risk are negligible. Safety costs cover gloves, masks, safety shoes and work clothes. Safety shoes are mandatory for employees in the food industry and must be changed at least every two years; a pair of costs approximately €60. Gloves cost about €5 per pair; they need to be changed twice a year. The annual cost of work clothes and of caps (about 30 €/year and 7 €/year) was also taken into account in the evaluation.

2.6. *Cleaning and sanitization*. Companies operating in the Italian food industry are requested to comply with Hazard Analysis and Critical Control Point (HACCP) standards, that contain a series of precautionary measures aimed at guaranteeing a minimum level of hygiene and safety for the final customer. This is why professional detergents are used for sanitization. The cost of these detergents, purchased from specialized websites, is approximately 17 €/kg; as two processes are carried out yearly, the total cost totals 34 €/year.

2.7. *Primary packaging*. The primary packaging material and its cost depend on the kind of food processed by the HPP plant, and is detailed below.

2.7.1. *Orange juice*. Orange juice is packaged in PP bottles, whose weight and economic value total 51.5 g and 1.5 €/kg respectively. Taking into account the number of liters processed per cycle, the amount of bottles filled in one year is 2,500,000; the resulting cost is approximately 193,125 €/year.

2.7.2. *Parma ham*. PA-PE 20/70 sealed pouches with vapour permeability≤2.6 g/m^2 (Pingen et al. 2016) are suitable packaging materials for HPP of meat products. For a whole ham, 600x400 mm pouches are required; the approximate weight of this packaging is estimated to be 0.216 kg, taking into account its size and the density of PA and PE (1.35 g/cm^3 and 0.9 g/cm^3, respectively), while its unitary cost totals approximately 0.87 €/kg.

2.8. *Secondary packaging*. This cost component depends on the product treated, and is detailed below.

2.8.1. *Orange juice*. Thirty-five orange juice bottles can be packaged in 600x400x250 mm plastic boxes (weight≈2 kg and unitary cost≈€7.49). Four boxes per layer can be placed on the tertiary packaging. The useful life of these boxes is assumed to be 20 rotations;

2.8.2. *Parma ham*. Disposable corrugated cardboard boxes measuring 600x400x450 mm (weight≈720 g and unitary cost≈€2.92) are used to package 2 whole hams. Again, four boxes per layer can be placed on the tertiary packaging;

2.9. *Tertiary packaging*. Euro-pallets (size 800x1200 mm, weight≈20 kg, unitary cost≈€9.00) are assumed as the tertiary packaging for both products. To obtain suitable weight and height of the stock keeping unit, the allowed number of layers of secondary packaging is 5 for orange juice bottles and 4 for Parma ham. The useful life of a pallet is assumed to be 20 rotations (Niero et al. 2014);

2.10. *Other costs*. Insurance and other annual fees are due in order for the plant to function. These amount to 1,300 €/year and 12,000 €/year respectively.

3. *Maintenance costs*. Maintenance activities consist of the following components:

3.1. *Preventive maintenance*. Periodical maintenance activities need to be carried out on the HPP plant. Their frequency is either determined by a cycle counter or by set time intervals, and is detailed in the machine use and maintenance manual. The following maintenance interventions were identified from the analysis of the manual.

- The following components should be replaced every 4,000 production cycles (i.e. approximately twice a year):
    - Radial seals for the right and left closure, totaling 4 spare parts (two per closure) and costing 154 €;
    - Box seals for the right and left closures, totaling 4 pieces (two per each closure) and costing 182 €.

The cost for the two interventions totals €336, resulting in an annual cost of 672 €/year.

- The following components should be replaced every 8,000 production cycles (i.e. approximately once a year):
    - Support rings for the right and left closures, totaling 4 pieces (two per closure) and costing is €4,732 (€2,366 per pair of rings);
    - Components subject to wear in the pump multipliers, costing €9,113.

The total cost of these interventions is 13,845 €/year.

- Every 16,000 production cycles (i.e. approximately once every two years), the high pressure equipment and its gaskets need to be replaced. This costs €23,894 and €134 respectively, resulting in a total cost of €24,028;
- Every 36,000 production cycles (i.e. approximately once every 4 years), two components need to be replaced, generating a total cost of €619. These components are:
    - Glyd ring (a type of O-Ring), costing €20 (€10 per closure) and €6 (€3 per manipulator left/right), for a total of €26;
    - Valve body, costing €593.

3.2. *Scheduled maintenance*. Scheduled maintenance activities are typically planned on the basis of statistical analyses on the expected life of the machine components. The components most subject to wear and friction are replaced at regular intervals. When the plant is purchased, it includes a sufficient number of spare parts to cover scheduled maintenance activities in the first two years of use. After that, scheduled maintenance requires spare parts to be purchased and generates a cost of 31,500.00 €/year taking into account the number of production cycles per year.

3.3. *Reactive maintenance*. Maintenance operators typically spend part of their time disassembling worn parts and replacing them with spare parts in the event of unexpected damage or failure. Since reactive maintenance activities are a consequence of emergency situations, they may need to be carried out when working overtime, at the weekend or during holidays, involving an extra cost of employees. The intervention of a specialist employee, costing approximately 170 €/h, may also sometimes be necessary. As reactive maintenance activities are difficult to predict, a lump sum of 5,000 €/year is estimated to be their total cost.

4. *End-of-life cost*. At the end of their useful life or after a given lifetime, the plant and its components or materials can be sold, generating a profit; the following cost component has therefore been considered in the evaluation:

4.1. *Residual value*. To evaluate the residual value of the HPP plant, quotations were requested in September 2016 to estimate the economic value of the key metallic components making up the HPP machine. The machine is made almost entirely of 304 stainless steel, which has an economic value of 0.70 €/kg, and its total weight is approximately 46,000 kg. The external parts of the plant, again made from steel, have a total weight of approximately 9,960 kg. Overall, the residual value of the plant totals approximately €39,172.

4 HPP VS. TP: ORANGE JUICE

This section compares HPP and TP for orange juice processing. The TP treatment, its main cost components and its environmental impact are detailed in the following subsection.

4.1 THERMAL PASTEURISATION OF ORANGE JUICE

4.1.1 System description

TP is a heat treatment capable of destroying pathogenic forms of microorganisms present in food. The percentage of bacteria removed is proportional (according to the two laws of Bigelow) to the temperature and duration of the product treatment. These depend on the food being processed and on its contamination level; orange juice processing usually occurs at 95°C for 15s (Manfredi & Vignali, 2015). These settings preserve the product's characteristics more effectively than traditional pasteurization at 75-85°C with a longer treatment time. Pasteurization alters the quality of the original product; however, the product can be preserved for a long time. Two different approaches can be used to pasteurize food products, i.e. indirect thermal treatment to the product prior to packaging or thermal treatment of the packaged product ("retort" process).

The indirect thermal treatment of the product needs a hygienic filling phase, which can be obtained by keeping the product at high (≈80°C) temperature or ensuring aseptic conditions (Manfredi & Vignali 2015). Hence, to compare this technology with HPP or with retort TP, the energy and fluids consumption in the filling phase has to be taken into account. An exhaustive description of this system can be found in Manfredi & Vignali (2015) for a plant processing of 36,000 bottles (0.5l of volume) per hour. To make the comparison with the HPP system effective, specific data of a system with more similar (smaller) capacity was retrieved from TP plant manufacturers (e.g. Easy Term Adue S.p.A.[3] or Prismatech[4]).

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[3] https://www.adue.it/oursolutions/beverage-thermal-treatment/#1469543564325-fa9bc465-7857

[4] https://www.prismatech.it/prodotti/pastorizzatore-sterilizzatore-omo-dar/

The retort process, which is more similar to HPP, involves three main phases: product heating, temperature holding and rapid cooling. The first phase makes use of a heating medium to ensure rapid heat transmission to the product. In the second phase, the product is held at a constant temperature for a set period. The third phase involves cooling the product rapidly using well-water as a medium (Mosna & Vignali, 2015). The packaged product is processed for approximately 35 min at 90°C, to ensure the core of the packaged product is also treated, which is the most difficult point to heat.

Key retort process data for a TP plant was taken from Pardo & Zufía (2012), with some adaptations for the manufacturing stage and preservation treatment. Further sources of data were quotations, specialist and professional websites or technical documents, such as datasheets or use and maintenance manuals, provided by TP plant manufacturers (e.g. JBT Technologies, Parma, Italy).

4.1.2 Cost components for TP-indirect with energy recovery

As for the HPP technology, four cost macro-categories were considered in the LCC analysis, as explained below.

1. *Initial investment*. The initial investment for a TP-indirect with energy recovery plant totals approximately €100,000. The transport/handling cost totals approximately €1000, considering the equipment weight (5000 kg) and the limited distance between the manufacturer and the user.
2. *Operating cost*. The operating cost of the TP plant includes the following costs:
   - 2.1. *Energy*. The annual cost of electric energy can be calculated taking into account the energy consumption of the plant, the unitary cost of electricity for industry and the work schedule. One 8-hour shift and 180 working days per year were assumed to make a meaningful comparison with the HPP technology (see point 2.3);
   - 2.2. *Steam generation*. Steam for orange juice processing is generated by boilers, which are fed with cold water heated by gas fuel (methane). The amount of steam required to process a kg of finished product is 0.337 kg, equivalent to 0.248 kWh. Taking into account the number of production cycles per year, the industrial cost of methane in Italy (0.2516 €/m^3 from Autorità di Regolazione per Energia Reti e Ambiente, 2018), the thermal production of methane (i.e. approximately 9.7 kWh/m^3) and an appropriate efficiency of the conversion process, the cost of steam generation was estimated to be around 16,342.14 €/year;
   - 2.3. *Water consumption*. Processing 1 kg of product with TP requires 0.353 kg of water. Considering the capacity of the pasteurizer (1800 l/h) it is easy calculate that the system processes approximately 2,799,360 kg of product per year (which is similar to the HPP process); water consumption therefore totals 986.94 m^3/year.
   - 2.4. *Manpower*. The annual cost of the two employees required is the same as that of the HPP plant.

2.5. *Safety*. Employees working on the TP plant are required to wear appropriate work clothes and safety shoes. The unitary cost of the safety equipment was taken from specialist websites selling safety equipment[5]; the annual cost can vary over time, because the different safety equipment needs to be replaced at different intervals;

2.6. *Cleaning and sanitization*. A yearly cost of €400 has been estimated for cleaning and sanitization. This cost takes into account the need for a cleaning the tubular system after each production shift (8 h) using sodium dichloride at 33% (Manfredi & Vignali 2015);

2.7. *Primary packaging*. The TP-indirect process coupled with hot filling typically requires orange juice to be packaged in PET bottles (weight≈30 g). A unitary cost of 1.2 €/kg was assumed for PET. Taking into account the capacity and the product density, it is easy to derive that the TP plant processes 2,592,000 l/year of orange juice, resulting in a packaging cost of 93,312 €/year;

2.8. *Secondary packaging*. The secondary packaging for TP is a cardboard box (weight≈220 g, size 330x250x263 mm) containing 12 bottles. Nine boxes per layer and 6 layer in height can be placed on the tertiary packaging to obtain a suitable stock keeping unit;

2.9. *Tertiary packaging*. The tertiary packaging for TP is the same as that used for HPP and will include 648 bottles of orange juice.

3. *Maintenance cost*.

3.1. *Preventive maintenance*. The cost of preventive maintenance activities of a typical TP plant was estimated to be 9,000 €/year from the analysis of the machine use and maintenance manual;

3.2. *Reactive maintenance*. A lump sum of 3,000 €/year, including the cost of components to be replaced and a maintenance technician, was assumed as the cost of reactive maintenance.

4. *End-of-life cost*.

4.1. *Residual value*. As for the HPP plant, the residual value of the TP plant was estimated on the basis of the amount of materials and components that can be disassembled and sold, generating a profit. The residual value of the TP plant was calculated using the same quotation applied to the HPP plant and totals € 3,500.

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[5] E.g. https://shop.tecnafood.com/business_it/antinfortunistica/scarpe-antinfortunistiche-bianche-da-lavoro-professionali/scarpe-antinfortunistiche-bianche-professionali.html

4.1.3 Cost components for TP-retort

The cost components for the four macro-categories considered in the LCC analysis are detailed below. Again, the characteristics of the TP-retort system were chosen to make it comparable with the HPP and TP indirect systems.

1. *Initial investment*. The initial investment for this TP plant totals approximately €55,000. The transport/handling cost totals approximately €600, because the distance between the manufacturer and the user of the plant is relatively short.
2. *Operating cost*. The operating cost of the TP-retort plant includes the following costs:
   - 2.1. *Energy*. The annual cost of electric energy can be calculated taking into account the energy consumption of the plant, the unitary cost of electricity for industry (0.175 €/kWh) and the work schedule. One 8-hour shift and 220 working days per year were assumed to make a meaningful comparison with the HPP technology (see point 2.3). Considering a consumption of 0.0120 kWh/kg of product during the treatment and 0.0266 kWh/kg for the cooling process, an overall cost of €17,833.20 per year has been obtained;
   - 2.2. *Steam generation*. The amount of steam required to process 1 kg of finished product is 1.05 kg, equivalent to 0.7 kWh. Applying the same computational procedure described for TP-indirect, the cost of steam generation was estimated to be around 47,933.69 €/year;
   - 2.3. *Water consumption*. Cooling 1 kg of product with TP requires 3.1 kg of water. The capacity of the pasteurizer is 1,000 kg/cycle and 12 production cycles are typically carried out per day (considering 40 min of treatment at 90°C, according to Pardo & Zufia, 2012), obtaining approximately 12,000 kg/day of product. Combining this data, it is easy calculate that the system processes approximately 2,640,000 kg of product per year (which is similar to the HPP process); water consumption therefore totals 8,148 m^3;
   - 2.4. *Manpower*. The annual cost of the two employees required is the same as that of the HPP plant;
   - 2.5. *Safety*. The safety cost is assumed to be the same as that of the TP-indirect process;
   - 2.6. *Cleaning and sanitization*. This cost is the same as that of the HPP plant, as the sanitization procedure does not vary;
   - 2.7. *Primary packaging*. The TP-retort process makes use of the same packaging as the HPP for orange juice. From the capacity of the pasteurizer and the product density, it can be calculated that the TP plant processes 2,442,000 l/year of orange juice, resulting in a packaging cost of 188,644.50 €/year;
   - 2.8. *Secondary packaging*. The secondary packaging for TP-retort is the same as that used for HPP;
   - 2.9. *Tertiary packaging*. The tertiary packaging for TP-retort is the same as that used for HPP.

3. *Maintenance cost*.
   3.1. *Preventive maintenance*. The cost of preventive maintenance is the same as that of the TP-indirect process, because of obvious analogies;
   3.2. *Reactive maintenance*. The cost of reactive maintenance is the same as that of the TP-indirect process, because of obvious analogies.
4. *End-of-life cost*.
   4.1. *Residual value*. The residual value of this plant, estimated on the basis of the amount of materials and components that can be disassembled and sold, totals € 4,312.

4.2 LCC ANALYSIS

The LCC analysis of HPP and TP for orange juice production was carried out assuming a 20-year lifecycle ($t = 1,...20$), reflecting the number of years after which the HPP cylinder needs replacing (approximately 200,000 production cycles). The LCC of both systems was computed as follows (Dhillon 2010):

$$LCC = initial\ investment + PV_{operating\ cost} + PV_{maintenance\ cost} - PV_{residual\ value}\ [€] \quad (1)$$

where the present value (PV) of the different cost components is computed according to the following formulae:

$$PV_{operating\ cost} = \sum_{t=1}^{20} \frac{operating\ cost(t)}{(1+\mathrm{r})^t} \quad [€] \quad (2)$$

$$PV_{maintenance\ cost} = \sum_{t=1}^{20} \frac{maintenance\ cost(t)}{(1+\mathrm{r})^t} \quad [€] \quad (3)$$

$$PV_{residual\ value} = \sum_{t=1}^{20} \frac{residual\ value(t)}{(1+\mathrm{r})^t} \quad [€] \quad (4)$$

An interest rate $r = 0.0096$ (European Commission, 2008) was assumed in the computation. The unitary cost of processing each kg of product was also computed to compare the different technologies.

