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Life cycle assessment of food-preservation technologies

Guillermo Pardo*, Jaime Zufía

Food Research Division, AZTI-Tecnalia, Bizkaia Technology Park, Astondo Bidea, Edificio 609, 48160 Derio, Vizcaya, Spain

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ABSTRACT

The environmental impacts of some traditional and novel food preservation technologies have been evaluated through LCA methodology in order to provide environmental criteria when selecting preservation methods for foods, as a way to develop more efficient and sustainable food products throughout its whole life cycle. Four thermal and non-thermal techniques (autoclave pasteurization, microwaves, high hydrostatic pressure and modified atmosphere packaging) were selected according to their suitability for the inactivation of the dish case study and a comparative cradle-to-grave LCA was performed following ReCiPe methodology for impact assessment. Emerging techniques showed reduced environmental impacts in terms of energy demand and CO_2 emissions in relation to conventional pasteurization. Additionally, lower water requirements were observed for non-thermal technologies (MAP, HPP) in comparison to equivalent thermal processes. Modified atmosphere packaging (MAP) was found to be the most sustainable option when a shelf life period below 30 days is required. The most significant impact sources of the life cycle from every technology were analyzed and several potential improvements were identified, based on a technical and environmental point of view.

1. Introduction

During the last years, the agri-food chain has been identified as a priority area of essential concern in terms of environmental sustainability, especially since the contribution of the products in the food and drink sectors to the environmental impact of the private consumption was estimated to be about 20–30% in the EU (Tukker et al., 2006), and the European Technology Platforms Food for Life defined sustainable food production as the most important challenge that will be faced by the European food industry. Therefore, there is increased awareness that the environmentally conscious consumer of the future will consider ecological and ethical criteria in selecting food products.

Together with environmental sustainability, in developed countries consumers demand for safe food products, with improved nutritious and sensorial attributes and an acceptable shelf life (Devlieghere et al., 2003). This challenge of enhancing microbial food safety and quality, without compromising the nutritional, functional and sensory characteristics of foods has created an increasing interest for improvements in existing technologies and for the development of new food preservation methods. As a result of these research efforts, in the last decade alternative food inactivation techniques have emerged being considered promising alternatives to gradually replace the traditional well-established preservation processes, such as thermal pasteurization, or sterilization, among others.

Traditional thermal methods are predominantly used in the food industry for their efficacy and product safety record. These techniques are based on indirect heat transference into the product by conduction and convection principles, using a heating medium such as steam or hot water externally generated by combustion of fossil fuels. This kind of processing often entails some restrictions and energy inefficiencies derived of slow heat conduction, losses of heat through the surfaces of the equipment and thermal damage by overheating, due to the time required to conduct sufficient heat into the thermal center of foods. Excessive heat treatment may not only imply a considerable consumption of natural resources but also cause undesirable protein denaturation and loss of vitamins and volatile flavor compounds leading to deterioration of food quality and finally reducing the efficiency of food chain (Lado and Yousef, 2002; Pereira and Vicente, 2010).

However, retorting can be greatly improved upon by eliminating the excessive heating with rapid and more uniform heating from a direct interaction between radio frequency (RF) or microwave (MW) energy and the food (Wang, 2003). Recently, electromagnetic technologies in food processing, which includes RF and MW heating have gained increased industrial interest, since they are regarded as forms of heating in which thermal energy is generated directly inside the food, which allows to overcome excessive

* Corresponding author. Tel.: +34 946574000; fax: +34 946572555.
E-mail address: gpardo@azti.es (G. Pardo).

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cooking times and consequently may have direct implications in terms of both energetic efficiency and food quality (Pereira and Vicente, 2010).

Alternatively, non-thermal preservation methods such as high hydrostatic pressure (HPP), pulsed electric fields (PEF) and modified atmosphere packaging (MAP), allow the processing of foods below temperatures used during thermal pasteurization, so flavors, essential nutrients, and vitamins undergo minimal or no changes (Morris et al., 2007; Wan et al., 2005; Devlieghere et al., 2003; Lado and Yousef, 2002). Although some of the advantages and limitations in food quality derived from the application of novel technologies have been described by several authors; there is still a lack of deeper study in regards to the environmental implications and potential improvements that the advances in food preservation could imply through the whole life cycle sustainability of a product.