4.2.1 LCC results for HPP

The LCC of the HPP system was computed applying eqs.1-4 to the data provided in section 3.2 and scores:

$$LCC_{HPP} = initial\ investment_{HPP} + PV_{operating\ cost,HPP} + PV_{maintenance\ cost,HPP} - PV_{residual\ value,HPP} = € \ 1,805,747.50 + \ € \ 7,146,968.19 \ + € \ 1,083,803.05 - \ € \ 32,358.54 = \ € \ 10,004,160.20$$

The initial investment in the HPP plant represents 17.99% of the LCC of the HPP equipment over the lifetime considered. The highest quota of the LCC is the operational cost, which accounts for 71.21%; in turn, this cost is primarily due to the primary packaging material required for processing orange juice, which accounts for 48.96% of the operating costs (Figure 1). Energy consumption (20.78%) and the salaries of the employees (17.87%) are further non-negligible contributions to the total operating cost. As far as maintenance is concerned (Figure 2), the highest quota in the LCC is the scheduled maintenance (47.22%), although preventive maintenance is also significant (44.45%). Reactive maintenance is considerably lower (8.33%).

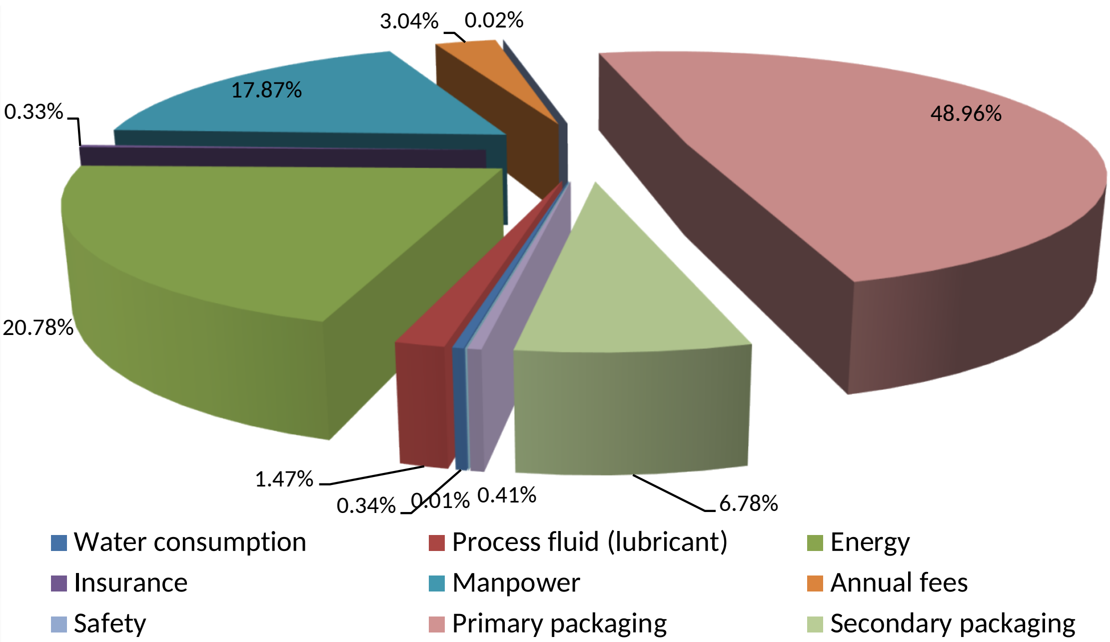

Figure 1: details of the operating costs of HPP for orange juice processing.

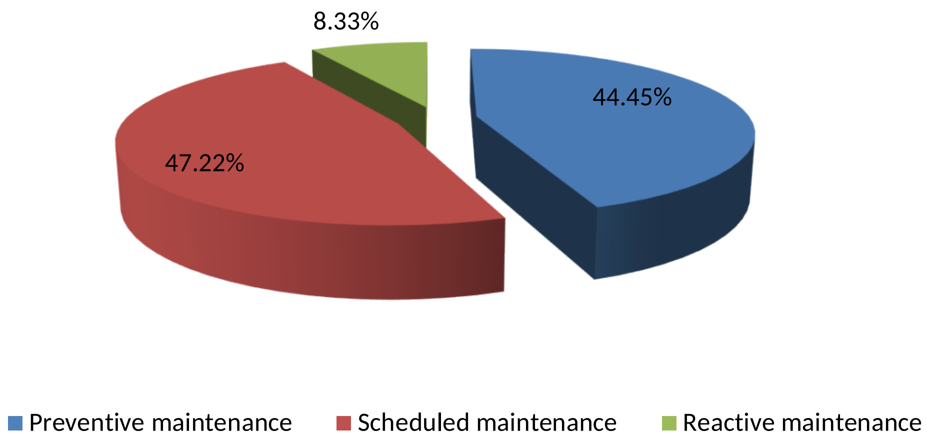

Figure 2: details of the maintenance costs of HPP for orange juice processing.

The HPP plant processes 270 kg of orange juice per cycle, as previously mentioned, resulting in 2,700,000 kg of product processed per year and 54,000,000 kg in the lifetime. The unitary cost of the product manufactured thus accounts for 18.53 c€/kg.

4.2.2 LCC results for TP–indirect with energy recovery

The LCC of the indirect TP processing system, computed applying eqs.1-4 to the data provided in section 4.1.2, accounts for:

$$LCC_{indirect} = initial\ investment_{indirect} + PV_{operating\ cost,indirect} + PV_{maintenance\ cost,indirect} - PV_{residual\ value,indirect} = € 101{,}000 + € 5{,}493{,}737.67 + € 211{,}941.31 - € 2{,}891.22 = € 5{,}803{,}787.76$$

An analysis of the cost components highlights that the initial investment forms a minimal part (1.74%) of the LCC of the system, while most of the LCC is due to the operating costs (94.61%). In turn, primary packaging (30.77%), manpower (23.25%) and secondary packaging (21.37%) contributes to the operating costs to the greatest extent (Figure 3).

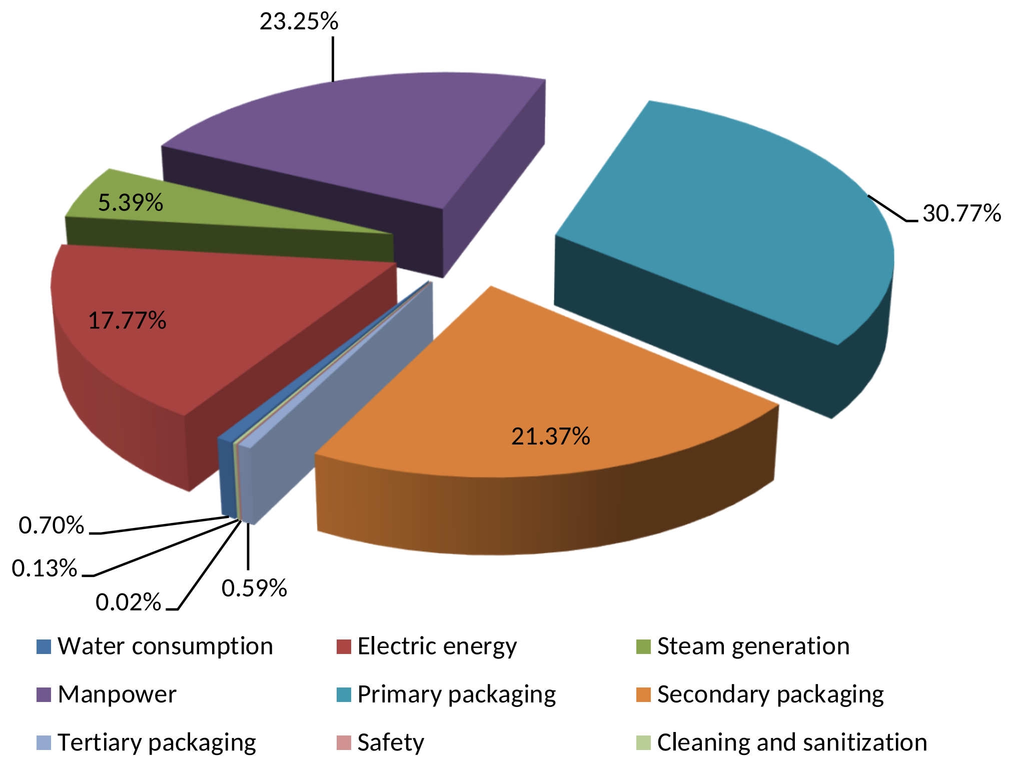

Figure 3: details of the operating cost of indirect TP for orange juice processing.

The system processes approximately 2,799,360 kg/year of orange juice, i.e. 55,987,200 in the whole lifecycle. The unitary cost of the product processed thus totals 10.37 c€/kg.

4.2.3 LCC results for TP-retort

The LCC of the TP retort system, computed applying eqs.1-4 to the data provided in section 4.1.3, accounts for:

$$LCC_{retort} = initial\ investment_{retort} + PV_{operating\ cost,retort} + PV_{maintenance\ cost,retort} - PV_{residual\ value,retort} = € 55{,}600 + € 6{,}709{,}224.54 + € 211{,}941.31 - € 3{,}561.98 = € 6{,}973{,}203.87$$

Again, the contribution of the initial investment to the LCC is almost negligible (0.80%), while the operating cost represents the highest share of the LCC of the system (96.17%). The operating cost is largely determined by primary packaging cost (50.94%), manpower cost (19.03%) and the cost for steam generation (12.94%), which represent more than 80% of the LCC of this technology (Figure 4).

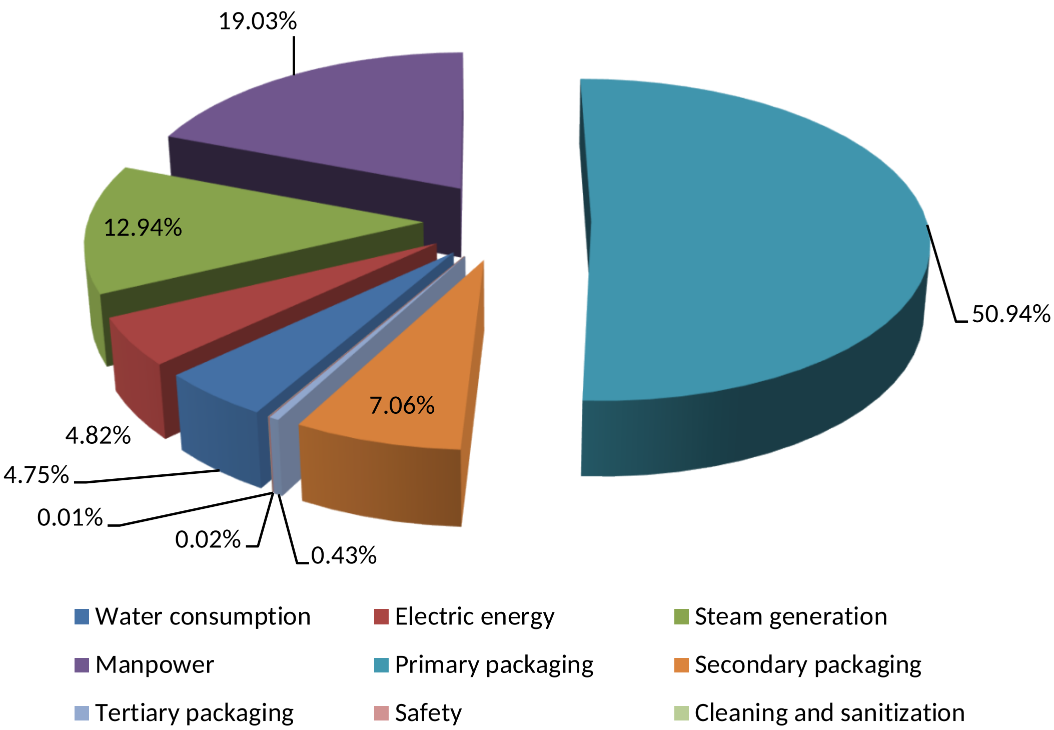

Figure 4: details of the operating cost of TP retort for orange juice processing.

The TP plant processes approximately 2,640,000 kg/year of orange juice, i.e. 52,800,000 in the whole lifecycle. The unitary cost of the product processed thus totals 13.21 c€/kg.

4.2.4 Comparative LCC results

A detailed comparison of the LCC of the HPP and TP systems is provided in Table 1 and shows that the HPP system exhibit the highest values in all cost macro-categories. The greatest difference can be observed in the initial investment, which is significantly higher for HPP than for TP-retort (more than 30 times higher) and TP-indirect (more than 17 times higher). The operating costs of the three technologies are comparable, although the HPP is slightly more expensive. The maintenance cost is approximately 5 times higher for the HPP than for the TP. The residual value is also higher for HPP, but this does not compensate for the remaining cost components. In terms of unitary cost, the HPP processing of orange juice costs 1.78 times the TP-indirect treatment and 1.40 times the TP-retort treatment.

	HPP		TP-indirect		TP-retort	
Cost macro-categories	**Total cost [€]**	**Unitary cost [€/kg]**	**Total cost [€]**	**Unitary cost [€/kg]**	**Total cost [€]**	**Unitary cost [€/kg]**
Initial investment	1,805,747.50	0.0334	101,000.00	0.0018	55,600.00	0.0011
$PV_{operating\ cost}$	7,146,968.19	0.1324	5,493,737.67	0.0981	6,709,224.54	0.1271
$PV_{maintenance\ cost}$	1,083,803.05	0.0201	211,941.31	0.0038	211,941.31	0.0040
$PV_{residual\ value}$	32,358.54	0.0006	2,891.22	0.0001	3,561.98	0.0001
LCC	10,004,160.20	0.1853	5,803,787.76	0.1037	6,973,203.87	0.1321

Table 1: Comparison of the LCC results for HPP, TP-indirect and TP-retort.

4.3 LCA ANALYSIS

4.3.1 Goal and scope definition

According to ISO 14040 and ISO 14044, this section defines the objectives of the analysis, the functional unit, the system boundaries and the assumptions made.

In food processing studies, the functional unit is typically defined in terms of system function, quantity, and duration of the product, taking into account real life conditions. In comparative assessments, it is important to verify that alternative packaging types fulfill the same function (Life cycle initiative, 2013). In the case under examination, the goal of the LCA analysis is to assess the environmental impact of different food treatments for the specific case of fruit juice processing. Although the primary packaging is not same for all treatments, the amount of product contained is the same. Also, the intended function of the finished product is similar too. The duration (shelf-life) of the finished product obtained using the different treatments is not directly evaluated in this study, which means that it is implicitly assumed to be the same across the various technologies. This assumption, although not verified in this study, is supported by the available literature (e.g. Aaby et al. 2018). On the basis of these considerations, the functional unit chosen for the LCA is 1 kg of finished pasteurized juice, bottled and ready for distribution.

As far as the system boundaries are concerned, a gate-to-gate approach was chosen, meaning that only the phases relating to the orange juice treatment are considered. The system boundaries are shown in Figure 6.