Thermal preservation treatment has been pointed out as one of the most energy consuming stages in food processing sector (EC, 2006) and non-thermal food processing methods have been considered more energy efficient than conventional thermally based processes leading to important resource savings (Morris et al., 2007). In addition to this, improved preservation methods, such as high pressure processing, have proven their efficacy in order to increase the shelf life of food products while reducing nutritional losses (Butz et al., 2004; Fernández García et al., 2001; Oey et al., 2008; Patras et al., 2009) thus meeting food caloric demand but also nutritional needs, and therefore they could represent a step forward towards more efficient and sustainable food chains.

To our knowledge, there are just a few recent references about the specific analysis of prepared meals from a LCA perspective. Zufía and Arana (2008) carried out a LCA of a cooked tuna with tomato dish with and eco-design approach. Fish harvesting and supply of tunids was identified as the most important stage whilst product elaboration accounted for 15–25% of the total impact depending on the impact category considered. More recently Calderón et al. (2010) investigated the entire life cycle of a canned ready meal based on cooked pulses and pork meat. Food production showed the highest environmental load, however energy assignable to gas and electricity used at industrial level was found to have a remarkable contribution (up to 26% of the global impact) in some specific categories such as global warming and abiotic depletion.

In addition to this, the importance of the processing stage in the whole life cycle of elaborated food products has been pointed by several authors (Andersson et al., 1998; Davis and Sonesson, 2008) whereas process heating required for processing and food preservation techniques such as dehydration or sterilization has been estimated approximately for about 29% of the total energy used in the food sector (EC, 2006).

Taking into account these findings the present report is an attempt to evaluate from a LCA perspective the preservation stage and all the requirements applied during manufacturing process in order to ensure food safety and extend the shelf life of prepared meals. Under the framework of a project funded by Basque Government, an LCA comparison of some traditional and novel food preservation technologies was performed as part of an eco-design initiative, in order to develop more efficient and sustainable food products throughout its whole life cycle. This study aims to identify potential improvements for every technology and to provide environmental criteria when selecting preservation processing for foods.

2. Life cycle assessment methodology

Life cycle assessment (LCA) is a methodology to quantify the potential environmental impacts associated with a product, process or activity. This method has become an important tool for authorities and industries in order to compare alternative products, processes or services, or to identify those parts of the life cycle where the greatest improvements can be made. According to ISO 14040 (International Organization for Standardization, 2006), there are three main phases in this kind of study: the goal and scope definition, the inventory analysis and the impact assessment.

LCA has been applied to food products since the early 1990s in order to address questions about the environmental impact of food products and processes, implying that the system under study was possible to investigate in detail; however when new products or processes are to be evaluated, some relevant issues may need careful attention. An important review was made by Hospido et al. (2010) who identified the key methodological elements to be considered for the specific application of LCA to novel products or processes. The recommended approach that was described in their work has been followed in the present study.

3. Goal and scope definition

3.1. Objectives

The main goal of this study, part of a research project funded by Basque Government, was to compare the environmental aspects and impacts associated with different food preservation methods and to identify the key issues of the life cycle of every evaluated technology as a way to potentially improve their environmental performance.

3.2. Type of LCA

Following the typology proposed by Sandén et al. (2005), LCA studies can be categorized in different ways, according to three different dimensions: responsibility, time perspective, and product or technology orientation.

Unlike more traditional LCAs, which investigate the impact of a specific production process or product, the present study aims to be a comparative assessment between some equivalent techniques, representing an example of technology LCA. Furthermore, since the analyzed system involves some emerging technologies, a prospective attributional LCA was assumed to be the most suitable approach, following previous authors' recommendations (Sandén et al., 2005; Hospido et al., 2010). In this way, an expected energetic scenario for 2020 has been included as an attempt to consider a hypothetical future situation.

3.3. The product and the system investigated

The target product is a ready-to-eat meal based on fish and vegetables, which is commonly commercialized in the Spanish market among others pre-cooked pasteurized items. In the last years the production of this kind of items has risen up significantly together with the consumers demand for high-quality foods that require only a minimum amount of time and effort for preparation, and a continuous growth is expected for the future. According to MARM (2007) the consumption of prepared meals in Spain increased 346.5% between 1988 and 2005. As can be seen in Fig. 1 prepared meals have risen continuously since 2000 whereas conventional fish products showed a slower growth in the Spanish market during the same period.