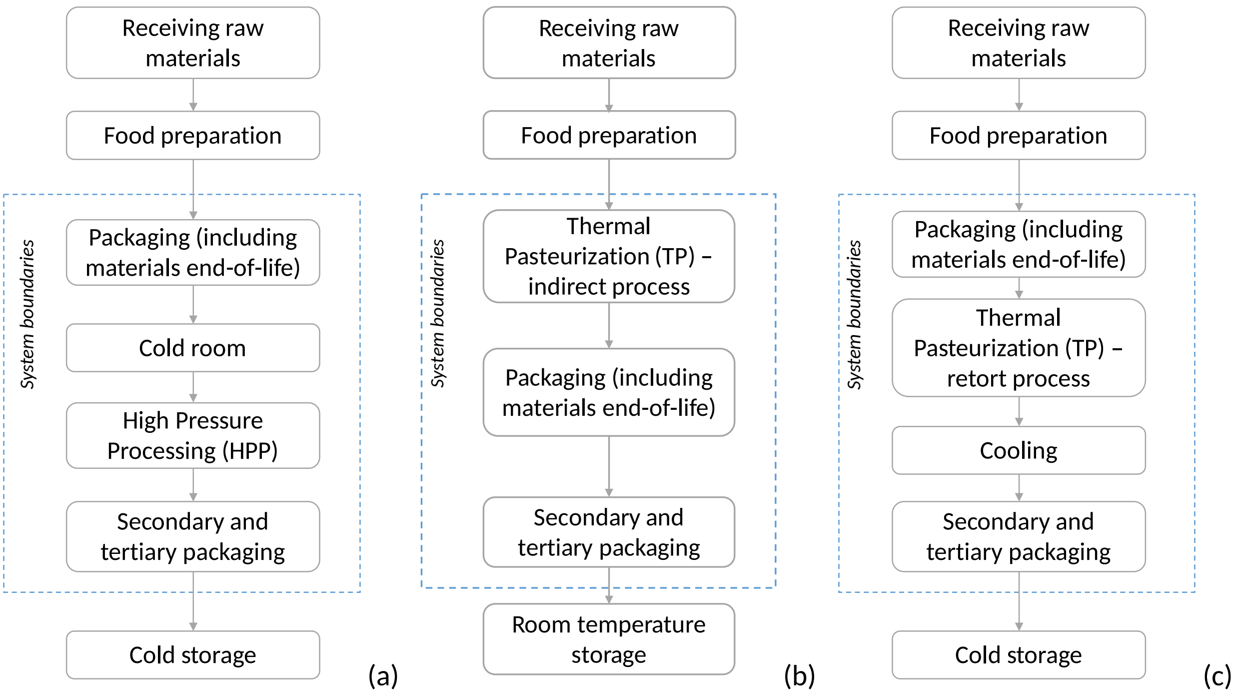

Figure 5: system boundaries for HPP (a), TP-indirect (b) and TP-retort (c) for orange juice processing.

4.3.2 Inventory analysis

Both primary and secondary data were used in this phase. Primary data was collected from HPP Italia S.r.l., a food manufacturing company that employs HPP, while TP data was taken by primary data or adapted from Pardo & Zufia (2012) for the TP-retort process; further secondary data was retrieved from the Ecoinvent 3.4 database and from other databases available in SimaPro 8.5.2 software, as well as from scientific literature. Table 3-Table 2 show the inventory data relating to the main phases of the TP and HPP processes. End-of-life data for the packaging assessment has been taken by Italian consortia (Corepla, 2018), considering the Italian percentage of recycling, energy recovery and landfilling.

Table 2: Inventory data for HPP.

Lifecycle stage	Input	Unit of measurement	Numerical value	Source	Dataset for impact assessment
Plant manufacturing	Steel for food industry machinery	kg	0.000852	Primary data	Steel, unalloyed {GLO} | market for| APOS, U
	Steel for the cooling system	kg	0.000184	Primary data	Steel, unalloyed {GLO} | market for| APOS, U
Preservation treatment	Electricity	Wh	173.5	Primary data	Electricity, medium voltage {IT} | market for | APOS, U
	Process water	kg	0.228	Primary data	Tap water {RoW} | market group for | APOS, U
	Compressed air	l	0.74	Primary data	Compressed air, 600 kPa gauge {RER}| compressed air production, 600 kPa gauge, >30 kW average generation| APOS, U
	Lubricant	g	0.133	Primary data	Lubricating oil {GLO} | market for | APOS, U
Primary packaging	PP bottle	kg	0.0477	Adapted from Pardo & Zufia (2012)	Polypropylene, granulate {RER} | production | APOS, U Blow moulding {RER}| production | APOS, U
Secondary packaging	Plastic boxes	kg	0.0026	Primary data	Polyethylene, high density, granulate {GLO}| market for | APOS, U
Tertiary packaging	Euro-pallet	amount	(1/756)/20	Primary data	EUR-flat pallet {GLO} | market for | APOS, U

Table 3: Inventory data for TP–indirect with energy recovery

Lifecycle stage	Input	Unit of measurement	Numerical value	Source	Dataset for impact assessment
Plant manufacturing	Steel for food industry machinery	kg	0.000089	Primary data	Steel, unalloyed {GLO} | market for| APOS, U
Preservation treatment	Electricity	Wh	110	Primary data	Electricity, medium voltage {IT} | market for | APOS, U
	Steam	kg	0.3376	Primary data	Steam, in chemical industry {GLO}|market for| APOS, U
	Compressed air	l	1.82	Primary data	Compressed air, 600 kPa gauge {RER}| compressed air production, 600 kPa gauge, >30 kW average generation| APOS, U
	Process water	kg	3.1	Primary data	Tap water {RoW} | market group for | APOS, U

Primary packaging	PET bottle	kg	0.028	Primary data	PET, granulate {RER} | production | APOS, U Blow moulding {RER}| production | APOS, U
Secondary packaging	Cardboard boxes	kg	0.0170	Primary data	Corrugated board box {GLO} | market for corrugated board box | APOS, U
Tertiary packaging	Euro-pallet	amount	(1/699.84)/20	Primary data	EUR-flat pallet {GLO} | market for | APOS, U

Table 4: Inventory data for TP-retort.

Lifecycle stage	**Input**	**Unit of measurement**	**Numerical value**	**Source**	**Dataset for impact assessment**
Plant manufacturing	Steel for food industry machinery	kg	0.000116	Adapted from Pardo & Zufia (2012)	Steel, unalloyed {GLO} | market for| APOS, U
Preservation treatment	Electricity	Wh	12	Primary data	Electricity, medium voltage {IT} | market for | APOS, U
	Steam	kg	1.05	Pardo & Zufia (2012)	Steam, in chemical industry {GLO}|market for| APOS, U
	Compressed air	l	1.82	Primary data	Compressed air, 600 kPa gauge {RER}| compressed air production, 600 kPa gauge, >30 kW average generation| APOS, U
Cooling process	Electricity	Wh	26.6	Pardo & Zufia (2012)	Electricity, medium voltage {IT} | market for | APOS, U
	Process water	kg	3.1	Pardo & Zufia (2012)	Tap water {RER} | market group for| APOS, U
Primary packaging	PP bottle	kg	0.0477	Adapted from Pardo & Zufia (2012)	Polypropylene, granulate {RER} | production | APOS, U Blow moulding {RER}| production | APOS, U
Secondary packaging	Plastic boxes	kg	0.0026	Primary data	Polyethylene, high density, granulate {GLO}| market for | APOS, U
Tertiary packaging	Euro-pallet	amount	(1/756)/20	Primary data	EUR-flat pallet {GLO} | market for | APOS, U

4.3.3 Method of impact assessment

The ReCiPe Midpoint (H) LCA impact assessment method was selected from those available in SimaPro 8.5.2 for this study. For the characterization phase, the data collected was classified into several categories based on its potential impact on the environment (ISO 14040, 2006). Characterization is intended to quantify the potential contribution of an input or output to each specific impact.

Impact values were calculated for 18 impact categories, namely: (i) Global warming, (ii) stratospheric ozone depletion, (iii) ionizing radiation, (iv) ozone formation, human health, (v) fine particulate matter formation, (vi) ozone formation, terrestrial ecosystems, (vii) terrestrial acidification, (viii) freshwater eutrophication, (ix) marine eutrophication, (x) terrestrial ecotoxicity , (xi) freshwater ecotoxicity, (xii) marine ecotoxicity, (xiii) human carcinogenic toxicity, (xiv) human non-carcinogenic toxicity, (xv) land use, (xvi) mineral resource scarcity, (xvii) fossil resource scarcity; (xviii) water consumption.

4.3.4 Life Cycle Impact Assessment (LCIA)

The first analyses performed refer to the three conservation treatments taken singly. Result for the indirect TP process are shown in Table 5 **Error! Reference source not found.**and Figure 6.

Table 5: Numerical values of the environmental impacts for each impact category for TP-indirect.

Impact category	Unit of measurement	Total	Manufacturing stage	Preservation treatment	Primary packaging	Secondary/tertiary packaging
Global warming	kg CO2 eq	3.03E-01	9.98E-05	1.60E-01	1.19E-01	2.34E-02
Stratospheric ozone depletion	kg CFC11 eq	1.21E-07	1.63E-11	5.65E-08	4.11E-08	2.30E-08
Ionizing radiation	kBq Co-60 eq	2.76E-02	1.42E-06	9.68E-03	1.59E-02	2.05E-03
Ozone formation, Human health	kg NOx eq	4.46E-04	1.95E-07	2.12E-04	1.83E-04	5.02E-05
Fine particulate matter formation	kg PM2.5 eq	3.41E-04	1.58E-07	1.70E-04	1.41E-04	2.99E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	4.57E-04	2.07E-07	2.16E-04	1.90E-04	5.10E-05
Terrestrial acidification	kg SO2 eq	8.76E-04	2.72E-07	4.86E-04	3.26E-04	6.40E-05
Freshwater eutrophication	kg P eq	8.10E-05	3.40E-08	2.67E-05	4.41E-05	1.02E-05
Marine eutrophication	kg N eq	1.26E-05	1.51E-09	2.24E-06	5.82E-06	4.49E-06
Terrestrial ecotoxicity	kg 1,4-DCB	7.00E-01	1.78E-04	3.43E-01	2.84E-01	7.24E-02
Freshwater ecotoxicity	kg 1,4-DCB	6.95E-03	1.47E-06	1.62E-03	4.27E-03	1.05E-03
Marine ecotoxicity	kg 1,4-DCB	9.89E-03	2.09E-06	2.35E-03	6.06E-03	1.48E-03
Human carcinogenic toxicity	kg 1,4-DCB	7.36E-03	1.29E-05	2.36E-03	4.20E-03	7.90E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	1.39E-01	3.83E-05	3.48E-02	7.97E-02	2.46E-02
Land use	m2a crop eq	1.98E-02	1.07E-06	2.30E-03	7.32E-03	1.02E-02
Mineral resource scarcity	kg Cu eq	3.37E-04	3.30E-06	6.83E-05	1.92E-04	7.37E-05
Fossil resource scarcity	kg oil eq	8.74E-02	1.61E-05	4.57E-02	3.70E-02	4.65E-03
Water consumption	m3	2.79E-03	5.88E-07	1.40E-03	1.22E-03	1.66E-04

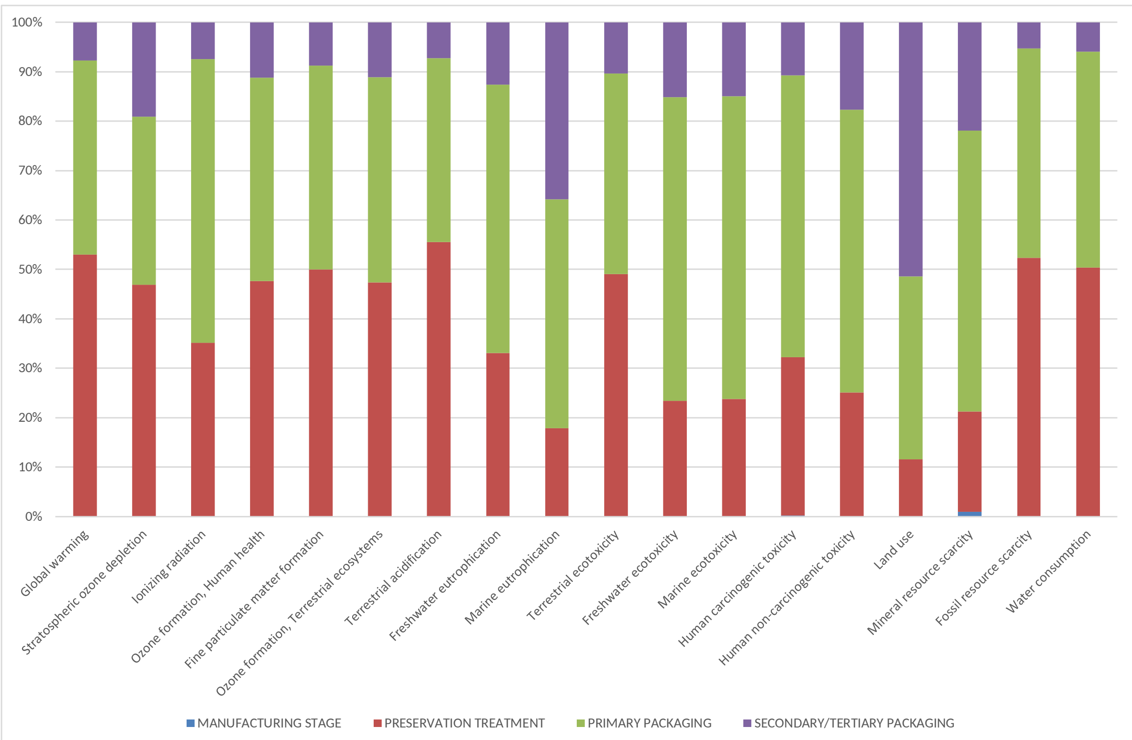

Figure 6: relative impacts of 1 kg of orange juice for TP-indirect.

As can be seen in Table 5**Error! Reference source not found.** and Figure 6, the indirect TP process shows a positive impact for all categories. The highest impact is made by the primary packaging, which has an average value of 47.22%. The highest contributions are in marine ecotoxicity and freshwater ecotoxicity impact categories and are due to the process of bottle molding. The impacts of the packaging are obviously influenced by the end-of-life considerations. Recycling and energy recovery positively influence the overall impacts, mainly due to the energy recovered from the PET bottles. The second most relevant contribution comes from the preservation treatment, whose average impact accounts for 37.44%, due to the values of energy/steam needed for heating the product. The energy recovery module contributes to have a low impact of the preservation treatment in all the impact categories.

In general, the secondary/tertiary packaging influences the impacts by 15.25% on average and reaches a maximum of 51.4% in land use, because of the raw material used to manufacture pallets and cardboard boxes.

Lastly, the impact generated by the manufacturing stage is very low, accounting for less than 0.1% on average and reaching a maximum value of approximately 1% in mineral resource scarcity.

Results for the TP-retort process are proposed in in Table 6 and Figure 7.

Table 6: Numerical values of the environmental impacts for each impact category for TP-retort.