According to their suitability for the preservation of the dish case study, four different technologies were selected following related literature, expert's advice and supplier's recommendations. Food preservation methods included in the analysis, together with critical factors considered and estimated operational conditions are shown in Table 1.

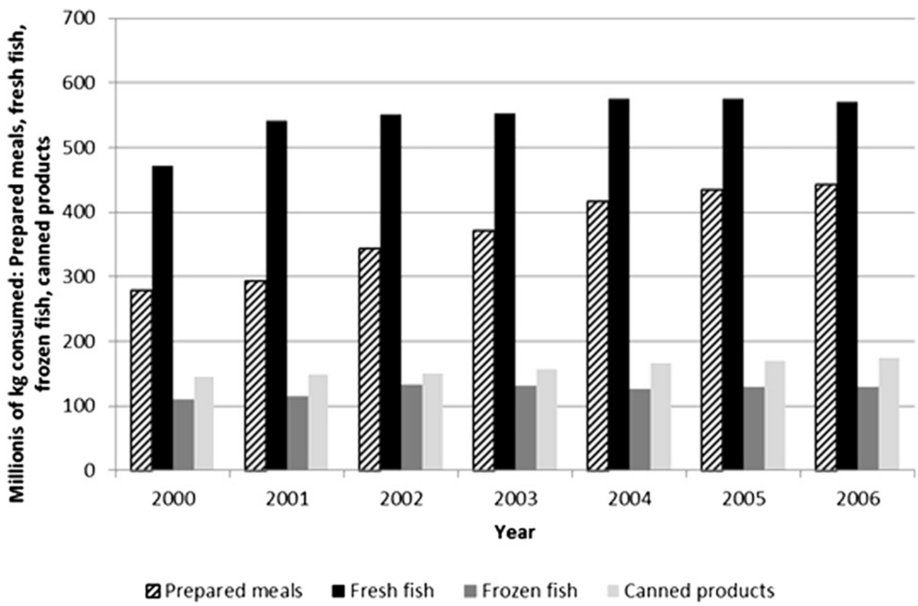

Fig. 1. Evolution in consumption of prepared meals and fish food products in Spain (2000–2006). Prepared meals in striped columns, fresh fish in black columns; frozen fish in dark gray columns; canned products in light gray columns.

3.3.1. Thermal pasteurization (AC)

Typical pasteurization retorting process involves three main phases: product heating, temperature holding and rapid cooling. The first stage, heating, utilizes a heating medium to ensure rapid heat transmission to the product. In the second stage the product is held at a constant temperature for a defined period. The third stage consists in rapid cooling and it involves specific devices (abattoirs) which guarantee a rapid temperature drop in the product.

3.3.2. Thermal pasteurization (MW)

Microwave heating can be used to deliver thermal energy to kill microorganisms in foods and has been investigated for in-package pasteurization of different food items (Huang and Sites, 2007; Wang, 2003; Tang et al., 2008). It utilizes electromagnetic energies at frequencies of 915 MHz or 2450 MHz to generate heat in foods. The electromagnetic energies at these frequencies can induce rotation and friction among water molecules in foods, thus causing internal heat generation. Therefore microwave energies that penetrate into solid foods can produce volumetrically distributed heating effects (Oliveira and Franca, 2002), thus rapidly increase the internal temperatures of foods. Compared with conventional heating using water or steam as the heating media for package foods, MW energy has the potential to provide more uniform and rapid volumetric heating.

3.3.3. High pressure processing (HPP)

In the past, the potential of HPP for commercial utilization was restricted, mainly due to limitations on the capacity of the pressure vessels, making the process impractical (Defaye et al., 1995; Farr, 1990). Nowadays, with advances in technology and cost reduction, the process has become feasible for a great variety of products in the United States, Europe and Japan (i.e: jams, jellies, squid, oysters, meat products, juices, and yogurt) (Sizer et al., 2002). Its applicability to treat different kind of fish products has also been reported by several authors (Ramirez-Suárez and Morrissey, 2006; Sequeira-Muñoz et al., 2006; Gomez-Estaca et al., 2007; Lakshmanan et al., 2003).