Impact category	Unit of measurement	Total	Manufacturing stage	Preservation treatment	Cooling process	Primary packaging	Secondary/tertiary packaging
Global warming	kg CO2 eq	5.32E-01	3.87E-04	3.46E-01	1.30E-02	1.65E-01	8.13E-03
Stratospheric ozone depletion	kg CFC11 eq	1.15E-07	6.31E-11	7.32E-08	8.55E-09	2.88E-08	3.94E-09
Ionizing radiation	kBq Co-60 eq	2.80E-02	5.52E-06	5.72E-03	2.27E-03	1.99E-02	1.10E-04
Ozone formation, Human health	kg NOx eq	6.70E-04	7.58E-07	4.07E-04	2.18E-05	2.25E-04	1.51E-05
Fine particulate matter formation	kg PM2.5 eq	4.91E-04	6.12E-07	3.21E-04	1.77E-05	1.45E-04	6.38E-06
Ozone formation, Terrestrial ecosystems	kg NOx eq	6.94E-04	8.02E-07	4.17E-04	2.21E-05	2.38E-04	1.60E-05
Terrestrial acidification	kg SO2 eq	1.33E-03	1.06E-06	8.91E-04	5.26E-05	3.66E-04	1.54E-05
Freshwater eutrophication	kg P eq	8.98E-05	1.32E-07	3.94E-05	4.08E-06	4.54E-05	7.34E-07
Marine eutrophication	kg N eq	7.55E-06	5.87E-09	2.74E-06	3.85E-07	4.27E-06	1.53E-07
Terrestrial ecotoxicity	kg 1,4-DCB	1.18E+00	6.91E-04	9.30E-01	1.32E-02	2.22E-01	1.62E-02
Freshwater ecotoxicity	kg 1,4-DCB	8.87E-03	5.70E-06	1.75E-03	2.87E-04	6.45E-03	3.80E-04
Marine ecotoxicity	kg 1,4-DCB	1.30E-02	8.11E-06	2.94E-03	3.83E-04	9.12E-03	5.42E-04
Human carcinogenic toxicity	kg 1,4-DCB	8.63E-03	5.02E-05	3.74E-03	6.14E-04	4.04E-03	1.86E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	1.47E-01	1.49E-04	5.11E-02	5.26E-03	8.52E-02	4.87E-03
Land use	m2a crop eq	1.49E-02	4.15E-06	1.95E-03	4.49E-04	1.01E-02	2.44E-03
Mineral resource scarcity	kg Cu eq	2.04E-04	1.28E-05	8.38E-05	2.08E-05	8.10E-05	5.97E-06
Fossil resource scarcity	kg oil eq	1.64E-01	6.23E-05	1.01E-01	3.45E-03	5.64E-02	2.77E-03
Water consumption	m3	5.13E-03	2.28E-06	4.73E-04	3.34E-03	1.29E-03	2.29E-05

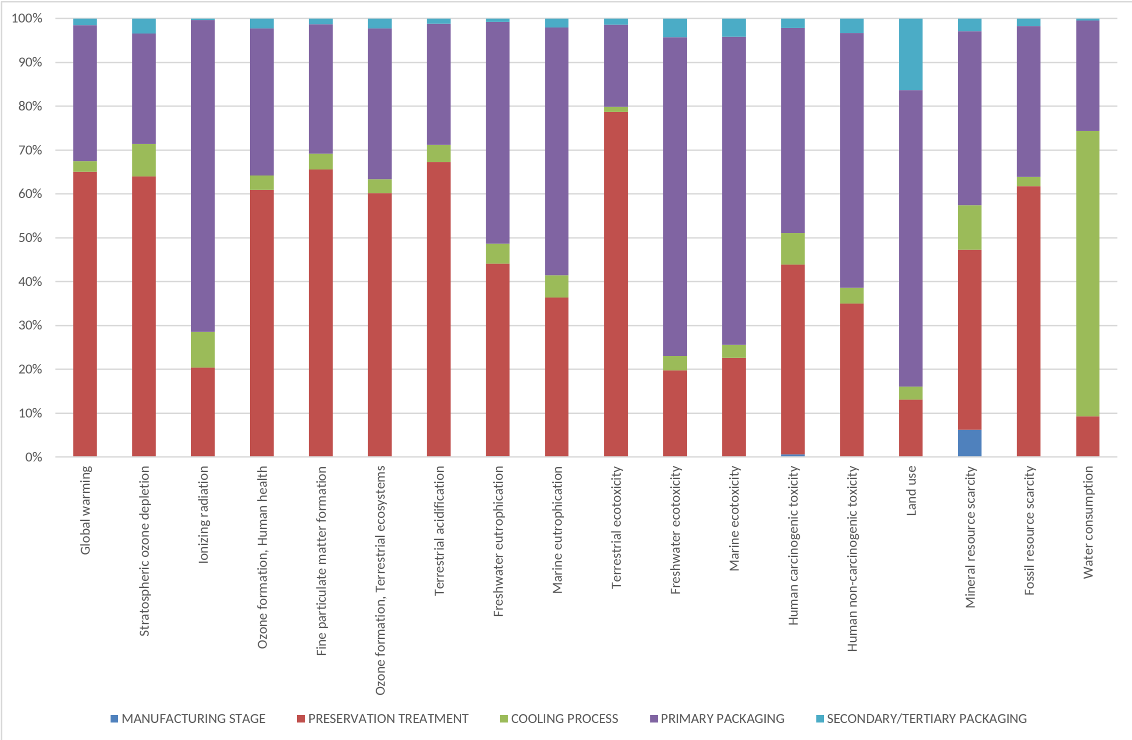

Figure 7: relative impacts of 1 kg of orange juice for TP-retort.

As can be seen in Table 6 and Figure 7, the TP-retort process shows a positive impact for all categories. The highest impact comes from the preservation treatment, whose average contribution to the impact categories is 44.85%, due to the higher values of energy/steam needed for heating the product compared to the TP-indirect process. Because heat and electricity production often involves hydrocarbon combustion processes, this phase also generates most of the atmospheric emissions affecting climate change, fine particulate matter formation and many other impact categories according to Figure 7.

The second most relevant contribution is made by the primary packaging, whose average impact across the different categories accounts for 44.04%. The three highest contributions (i.e. freshwater toxicity, marine ecotoxicity and ionizing radiations impact categories) are mainly due to the process of bottle molding.

In general, the cooling phase slightly influences the impacts: its average contribution to the impact categories accounts for 7.78%. The only exception is the water consumption impact category, because of the large volumes of processing water required; in this category, the contribution of the cooling process reaches 65.13%. Secondary and tertiary packaging show overall lower impacts compared to the indirect TP process, because plastic boxes are used here (as also done in the HPP process) rather than cardboard boxes, and the influence of the pallet has been evaluated taking into account the amount of bottles loaded on it.

Lastly, the impact generated by the manufacturing stage is very low, accounting for 0.45% on average and reaching a maximum value of 6.27% in mineral resource scarcity.

Table 7 and Figure 8 show the impact analysis of the HPP process.

Table 7: Numerical values of the environmental impacts for each impact category for HPP.

Impact category	Unit of measurement	Total	Manufacturing stage	Preservation treatment	Primary packaging	Secondary and tertiary packaging	Cold room
Global warming	kg CO_2 eq	2.52E-01	2.35E-03	4.68E-02	1.65E-01	8.13E-03	3.01E-02
Stratospheric ozone depletion	kg CFC_{11} eq	8.59E-08	3.83E-10	3.21E-08	2.88E-08	3.94E-09	2.07E-08
Ionizing radiation	kBq Co-60 eq	3.26E-02	3.35E-05	7.64E-03	1.99E-02	1.10E-04	4.91E-03
Ozone formation, Human health	kg NO_x eq	3.72E-04	4.60E-06	7.76E-05	2.25E-04	1.51E-05	4.95E-05
Fine particulate matter formation	kg PM2.5 eq	2.57E-04	3.71E-06	6.25E-05	1.45E-04	6.38E-06	4.01E-05
Ozone formation, Terrestrial ecosystems	kg NO_x eq	3.88E-04	4.87E-06	7.89E-05	2.38E-04	1.60E-05	5.02E-05
Terrestrial acidification	kg SO_2 eq	7.03E-04	6.42E-06	1.91E-04	3.66E-04	1.54E-05	1.23E-04
Freshwater eutrophication	kg P eq	6.85E-05	8.01E-07	1.31E-05	4.54E-05	7.34E-07	8.38E-06
Marine eutrophication	kg N eq	6.58E-06	3.56E-08	1.29E-06	4.27E-06	1.53E-07	8.31E-07
Terrestrial ecotoxicity	kg 1,4-DCB	3.10E-01	4.19E-03	4.17E-02	2.22E-01	1.62E-02	2.65E-02
Freshwater ecotoxicity	kg 1,4-DCB	8.46E-03	3.46E-05	9.73E-04	6.45E-03	3.80E-04	6.22E-04
Marine ecotoxicity	kg 1,4-DCB	1.18E-02	4.93E-05	1.29E-03	9.12E-03	5.42E-04	8.25E-04
Human carcinogenic toxicity	kg 1,4-DCB	6.25E-03	3.05E-04	1.06E-03	4.04E-03	1.86E-04	6.61E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	1.19E-01	9.03E-04	1.72E-02	8.52E-02	4.87E-03	1.10E-02
Land use	m^2a crop eq	1.52E-02	2.52E-05	1.64E-03	1.01E-02	2.44E-03	1.06E-03
Mineral resource scarcity	kg Cu eq	2.28E-04	7.78E-05	3.90E-05	8.10E-05	5.97E-06	2.43E-05
Fossil resource scarcity	kg oil eq	8.04E-02	3.78E-04	1.27E-02	5.64E-02	2.77E-03	8.12E-03
Water consumption	m^3	3.00E-03	1.39E-05	1.11E-03	1.29E-03	2.29E-05	5.67E-04

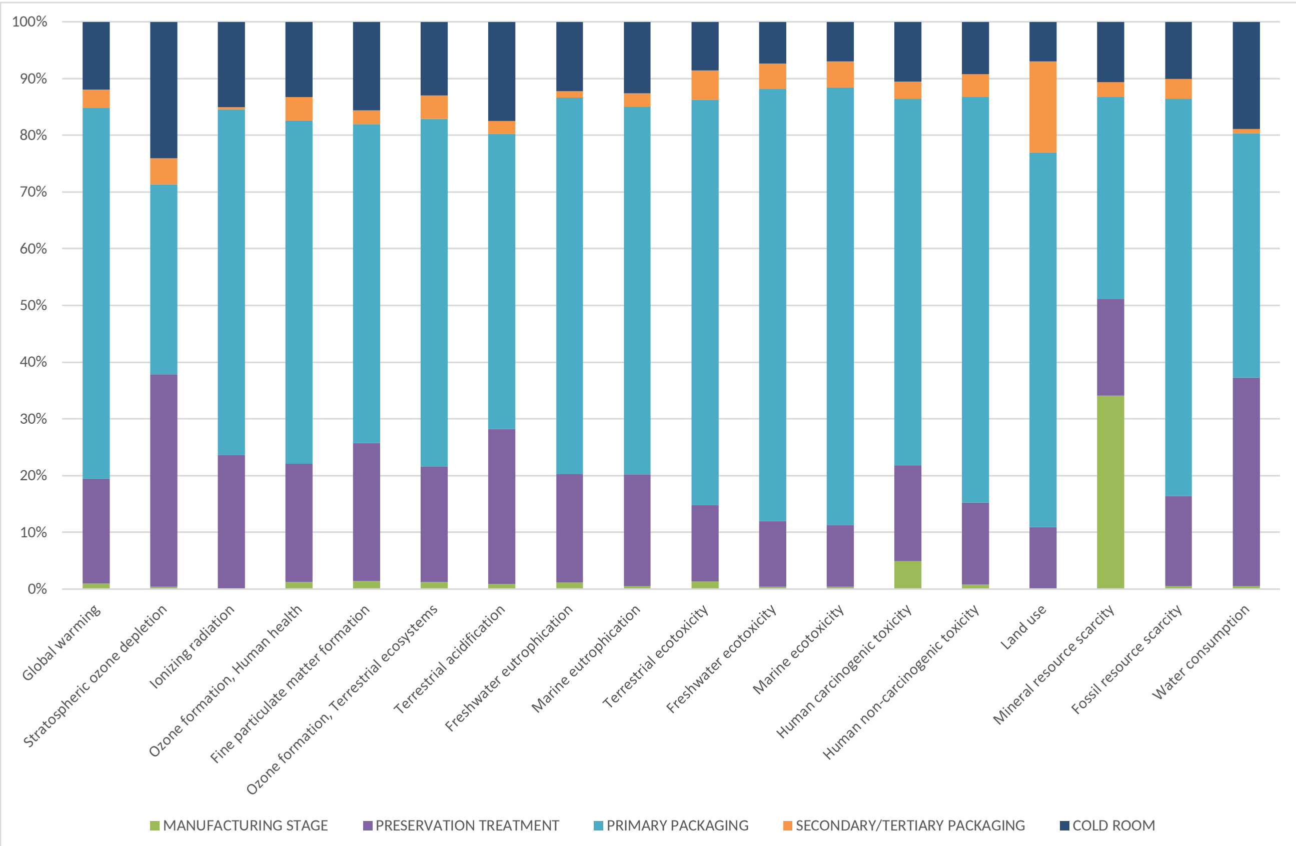

Figure 8: relative impacts of 1 kg of orange juice for HPP.

For this process, the highest impact is made by the primary packaging, with an average of 60.95%. As the primary packaging used is the same in both TP-retort and HPP, its contribution to the impacts remains unchanged in absolute terms. The impact is particularly high (>70%) in categories such as marine ecotoxicity and freshwater ecotoxicity. Compared to the TP systems, the HPP process also has a more significant effect on the manufacturing process (2.84% on average) due to the larger amount of stainless steel needed to build the machinery, and as expected its highest value (34.10%) is represented in mineral resource scarcity.

The preservation treatment represents the second most relevant contribution to the environmental impact of the HPP process (19.93% on average). The highest impact is observed for stratospheric ozone depletion and is mainly due to the energy needed to carry out the high pressure treatment. The impact of the cold room needed to keep the product refrigerated before and after the HPP treatment, accounts for 12.47% on average; the highest impacts are observed in stratospheric ozone depletion and water consumption.

The secondary and tertiary packaging contributes to the total impact to a limited extent (3.81% on average); the most significant contribution, which is observed for the land use impact category, is due to the raw material required to manufacture pallets.

4.3.5 Comparative LCA analysis

The comparison between the three processes, shown in Figure 9 and Table 8, highlights that for most of the impact categories considered (13 out of 18), higher values were found for TP-retort than for the remaining processes. The HPP generates a higher impact only in the ionizing radiation category, while the indirect TP shows the highest impact in the stratospheric ozone depletion, marine eutrophication, land use and mineral resource scarcity categories, mainly due to the energy consumption and materials used in this process. Overall, the HPP treatment turns out to be more environmentally friendly than TP for fruit juice processing; even if the HPP process is energy intensive, absence of steam within the process helps reduce environmental impact.

Table 8: Comparison of the environmental impacts of HPP and TP for orange juice processing.

Impact category	Unit of measurement	TP-indirect	TP-retort	HPP
Global warming	kg CO_2 eq	3.03E-01	5.32E-01	2.52E-01
Stratospheric ozone depletion	kg CFC_{11} eq	1.21E-07	1.15E-07	8.59E-08
Ionizing radiation	kBq Co-60 eq	2.76E-02	2.80E-02	3.26E-02
Ozone formation, Human health	kg NO_x eq	4.46E-04	6.70E-04	3.72E-04
Fine particulate matter formation	kg PM2.5 eq	3.41E-04	4.91E-04	2.57E-04
Ozone formation, Terrestrial ecosystems	kg NO_x eq	4.57E-04	6.94E-04	3.88E-04
Terrestrial acidification	kg SO_2 eq	8.76E-04	1.33E-03	7.03E-04
Freshwater eutrophication	kg P eq	8.10E-05	8.98E-05	6.85E-05
Marine eutrophication	kg N eq	1.26E-05	7.55E-06	6.58E-06
Terrestrial ecotoxicity	kg 1,4-DCB	7.00E-01	1.18E+00	3.10E-01
Freshwater ecotoxicity	kg 1,4-DCB	6.95E-03	8.87E-03	8.46E-03
Marine ecotoxicity	kg 1,4-DCB	9.89E-03	1.30E-02	1.18E-02
Human carcinogenic toxicity	kg 1,4-DCB	7.36E-03	8.63E-03	6.25E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	1.39E-01	1.47E-01	1.19E-01
Land use	m^2a crop eq	1.98E-02	1.49E-02	1.52E-02
Mineral resource scarcity	kg Cu eq	3.37E-04	2.04E-04	2.28E-04
Fossil resource scarcity	kg oil eq	8.74E-02	1.64E-01	8.04E-02
Water consumption	m^3	2.79E-03	5.13E-03	3.00E-03

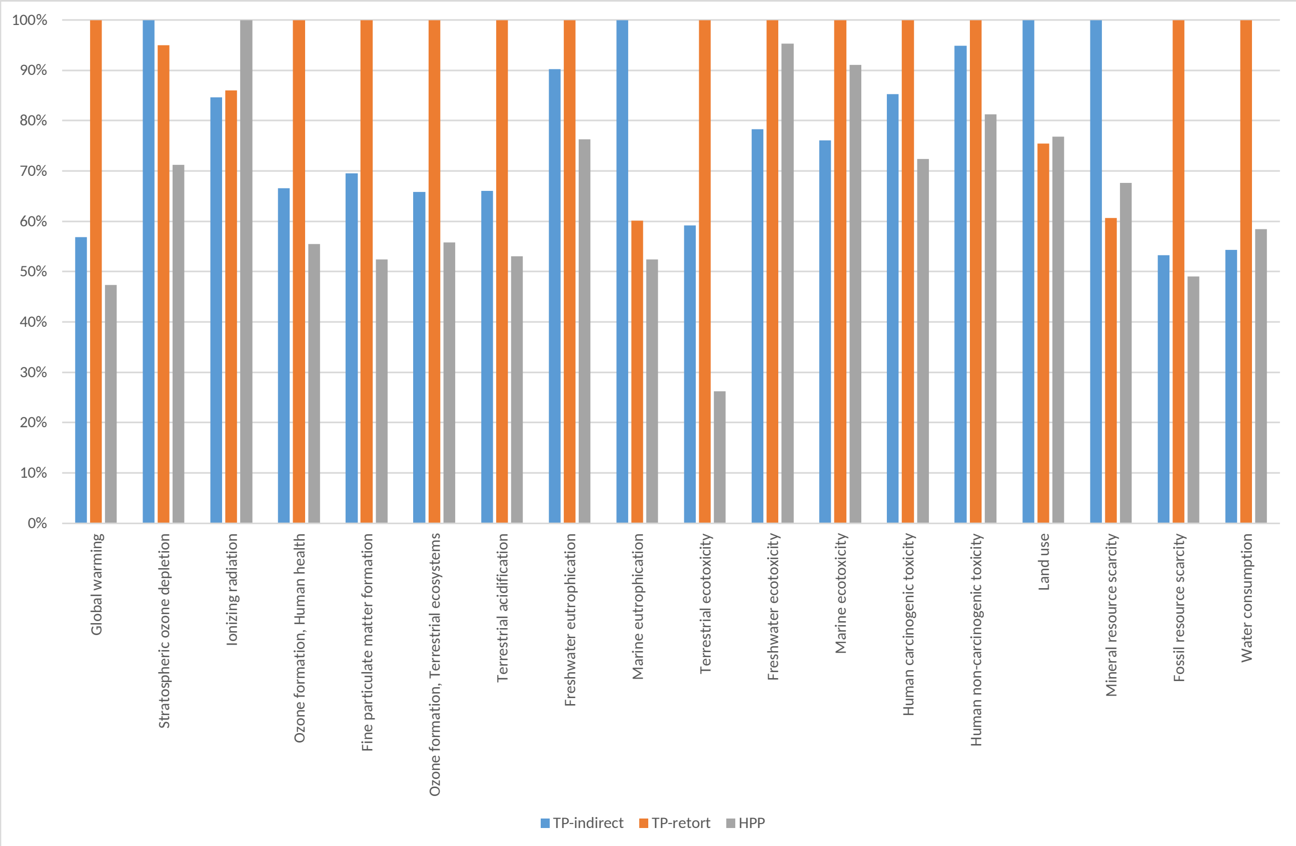

Figure 9: comparison of the environmental impacts of HPP, TP-indirect and TP-retort for orange juice processing.

5 HPP VS. MAP: SLICED PARMA HAM

We now compare HPP and MAP technologies for the processing of Parma ham. The MAP process, its main cost components and its environmental impact are detailed in the following subsection.

5.1 MAP OF SLICED PARMA HAM

5.1.1 System description

MAP is a technique that extracts air from within the product packaging and replaces it with one or more special gases, to create a "modified atmosphere" around the food. The MAP technique has several important characteristics compared to vacuum packaging. Firstly, it is a more delicate technology, since not only is the air removed from the packaging (thus avoiding product deterioration), but new elements (gases) are introduced to actively counteract this process. This packaging method also eliminates the need to monitor the atmosphere around the product, which is an expensive and complex process, making it accessible for small production volumes.

One interesting aspect of this technology is its ability to define a specific gas mixture for all product/packaging systems. This is why films and/or trays must be made of materials suitable for this type of conditioning. The most widely used gases for MAP food are oxygen (O_2), carbon dioxide (CO_2), nitrogen (N_2) and argon (Ar). These gases have the specific role of extending product shelf-life and maintaining the appearance of the product in the best possible way. All these gases are defined by European Directive 95/2/CE on additives as "packaging gases", i.e. "gases other than air introduced into a container before, during or after the placing of a foodstuff in that container".

The *VKF90* thermoforming machine[6] (Veripack, Varese, Italy) was taken as reference to analyze the MAP process. This automatic packaging machine carries out thermoforming of trays starting from coil, by forming the bottom of the tray, and welds it thermally with top closure films.

The main scenario considered is that of a tray made from PET (400 µm), polyethylene (50 µm) and EVOH (5 µm), containing 100 g of sliced ham. A tray with a weight of 18 g and costing the approximately 2.21 €/kg is assumed as packaging material. The machine processes 4 trays per production cycle and is able to complete up to 13,440 production cycles/day (28 cycles/minute), resulting in 53,760 trays packaged per day and 13,440,000 per year (assuming 250 working days); hence, a thermoforming machine processes 1,344,000 kg/year of product. To make a meaningful comparison with HPP technology, which processes a greater product volume, two thermoforming machines will be considered in the evaluation, resulting in 2,688,000 kg/year of product processed.

The power of these machines is:

- 6,000 kcal/h (6.973 kW) for the chiller;
- 60 kW with a voltage of 400 V at 50 Hz average input power.

The total power of the plant thus stands at 66.973 kW.

5.1.2 Cost components

In the main scenario, the cost components relating to the cost macro-categories considered for LCC evaluation are listed below (with respect to one thermoforming machine). The input data for the computation were either derived from quotations or interviews with companies using MAP technology to process sliced ham.

1. *Initial investment*. According to a quotation, the cost of a thermoforming machine is €120,000. The transport/handling cost totals approximately €1,500, required to ship the machine from the manufacturer to the user's site.

[6] http://www.veripack.com/documenti/veripack_scheda-tecnica_termoformatrici_ok_vkf90.pdf

2. *Operating costs*. MAP plant operating costs include the following:
    2.1. *Energy*. The annual cost for electricity consumption can be calculated taking into account the energy consumption of the MAP plant, the unitary cost of electricity for industry in Italy and the work schedule (i.e. one 8-hour shift and 250 working days/year, to obtain production data comparable with HPP);
    2.2. *Manpower*. The annual cost of the employees required for the plant is the same as that of the previous technologies, as each machine requires two employees to operate;
    2.3. *Safety*. Employees working on the MAP plant are required to wear appropriate work clothes and safety shoes. The unitary cost of the safety equipment was taken from specialist websites[7]; the annual cost can vary over time, as the different safety equipment needs to be replaced at different intervals;
    2.4. *Cleaning and sanitization*. This cost is the same as that of the HPP plant, as the sanitization procedure does not vary;
    2.5. *Primary packaging*. Each tray consists of 0.018 kg of packaging materials. Taking into account the annual number of trays processed by one thermoforming machine, the cost of packaging material totals approximately 536,253.97 €/year. Moreover, the amount of carbon dioxide (CO_2) and nitrogen (N_2) to be introduced in the tray are taken into account in this cost component; relating costs were obtained from quotations;
    2.6. *Secondary packaging*. The trays of sliced ham are packaged into corrugated disposable cardboard boxes measuring 400x300x300 mm (weight≈350 g and unitary cost≈2.56 €); each box contains 60 trays;
3. *Tertiary packaging*. The tertiary packaging is the same as that used for HPP. To obtain a suitable stock keeping unit, 48 boxes can be placed on a pallet;
4. *Maintenance costs*. The MAP plant requires both preventive and reactive maintenance activities.
    4.1. *Preventive maintenance.* The annual cost of preventive maintenance activities was derived from the analysis of the use and maintenance manual of the MAP plant and was estimated to be 12,000 €/year;
    4.2. *Reactive maintenance.* A lump sum of 1,500 €/year was assumed to cover maintenance activities caused by emergency situations (e.g. failure of some components);
5. *End-of-life cost*.

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[7] https://shop.tecnafood.com/business_it/antinfortunistica/calzature-e-scarpe-antinfortunistiche-bianche-da-lavoro-professionali/scarpe-per-il-settore-alimentare.html

5.1. *Residual value*. Taking into account the quotation of the metallic materials and the total weight of the MAP machine, the residual value of one machine totals approximately € 9,450.

5.2 LCC ANALYSIS FOR SLICED PARMA HAM

5.2.1 LCC results for HPP

The LCC cost for Parma ham processing accounts for:

$$\begin{aligned} LCC_{HPP} &= initial\ investment_{HPP} + PV_{operating\ cost,HPP} + PV_{maintenance\ cost,HPP} - PV_{residual\ value,HPP} \\ &= €\ 1{,}805{,}747.50 + €\ 11{,}264{,}313.18 + €\ 1{,}083{,}803.05 - €\ 32{,}358.54 \\ &= €\ 14{,}121{,}505.19 \end{aligned}$$

Compared to orange juice processing, the only cost component that varied is the operating cost and in particular the higher packaging cost, as highlighted in Figure 10. As this figure show, the operating cost covers 79.58% of the LCC, while the initial investment and maintenance cost now score 12.76% and 7.66% of the total LCC respectively. The packaging cost still represents most of the operating cost: indeed, the most significant contribution to the operating cost is secondary packaging (63.41%). The HPP plant processes approximately 2,700,000 kg/year of product; therefore, the unitary cost of this technology is 26.15 c€/kg for Parma ham processing.

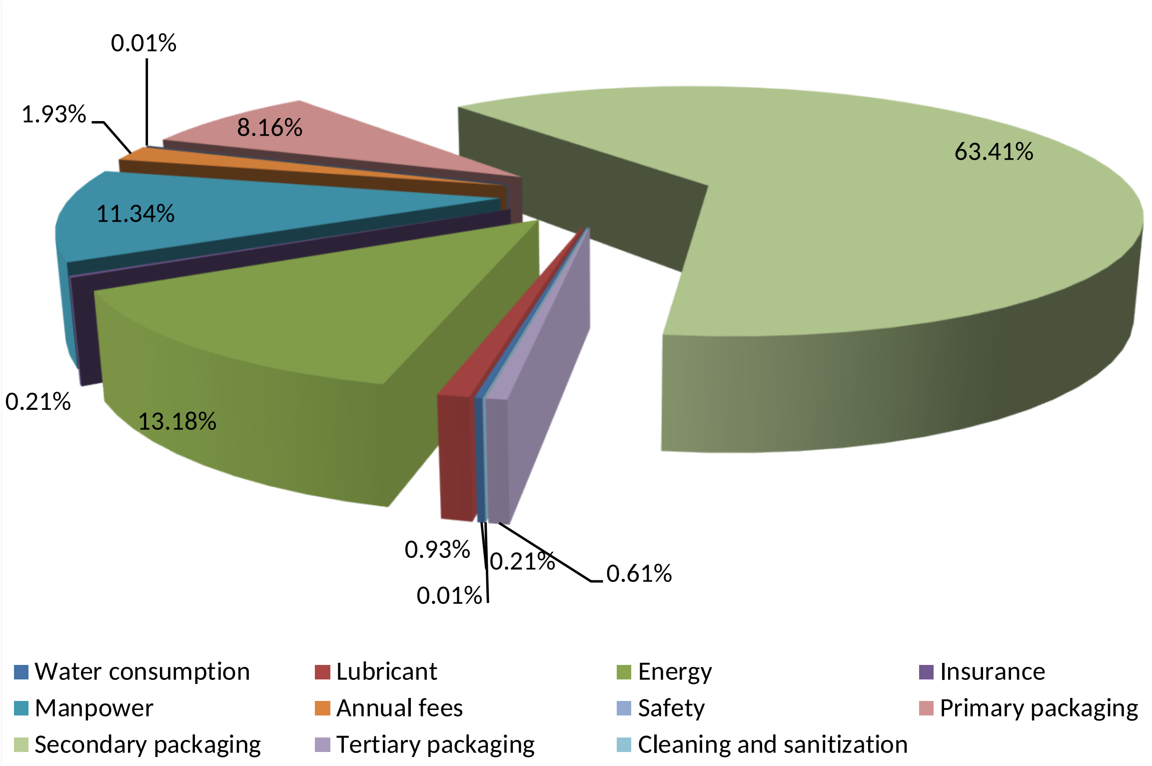

Figure 10: details of the operating costs of HPP for Parma ham processing.

5.2.2 LCC results for MAP

The LCC of the MAP technology (2 machines) for Parma ham processing totals:

$$LCC_{MAP} = initial\ investment_{MAP} + PV_{operating\ cost,MAP} + PV_{maintenance\ cost,MAP} - PV_{residual\ value,MAP} = € \ 243{,}000.00 + \ € \ 43{,}774{,}948.00 + \ € \ 489{,}197.86 - \ € \ 15{,}612.59 = € \ 44{,}491{,}533.26$$

The operating costs account for almost the entire LCC (98.35%); the purchasing cost of the thermoforming machines has a negligible impact on the total LCC (0.55%), while maintenance cost accounts for about 1.1% of the LCC. Details of the operating costs are proposed in Figure 11, which confirms that most of the operating cost (more than 90% overall) is due to the primary and secondary packaging cost. The high cost of primary packaging was expected because of the high cost of plastic material required to form the trays; as far as the secondary packaging is concerned, its significant cost is due fact that packaging is less efficiently used when shipping sliced ham rather than whole ham.

With two thermoforming machines, the amount of product processed is 2,688,000 kg/year. The unitary cost of processing one kg of sliced ham in MAP thus stands at 82.76 c€/kg.

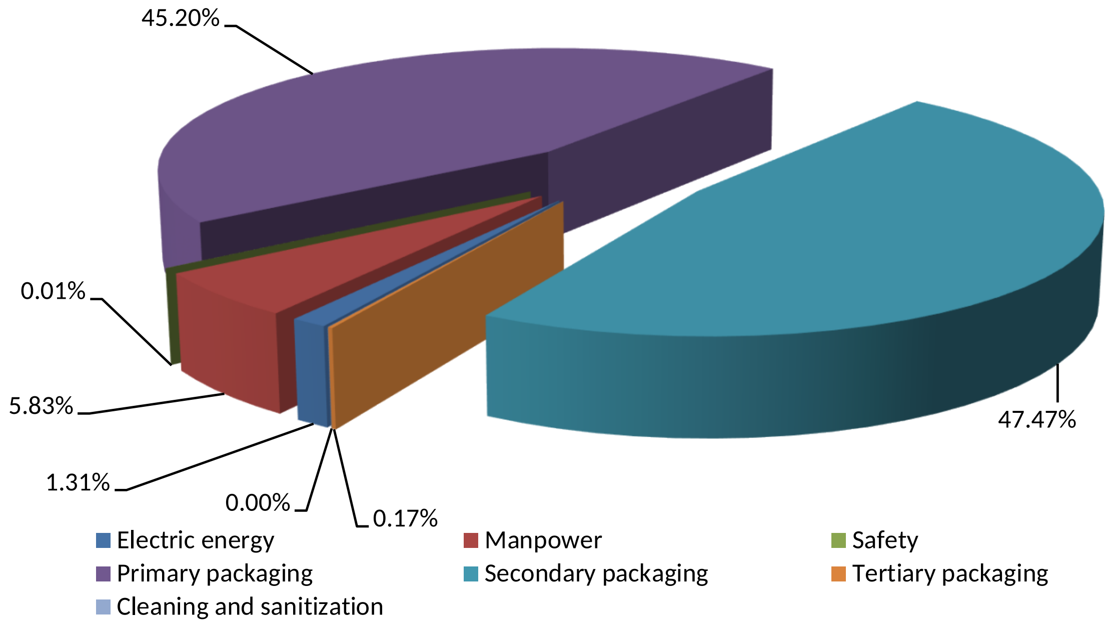

Figure 11: details of the operating costs of MAP for Parma ham processing.

5.2.3 Sensitivity analysis

A tray of 100 g of finished product reflects a typical market size for the sliced Parma ham. Nonetheless, the same MAP technology can be used to package a tray of different (greater) size, with a resulting saving in the system cost. A sensitivity analysis was thus carried out to show how the total cost of the MAP system can vary as a function of the packaging size. To this end, trays containing 200 g of sliced ham have been considered. In these trays, the amount of gases required to preserve the quality of the product doubles, while the weight of the packaging material increases slightly, reaching 0.022 kg. The tray thickness increases as well, to contain a greater amount of product; therefore, the number of trays in a box or pallet should be updated taking into account the modified size. As the cycle time depends mainly on the vacuum level while it is not affected by the tray thickness, one single machine is sufficient to ensure a production capacity of 2,688,000 kg/year of product.

On the basis of the considerations above, the LLC of this configuration becomes:

$$LCC_{MAP'} = initial\ investment_{MAP'} + PV_{operating\ cost,MAP'} + PV_{maintenance\ cost,MAP'} - PV_{residual\ value,MAP'} \\ = €\ 121{,}500.00 + €\ 34{,}846{,}179.99 + €\ 241{,}858.95 - €\ 7{,}806.30 = €\ 35{,}201{,}732.65$$

Variations in the LCC obviously concern the initial investment, maintenance cost and residual value, which are halved compared to the previous configuration; the operating cost, instead, decreases by 20.4%. The unitary cost of processing one kg of sliced ham in trays containing 200 g of product accounts for 65.48 c€/kg (20.9% less than the previous configuration).

5.2.4 Comparative LCC results

A comparison of the LCC of the HPP and MAP systems for Parma ham is made in Table 9. As the comparison shows, the total LCC of the MAP system is significantly higher than that of the HPP technology, despite the higher initial investment and maintenance cost of HPP. This result is mainly due to the considerable operating cost of MAP, which is more than twice as much the operating cost of HPP. Overall, the unitary cost of processing Parma ham is 3.16 times higher adopting MAP technology compared to HPP (2.5 in case of 200 g trays).

	HPP		MAP - 100 g		MAP - 200 g	
Cost macro-categories	**Total cost [€]**	**Unitary cost [€/kg]**	**Total cost [€]**	**Unitary cost [€/kg]**	**Total cost [€]**	**Unitary cost [€/kg]**
Initial investment	1,805,747.50	0.033	243,000.00	0.0045	121,500.00	0.0023
$PV_{operating\ cost}$	11,264,313.18	0.209	43,774,948.00	0.8143	34,846,179.99	0.6482
$PV_{maintenance\ cost}$	1,083,803.05	0.020	489,197.86	0.0091	241,858.95	0.0045
$PV_{residual\ value}$	32,358.54	0.001	15,612.59	0.0003	7,806.30	0.0001
LCC	14,121,505.19	0.26151	44,491,533.26	0.82760	35,201,732.65	0.65479

Table 9: Comparison of the LCC for HPP and MAP.

5.3 LCA ANALYSIS

5.3.1 Goal and scope definition

The functional unit chosen for this LCA analysis is 1 kg of Parma ham processed with HPP or MAP technologies. In the case of MAP, this corresponds to 10 trays (of 100 g each) of product processed.

A gate-to-gate approach was used, including the phases from the product arrival at the plant to its processing and packaging with HPP or MAP. As far as the primary packaging end-of-life is concerned, trays from MAP are not recyclable, due to the presence of three different materials; hence, thermal valorization has been set as the end-of-life destination. The preparation of stock keeping units with secondary and tertiary packaging are also taken into account in the evaluation. Suitable data for the end-of-life of cardboard boxes (secondary packaging) was taken from the corrugated board box production of Europe (Eurostat, 2018). Finally, as previously mentioned, it is hypothesized that the useful life of a pallet (tertiary packaging) is 20 rotations. Figure 12 illustrates the process diagrams for HPP and TP treatments.

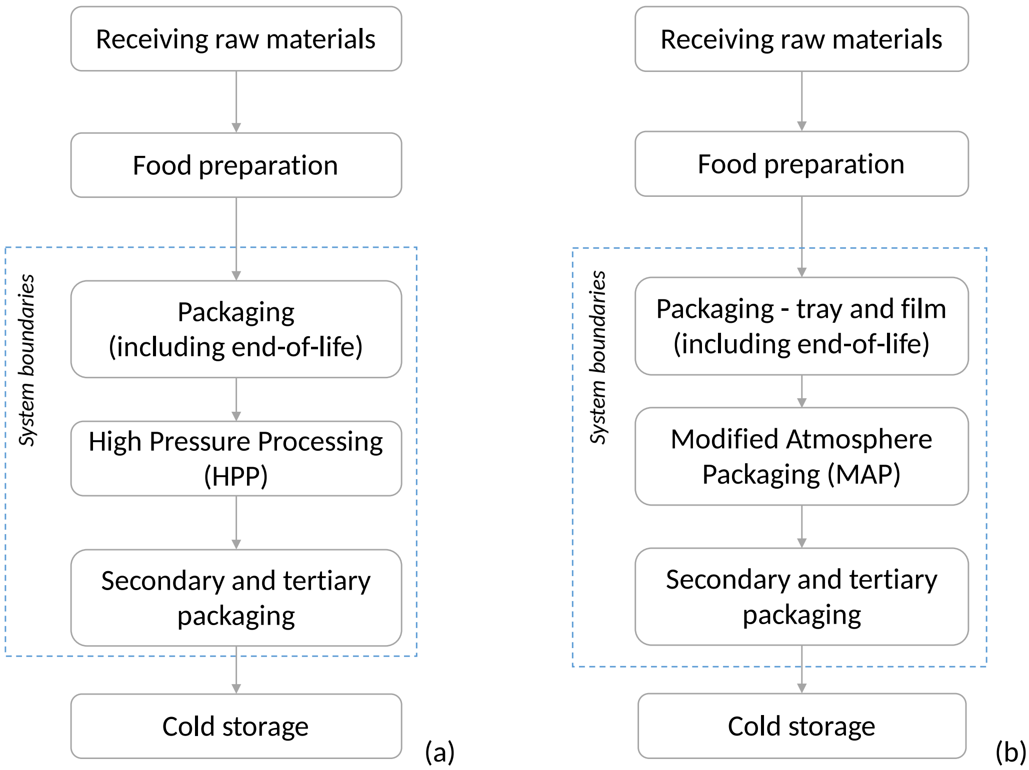

Figure 12: system boundaries of HPP (a) and MAP (b) for Parma ham processing.

5.3.2 Inventory analysis

Primary data relating to MAP technology consumption was collected from a local company, while secondary data was retrieved from the Ecoinvent 3.4 database (see Table 10). As far as HPP is concerned, most of the data is the same as that used previously; additional or modified data is proposed in Table 11. The impacts were computed using the SimaPro 8.5.2 software package.

Table 10: Inventory data for MAP

Lifecycle stage	Input	Unit of measurement	Numerical value	Source	Dataset for impact assessment
Plant manufacturing	Steel for food industry machinery	kg	0.000251	Primary data	Steel, unalloyed {GLO} | market for | APOS, U
Preservation treatment	Electricity	Wh	67.36	Primary data	Electricity, medium voltage {IT} | market for | APOS, U
	Compressed air	l	223	Primary data	Compressed air, 800 kPa gauge {RER}| compressed air production,

					800 kPa gauge, >30 kW average generation| APOS, U
Primary packaging	PET	kg	0.158	Primary data	Polyethylene, granulate, amorphous {RER} | production | APOS, U
	Ethyl-vinyl-acetate	kg	0.002	Primary data	Ethyl-vinyl-acetate, foil {RER} | production | APOS, U
	Polyethylene	kg	0.02	Primary data	Polyethylene, low density, granulate {RER} | production | APOS, U
	CO_2	kg	0.0015	Primary data	Carbon dioxide, liquid {RER} | market for | APOS, U
	N_2	kg	0.0021	Primary data	Nitrogen, liquid {RER} | market for | APOS, U
Secondary packaging	Cardboard	kg	0.058	Primary data	Corrugated board box {GLO} | market for corrugated board box | APOS, U
Tertiary packaging	Euro-pallet	amount	0.00017	Primary data	EUR-flat pallet {GLO} | market for | APOS, U

Table 11: Additional/modified inventory data for HPP

Lifecycle stage	Input	Unit of measurement	Numerical value	Source	Dataset for impact assessment
Primary packaging	PET	kg	0.01512	Primary data	Polyethylene, low density, granulate {RER} | production | APOS, U
	Nylon	kg	0.00648	Primary data	Nylon 6 {GLO} | market for | APOS, U
Secondary packaging	Cardboard	kg	0.036	Primary data	Corrugated board box {GLO} | market for corrugated board box | APOS, U
Tertiary packaging	Euro-pallet	amount	0.000156	Primary data	EUR-flat pallet {GLO} | market for | APOS, U

5.3.3 Method of impact assessment

As per the previous case, 18 ReCiPe Midpoint (H) indicators were considered.

5.3.4 Life Cycle Impact Assessment (LCIA)

Figure 13 and Table 12 show the results of the analysis for the MAP process. Positive impacts are observed in most of the categories (17 out of 18). The preservation treatment shows a positive impact in all impact categories and the overall contribution to the impacts accounts for 28.2% on average; the most relevant contributions are observed for mineral resource scarcity, terrestrial ecotoxicity and human non-carcinogenic toxicity.

The end-of-life of the primary, secondary and tertiary packaging reduce the total impact of the MAP technology. In particular, secondary and tertiary packaging generates high impact on two categories, namely land use and marine eutrophication; this result is due to the impact of producing corrugated cardboard boxes and Euro-pallets. It is interesting to note that the incineration and recycling of the secondary packaging and Euro-pallets cause negative impacts in 8 out of 18 categories, namely ionizing radiation, terrestrial acidification, terrestrial ecotoxicity, marine ecotoxicity, freshwater ecotoxicity, water consumption, human non-carcinogenic toxicity and mineral resource scarcity.

Looking at the global warming impact category the analysis shows that the contribution to the CO_2 production is almost entirely shared among primary packaging (87.04%) and preservation treatment (9.82%), while the contribution of the remaining processes is negligible.

Impact category	**Unit**	**Total**	**Manufacturing Stage**	**Preservation Treatment**	**Primary Packaging**	**Secondary and tertiary packaging**
Global warming	kg CO_2 eq	1.23E+00	1.09E-03	1.21E-01	1.07E+00	3.76E-02
Stratospheric ozone depletion	kg CFC_{11} eq	4.49E-07	1.94E-10	6.88E-08	3.28E-07	5.14E-08
Ionizing radiation	kBq Co-60 eq	-1.19E-01	1.65E-05	1.31E-02	4.98E-02	-1.82E-01
Ozone formation, Human health	kg NO_x eq	1.73E-03	2.39E-06	2.93E-04	1.39E-03	3.83E-05
Fine particulate matter formation	kg PM2.5 eq	1.23E-03	1.77E-06	3.25E-04	9.02E-04	3.99E-06
Ozone formation, Terrestrial ecosystems	kg NO_x eq	1.80E-03	2.52E-06	2.98E-04	1.46E-03	3.94E-05
Terrestrial acidification	kg SO_2 eq	2.72E-03	2.95E-06	6.89E-04	2.04E-03	-7.98E-06
Freshwater eutrophication	kg P eq	3.22E-04	3.98E-07	1.24E-04	1.95E-04	3.02E-06
Marine eutrophication	kg N eq	3.75E-05	1.79E-08	7.67E-06	1.84E-05	1.14E-05
Terrestrial ecotoxicity	kg 1,4-DCB	3.08E+00	2.07E-03	1.82E+00	1.84E+00	-5.82E-01
Freshwater ecotoxicity	kg 1,4-DCB	4.92E-02	1.70E-05	1.78E-02	3.25E-02	-1.15E-03
Marine ecotoxicity	kg 1,4-DCB	6.77E-02	2.42E-05	2.52E-02	4.45E-02	-2.00E-03
Human carcinogenic toxicity	kg 1,4-DCB	4.45E-02	1.48E-04	1.36E-02	3.06E-02	8.23E-05
Human non-carcinogenic toxicity	kg 1,4-DCB	1.19E+00	4.47E-04	5.61E-01	6.94E-01	-6.83E-02
Land use	m^2a crop eq	3.63E-02	1.24E-05	3.00E-03	2.15E-02	1.18E-02
Mineral resource scarcity	kg Cu eq	1.81E-03	3.79E-05	1.70E-03	1.35E-03	-1.27E-03
Fossil resource scarcity	kg oil eq	3.52E-01	1.82E-04	3.15E-02	3.12E-01	7.61E-03
Water consumption	m^3	4.56E-03	6.98E-06	1.25E-03	1.10E-02	-7.73E-03

Table 12: Numerical value of the environmental impacts for each impact category for MAP.

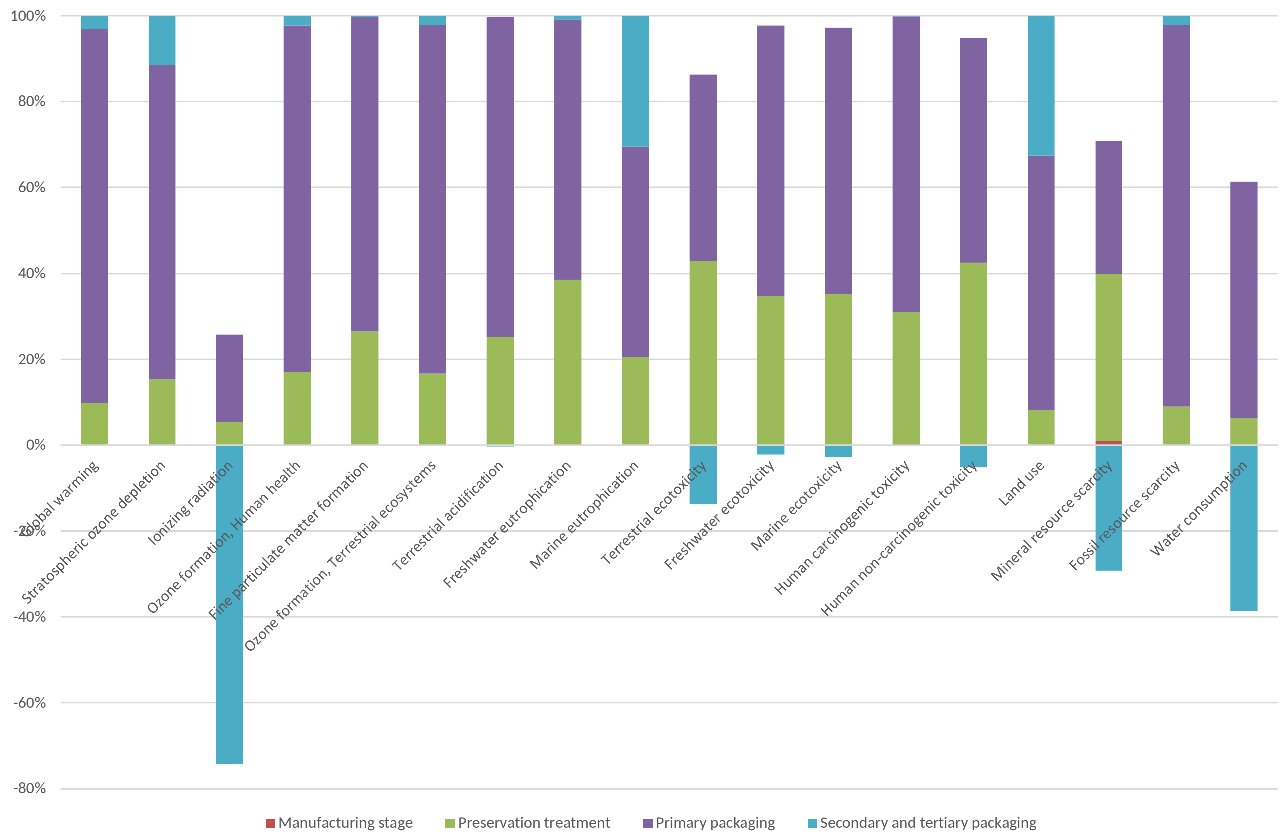

Figure 13: LCA analysis of 1 kg of Parma ham for MAP.

Figure 14 and Table 13 show the results of the impact assessment for the production of Parma ham with HPP. As highlighted in Figure 14, the total impact generated by HPP is positive in 14 out of 18 impact categories, while it is negative in ionizing radiations, terrestrial ecotoxicity, mineral resource scarcity and water consumption. The preservation treatment shows positive contributions to all impact categories; the contribution is particularly relevant for freshwater eutrophication, fine particulate matter formation and terrestrial acidification. The primary packaging shows the greatest positive impact (more than 40% on average); the biggest impact is observed on stratospheric ozone depletion. The incineration and recycling of the secondary packaging and Euro-pallets cause negative impacts in 7 out of 18 categories, namely ionizing radiation, terrestrial and marine ecotoxicity, water consumption, human non-carcinogenic toxicity, mineral resource scarcity and freshwater eutrophication.

The global warming impact category is largely determined by primary packaging (64.12%) and preservation treatment (19.18%), while the incidence of secondary/tertiary packaging is lower (15.74%).

Impact category	Unit	Total	Manufacturing Stage	Preservation Treatment	Primary Packaging	Secondary and tertiary packaging
Global warming	kg CO_2 eq	2.44E-01	2.35E-03	4.68E-02	1.56E-01	3.84E-02
Stratospheric ozone depletion	kg CFC_{11} eq	7.13E-07	3.83E-10	3.21E-08	6.39E-07	4.15E-08
Ionizing radiation	kBq Co-60 eq	-1.12E-01	3.35E-05	7.64E-03	2.80E-03	-1.22E-01
Ozone formation, Human health	kg NO_x eq	3.64E-04	4.60E-06	7.76E-05	2.27E-04	5.48E-05
Fine particulate matter formation	kg PM2.5 eq	1.77E-04	3.71E-06	6.25E-05	9.31E-05	1.75E-05
Ozone formation, Terrestrial ecosystems	kg NO_x eq	3.81E-04	4.87E-06	7.89E-05	2.41E-04	5.65E-05
Terrestrial acidification	kg SO_2 eq	5.07E-04	6.42E-06	1.91E-04	2.83E-04	2.66E-05
Freshwater eutrophication	kg P eq	2.82E-05	8.01E-07	1.31E-05	6.68E-06	7.57E-06
Marine eutrophication	kg N eq	1.26E-05	3.56E-08	1.29E-06	2.88E-06	8.35E-06
Terrestrial ecotoxicity	kg 1,4-DCB	-2.98E-01	4.19E-03	4.17E-02	4.86E-02	-3.92E-01
Freshwater ecotoxicity	kg 1,4-DCB	3.01E-03	3.46E-05	9.73E-04	2.60E-03	-5.98E-04
Marine ecotoxicity	kg 1,4-DCB	3.70E-03	4.93E-05	1.29E-03	3.47E-03	-1.11E-03
Human carcinogenic toxicity	kg 1,4-DCB	4.78E-03	3.05E-04	1.06E-03	3.04E-03	3.84E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	1.74E-02	9.03E-04	1.72E-02	4.25E-02	-4.32E-02
Land use	m^2a crop eq	2.22E-02	2.52E-05	1.64E-03	1.14E-03	1.94E-02
Mineral resource scarcity	kg Cu eq	-7.01E-04	7.78E-05	3.90E-05	3.15E-05	-8.49E-04
Fossil resource scarcity	kg oil eq	6.40E-02	3.78E-04	1.27E-02	4.16E-02	9.24E-03
Water consumption	m^3	-2.74E-03	1.39E-05	1.11E-03	1.14E-03	-5.00E-03

Table 13: Numerical values of the environmental impacts for each impact category for HPP.

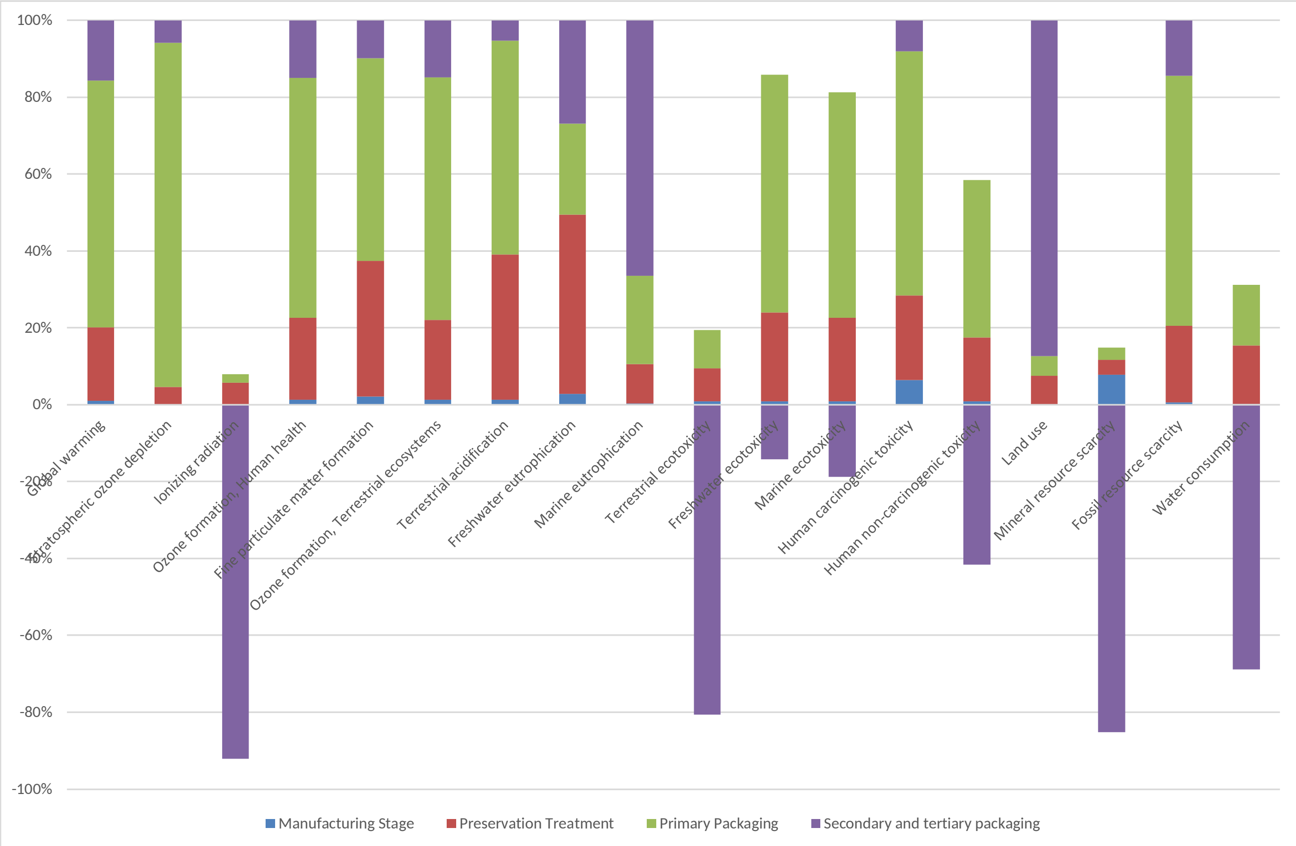

Figure 14: LCA analysis of 1 kg of Parma ham for HPP.

5.3.5 Sensitivity analysis

Using the settings described in section 5.2.3, a sensitivity analysis was carried out to evaluate the changes in the environmental impact caused by a variation of the amount of finished product packaged in a tray (200 g vs. 100 g). Results, in terms of the total impact and percentage variation, are proposed in Table 14 and Figure 15 and show that the use of 200 g trays involves a decrease in the environmental impact for all categories.

		Sensitivity analysis	
Impact category	**Unit of measurement**	**Tray 100 g**	**Tray 200 g**
Global warming	kg CO2 eq	1.23E+00	8.15E-01
Stratospheric ozone depletion	kg CFC11 eq	4.49E-07	3.20E-07
Ionizing radiation	kBq Co-60 eq	-1.19E-01	-1.39E-01
Ozone formation, Human health	kg NOx eq	1.73E-03	1.18E-03
Fine particulate matter formation	kg PM2.5 eq	1.23E-03	8.82E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.80E-03	1.23E-03
Terrestrial acidification	kg SO2 eq	2.72E-03	1.93E-03
Freshwater eutrophication	kg P eq	3.22E-04	2.47E-04
Marine eutrophication	kg N eq	3.75E-05	3.04E-05
Terrestrial ecotoxicity	kg 1,4-DCB	3.08E+00	2.36E+00
Freshwater ecotoxicity	kg 1,4-DCB	4.92E-02	3.65E-02
Marine ecotoxicity	kg 1,4-DCB	6.77E-02	5.04E-02
Human carcinogenic toxicity	kg 1,4-DCB	4.45E-02	3.25E-02

Human non-carcinogenic toxicity	kg 1,4-DCB	1.19E+00	9.17E-01
Land use	m2a crop eq	3.63E-02	2.80E-02
Mineral resource scarcity	kg Cu eq	1.81E-03	1.26E-03
Fossil resource scarcity	kg oil eq	3.52E-01	2.30E-01
Water consumption	m3	4.56E-03	2.45E-04

Table 14: Sensitivity analysis of total impact for MAP (100 g vs. 200 g).

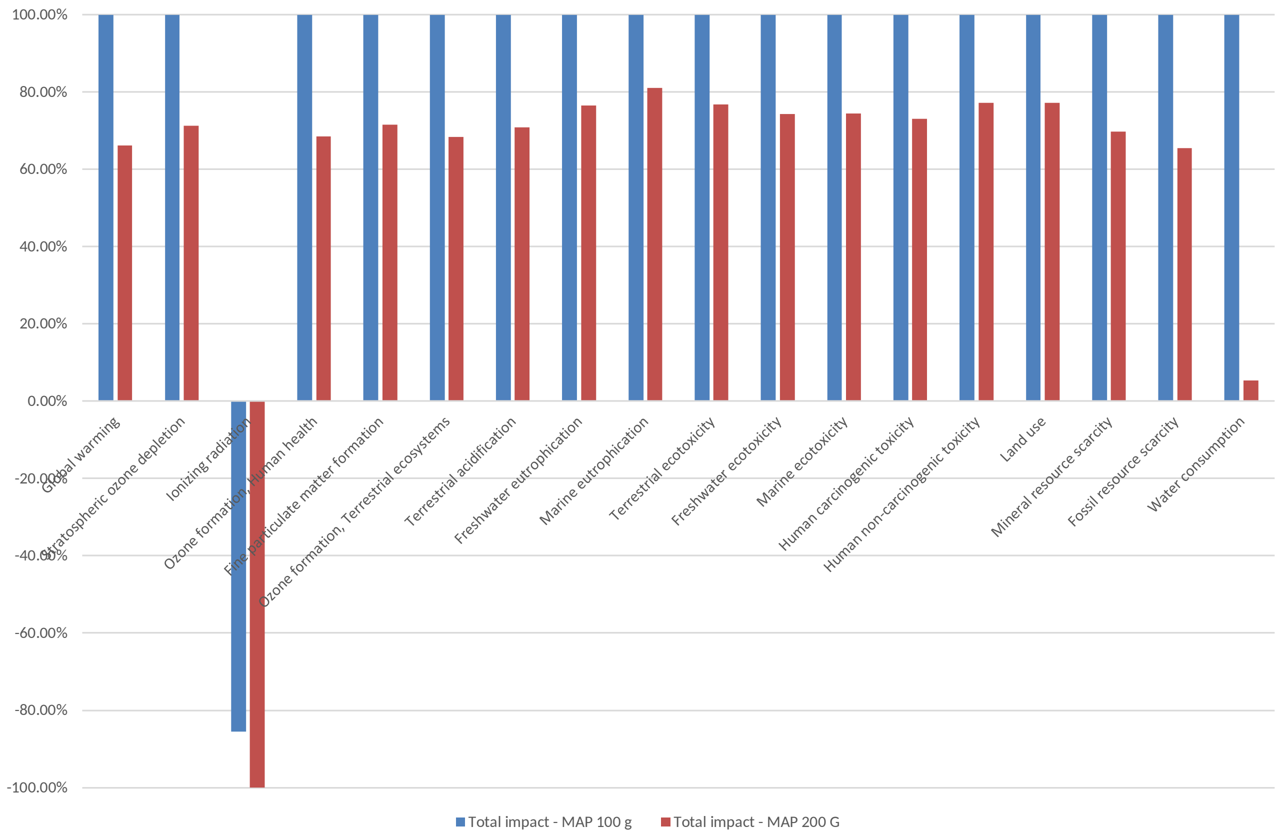

Figure 15: Sensitivity analysis of total impact for MAP (100 g vs. 200 g).

5.3.6 Comparative LCA analysis

The comparison between MAP and HPP for Parma ham (Table 15 and Figure 16) highlights a significant difference in the environmental impact of these technologies. MAP generates the highest environmental impact and the lowest environmental benefits in almost all impact categories (17 out of 18), whilst having a lower environmental impact than HPP in stratospheric ozone depletion only. This indicates that HPP is the most environmentally sound process for Parma ham, and confirms the results of the previous evaluation. The higher environmental impact of MAP is mainly due to the high volume of primary packaging material required for processing.

Impact category	**Unit of measurement**	**HPP**	**MAP 100g**	**MAP 200g**
Global warming	kg CO_2 eq	2.44E-01	1.23E+00	8.15E-01
Stratospheric ozone depletion	kg CFC_{11} eq	7.13E-07	4.49E-07	3.20E-07
Ionizing radiation	kBq Co-60 eq	-1.12E-01	-1.19E-01	-1.39E-01
Ozone formation, Human health	kg NO_x eq	3.64E-04	1.73E-03	1.18E-03

Fine particulate matter formation	kg PM2.5 eq	1.77E-04	1.23E-03	8.82E-04
Ozone formation, Terrestrial ecosystems	kg NO_x eq	3.81E-04	1.80E-03	1.23E-03
Terrestrial acidification	kg SO_2 eq	5.07E-04	2.72E-03	1.93E-03
Freshwater eutrophication	kg P eq	2.82E-05	3.22E-04	2.47E-04
Marine eutrophication	kg N eq	1.26E-05	3.75E-05	3.04E-05
Terrestrial ecotoxicity	kg 1,4-DCB	-2.98E-01	3.08E+00	2.36E+00
Freshwater ecotoxicity	kg 1,4-DCB	3.01E-03	4.92E-02	3.65E-02
Marine ecotoxicity	kg 1,4-DCB	3.70E-03	6.77E-02	5.04E-02
Human carcinogenic toxicity	kg 1,4-DCB	4.78E-03	4.45E-02	3.25E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	1.74E-02	1.19E+00	9.17E-01
Land use	m^2a crop eq	2.22E-02	3.63E-02	2.80E-02
Mineral resource scarcity	kg Cu eq	-7.01E-04	1.81E-03	1.26E-03
Fossil resource scarcity	kg oil eq	6.40E-02	3.52E-01	2.30E-01
Water consumption	m^3	-2.74E-03	4.56E-03	2.45E-04

Table 15: Comparison of the environmental impacts of HPP and MAP for Parma ham processing.

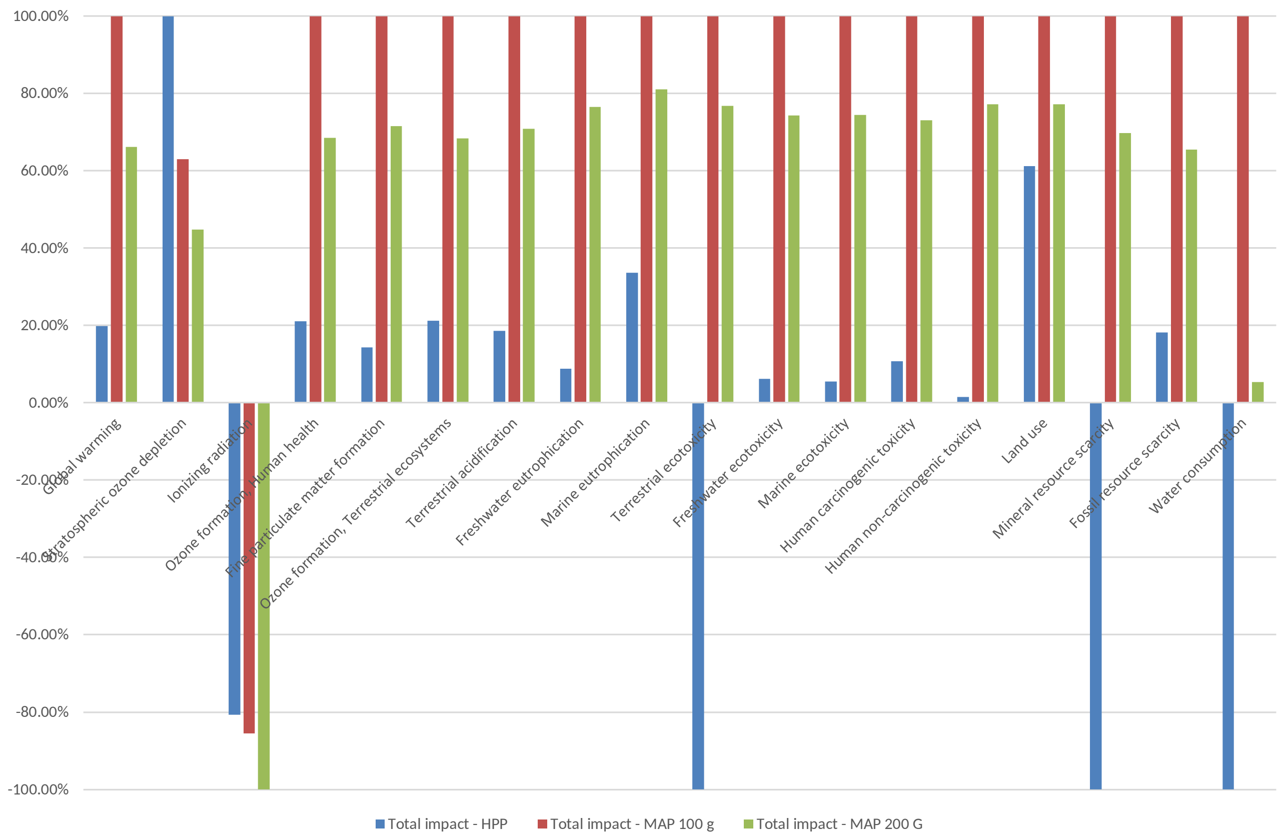

Figure 16: comparison of the environmental impacts of HPP and MAP for Parma ham processing.

6 DISCUSSION AND CONCLUSIONS

Two different methodologies, i.e. LCC and LCA, were used in this study to analyze and compare four technologies typically used as conservation methods for food, i.e. indirect TP with hot filling, retort TP, HPP and MAP. As lifecycle-oriented methodologies, LCC and LCA are highly valuable for evaluating the full economic and environmental consequences associated with each processing technology, therefore facilitating comparisons between them.

The study took into account two different food products, i.e. orange juice and Parma ham. The former can be treated either with TP (indirect or retort) or HPP, while the latter can be processed either with MAP (sliced ham) or HPP (whole ham); accordingly, two comparisons were carried out in the study. The results of the first comparison showed that orange juice conservation with TP (both with indirect and retort processes) is more favorable than HPP from an economic perspective: the cost of processing 1 kg of juice with HPP is approximately 1.78 and 1.40 times the corresponding cost for the TP-indirect and the TP-retort treatments respectively. Looking at the cost categories, HPP requires a very high level of initial investment and a relatively high maintenance cost, both of which are significantly higher than the corresponding costs for TP systems. These results differ from those of Sampedro et al. (2014), who found that HPP was significantly (7 times) more expensive than conventional thermal processing; however, their analysis did not include the processes associated with the juice treatment before or after pasteurization nor the packaging of the juice.

From an environmental point of view, HPP is more efficient than both TP processes, which exhibit higher numerical values in most of the impact categories considered in the evaluation. A possible explanation for this outcome is that while HPP makes use of more electricity than TP, the TP processes make use of steam, which is (typically) produced burning methane in industrial boilers. As the treatments are different, not necessarily the impact of TP should be lower than that of HPP. This interesting result demonstrates that not always the less expensive technology is also the most environmental friendly. The previous study by Manfredi & Vignali (2015) reported lower impact values for higher capacity industrial aseptic and hot-filling plants for orange juice treatment, considering an indirect heat exchange between the juice and superheated hot water. Generally, analyses made on bigger industrial plant show lower consumption per liter or kg, as reported also for retort TP by JBTC[8].

The second comparison shows instead that HPP is more efficient than MAP both from an environmental and an economic perspective. The cost of processing 1 kg of Parma ham with MAP is 3.16 times higher than that of HPP processing (2.5 in case of 200 g trays). Besides the fact that the secondary packaging is less efficient when shipping sliced ham rather than whole ham, most of the cost of MAP is due to the volume of packaging material required for the trays. From an environmental perspective, MAP generates a higher environmental impact and lower environmental benefits than HPP in almost all impact categories considered, whilst the MAP process has a lower environmental impact than HPP in stratospheric ozone depletion and ionizing radiation only. This result is different from that obtained by Pardo & Zufia (2012), who found that MAP was more

[8] https://www.jbtc.com/-/media/files/foodtech/products/pasteurization-sterilization/jbt-whitepaper-abrs-en.ashx

suitable than HPP for food preservation. However, these authors evaluated a different food product (i.e. 1 kg of pre-cooked dish of fish and vegetables), with a shelf-life lower than 30 days. This kind of product requires a pre-cooking (for both HPP and MAP) and cooling process (for HPP only), which are not required when processing Parma ham. Moreover, a cradle-to-grave approach was adopted in the analysis, instead of the gate-to-gate approach used in this paper.

The present study is technical in nature and aims primarily at evaluating and comparing the cost and environmental effects of the MAP, HPP and TP treatments used for processing food products. In line with this aim, aspects related to the properties of the finished products (e.g. shelf-life or quality) were not directly evaluated, which means that they were implicitly assumed not to be influent in the consumers' choice across the different technologies. Although this assumption is supported by the available literature, future research activities could be directed toward the evaluation of the cost and environmental impact of finished products processed using the different technologies able to give different shelf-life, to complement this work, considering also the impact of food waste.

REFERENCES

1. Aaby, K., Grimsbo, I.H., Hovda, M.B., Rode, T.M., 2018. Effect of high pressure and thermal processing on shelf life and quality of strawberry purée and juice, Food Chemistry, 260, 115-123.
2. Aganovic, K., Smetana, S., Grauwet, T., Toepfl, S., Mathys, A., Van Loey, A., Heinz, V., 2017. Pilot scale thermal and alternative pasteurization of tomato and watermelon juice: An energy comparison and life cycle assessment. Journal of Cleaner Production, 141, 514-525.
3. Atuonwu, J. C., Tassou S. A., 2018. Model-based energy performance analysis of high pressure processing systems, Innovative Food Science and Emerging Technologies, 47, 214 224.
4. Autorità di Regolazione per Energia Reti e Ambiente, 2018. Prezzi e tariffe. Available online at https://www.arera.it/it/prezzi.htm (accessed May 2018)
5. Bak, K.H., Lindahl, G., Karlsson, A.H., Lloret, E., Gou, P., Arnau, J., Orlien, V., 2013. The effect of high pressure and residual oxygen on the color stability of minced cured restructured ham at different levels of drying, pH, and NaCl. Meat Science, 95(2), 433-443.
6. Cilla, I., Martínez, L., Beltrán, J.A., Roncalés, P., 2006. Dry-cured ham quality and acceptability as affected by the preservation system used for retail sale. Meat Science, 73(4), 581-589.
7. Contratto collettivo nazionale del lavoro per i lavoratori dell'industria alimentare, 2015. Available online at http://www.faicislverona.it/wp-content/uploads/2017/08/CCNL-Industria-Alimentare-2015-2019.pdf (accessed May 2018).

8. Corepla, 20186. Relazione sulla gestione. Retrieved June 2019 May 2018 from 641 http://www.corepla.it/documenti/c3cc963b-c446-46c3-809b-e17e487f8e2d/RELAZIONE+SULLA+GESTIONE+2018.pdfhttp://www.corepla.it/documenti/621248cb-892c-4351-bef3-4e55f4559919/03+Relazione+sulla+gestione+2016.pdf

9. De Luca, A.I., Falcone, G., Stillitano, T., Strano, A., Gulisano, G., 2014. Sustainability assessment of quality-oriented citrus growing systems in Mediterranean area. Quality - Access to Success, 15(141), 103-108.

10. Dhillon, B.S., 2010. Life Cycle Costing for Engineers. Taylor & Francis, Boca Raton (US).

11. Eurostat, 2018. Packaging waste statistics. Available at http://ec.europa.eu/eurostat/statistics-explained/index.php/Packaging_waste_statistics (accessed July 2018).

12. Ireti, 2016. Tariffe 2016-2017. Available at http://acquaemilia.ireti.it/upload/pagine/pagine/2602-parma%20tariffe%202016.pdf (accessed May 2018).

13. ISO 14040:2006. Environmental management – Life cycle assessment – Principles and framework. International Standards Organisation.

14. ISO 14044:2006. Environmental management – Life cycle assessment – requirements and guidelines. International Standards Organisation.

15. Koutchma, T., 2014. Adapting High Hydrostatic Pressure (HPP) for Food Processing Operations - 1st ed. Academic Press ISBN: 9780124200913.

16. Life cycle initiative, 2013. An Analysis of Life Cycle Assessment in Packaging for Food & Beverage Applications. Available at https://www.lifecycleinitiative.org/wp-content/uploads/2013/11/food_packaging_11.11.13_web.pdf (accessed September 4, 2019).

17. Manfredi, M., Fantin, V., Vignali, G., Gavara, R., 2015. Environmental assessment of antimicrobial coatings for packaged fresh milk. Journal of Cleaner Production 95, 291-300.

18. Manfredi, M., Vignali, G., 2015. Comparative life cycle assessment of hot filling and aseptic packaging systems used for beverages. Journal of Food Engineering 147, 39-48.

19. Martínez-Onandi, N., Rivas-Cañedo, A., Picon, A., Nuñez, M., 2018. Influence of compositional characteristics and high pressure processing on the volatile fraction of Iberian dry-cured ham after prolonged refrigerated storage. Innovative Food Science and Emerging Technologies, 49, pp. 127-135.

20. Milani, E.A., Ramsey, J.G., Silva, F.V.M., 2016. High pressure processing and thermosonication of beer: Comparing the energy requirements and Saccharomyces cerevisiae ascospores inactivation with thermal processing and modeling. Journal of Food Engineering, 181, 35-41.

21. Mosna, D., Vignali, G., 2015. Three-dimensional CFD simulation of a "steam water spray" retort process for food vegetable products. International Journal of Food Engineering, 11(6), 715-729.

22. Mujica-Paz, H., Valdez-Fragoso, A., Tonello, C., Welti-Chanes, J., & Torres, J. A., 2011. High pressure processing technologies for the pasteurization and sterilization of foods. Food and Bioprocess Technology, 4, 969–985.

23. Niero, M., Di Felice, F., Ren, J., Manzardo, A., Scipioni, A., 2014. How can a life cycle inventory parametric model streamline life cycle assessment in the wooden pallet sector? International Journal of Life Cycle Assessment, 19(4), 901-918.

24. Oey, I., Lille, M., Van Loey, A., Hendrickx, M., 2008. Effect of high-pressure processing on colour, texture and flavour of fruit- and vegetable-based food products: a review. Trends in Food Science and Technology, 19(6), 320-328.

25. Pardo G., Zufía J., 2012. Life cycle assessment of food-preservation technologies. Journal of Cleaner Production, 28, 198-207.

26. Parra, V., Viguera, J., Sánchez, J., Peinado, J., Espárrago, F., Gutierrez, J.I., Andrés, A.I., 2010. Modified atmosphere packaging and vacuum packaging for long period chilled storage of dry-cured Iberian ham. Meat Science, 84(4), 760-768.

27. Pérez-Santaescolástica, C., Carballo, J., Fulladosa, E., Munekata, P.E.S., Bastianello Campagnol, P.C., Gómez, B., Lorenzo, J.M., 2019. Influence of high-pressure processing at different temperatures on free amino acid and volatile compound profiles of dry-cured ham. Food Research International, 116, pp. 49-56.

28. Pingen, S., Sudhaus, N., Becker, A., Krischek, C., Klein, G., 2016. High pressure as an alternative processing step for ham production. Meat Science, 118, 22-27.

29. Rastogi, N.K, 2013. Recent Developments in High Pressure Processing of Foods, Springer, ISBN 978-1-4614-7055-7.

30. Ristimäki, M., Säynäjoki, A., Heinonen, J., Junnila, S., 2013. Combining life cycle costing and life cycle assessment for an analysis of a new residential district energy system design. Energy, 63, 168-179.

31. Sampedro, F., McAloon, A., Yee, W., Fan, X., Geveke, D.J., 2014. Cost Analysis and Environmental Impact of Pulsed Electric Fields and High Pressure Processing in Comparison with Thermal Pasteurization. Food and Bioprocess Technology, 7(7), 1928-1937.

32. Sampedro, F., McAloon, A., Yee, W., Fan, X., Zhang, H. Q., Geveke, D.J., 2013. Cost analysis of commercial pasteurization of orange juice by pulsed electric fields. Innovative Food Science and Emerging Technologies, 17, 72–78.

33. SETAC, 1993. Guidelines for Life- Cycle Assessment: a Code of Practice. Bruxelles.

34. Stillitano, T., Falcone, G., Spada, E., De Luca, A.I., Grillone, N., Strano, A., Gulisano, G., 2017. An economic sustainability assessment of "Fichi di Cosenza" PDO production compared with other profitable permanent crops. Acta Horticulturae, 1173, 395-400.

35. Wibowo, S., Essel, E.A., De Man, S., Bernaert, N., Van Droogenbroeck, B., Grauwet, T., Van Loey, A., Hendrickx, M. 2019. Comparing the impact of high pressure, pulsed electric field and thermal pasteurization on quality attributes of cloudy apple juice using targeted and untargeted analyses. Innovative Food Science and Emerging Technologies, 54, pp. 64-77.

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Authorship contributions

Please indicate the specific contributions made by each author (list the authors' initials followed by their surnames, e.g., Y.L. Cheung). The name of each author must appear at least once in each of the three categories below.

Category 1

Conception and design of study: G. Vignali, E. Bottani, ______, ______;

acquisition of data: F. Cacace, ______, ______, ______;

analysis and/or interpretation of data: G. Vignali, E. Bottani, A. Rizzi, ______.

Category 2

Drafting the manuscript: G. Vignali, E. Bottani, A. Rizzi, F. Cacace;

revising the manuscript critically for important intellectual content: G. Vignali, E. Bottani, ______, ______.

Category 3

Approval of the version of the manuscript to be published (the names of all authors must be listed):

G. Vignali, E. Bottani, A. Rizzi, F. Cacace, ______,

______, ______, ______, ______, ______.

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This statement is signed by all the authors (*a photocopy of this form may be used if there are more than 10 authors*):

Author's name (typed)	Author's signature	Date
Federica Cacace	Federica Cacace	December 19, 2019
Eleonora Bottani	Eleonora Bottani	December 19, 2019
Antonio Rizzi	Antonio Rizzi	December 19, 2019
Giuseppe Vignali	[illegible]	December 19, 2019