3.3.4. Modified atmosphere packaging (MAP)

Modification of the atmosphere within the package by decreasing the oxygen concentration, while increasing the content of carbon dioxide and/or nitrogen, has been shown to significantly prolong the shelf life of perishable food products at chill temperatures (Parry, 1993). Modified atmosphere packaging (MAP) along with refrigeration, have become increasingly popular preservation techniques, which have brought major changes in storage, distribution, and marketing of raw and processed products to meet consumer demands (Özogul, 2004). The effects of modified atmosphere packaging on seafood, fish products and ready-to-eat foods

Table 1
Selected food processing methods for the comparative analysis.

Process	Description	Critical factors for food processing	Process conditions
Thermal pasteurization (AC)	Thermal treatment using water or injected steam as heat medium.	Indirect heat transfer to the product. Loss of nutritional and sensory quality.	35 min, 90 °C
Microwaves (MW)	Thermal treatment by microwaves radiant exposure.	Efficient heat transfer to the product. Moderated loss of food nutritional and sensory quality.	35 min, 90 °C
High pressure processing (HPP)	Non-thermal processing by subjecting food to high hydrostatic pressures.	Slight changes in original food quality. Batch and semi-continuous systems.	8 min, 500 MPa
Modified atmosphere packaging (MAP)	Enclosure in gas-barrier materials, with controlled gaseous environment.	Original freshness and characteristics of food. Limited shelf life.	80% CO_2/20% N_2 Gas/product ratio = 1.5

have been studied extensively (Davis, 1993; Fernández et al., 2009; Murcia et al., 2003).

3.4. Functional unit

The functional unit (FU) provides a reference to which the inventory data can be normalized. In this case study FU was defined as the application of a preservation treatment to 1 kg of the selected product (200 g pre-cooked dish of fish and vegetables) in order to achieve a realistic shelf life period that could guarantee its commercial purpose. A threshold of 30 days was proposed and those techniques which didn't reach this requirement were discarded for the study.

3.5. System boundaries

Fig. 2 shows the scope of the study which ranges the different stages throughout the life cycle of every technology, including extraction of raw materials, manufacturing of equipment, transportation, food preservation processing and end-of-life scenario. With regards to the food processing stage, just those steps related with the preservation treatment were involved in the analysis, since the rest are similar in the four cases. Within the global product elaboration process, the boundaries of the study begin in the packaging stage, just before preservation treatment is performed, and it finishes once the product is stored, previously to its distribution. Furthermore, some especial considerations have been added in order to adapt non-thermal techniques (HPP, MAP) to the comparative study.

Previously to preservation in trays, ready-to-eat meals are usually cooked before they are placed into the packaging container. However in some cases, precooking step can be avoided if it is feasible to cook the food item subsequently during the pasteurization stage. The circumstances which enable precooking to be avoided and cooking to take place during the sterilization step depend on factors such as the size of the food pieces; the package characteristics; the recipe; ensuring the quality of the product and the length of the pasteurization time. According to consulted industrial processor, for the selected item under study, this procedure is applied, achieving reduced water and energy consumption.

Since non-thermal technologies (HPP, MAP) don't allow to cook the food during preservation treatment, in order to establish equivalent conditions for adequate comparison between the four technologies, an specific step of cooking has been considered for those scenarios involving HPP and MAP. This is especially adequate in the case of MAP, which requires a previous mild thermal treatment in order to enhance the targeted shelf life. In addition to this, differences in the packaging material were also considered, and gas cylinders consumption was accounted during modified atmosphere packaging process.

The following aspects were left outside the system boundaries:

- Product elaboration stages not related to food preservation.
- Packaging boxes and materials necessary for the transport of machinery.
- Materials which represent less than 1% of machinery weight
- Infrastructures and buildings required for processing.

Although some references estimate an average life span of 6 years for food cannery machinery and equipment (Office of financial management, 2010) in this study a minimum lifespan of 10 years for boilers and pressure vessels was set following producer's and manufacturer's indications. Nevertheless some devices, such as pumps, meters or electrical instrumentation may have shorter useful life, that was set around 5 years, and similarly, other parts of the installation involved in the preservation stage (i.e.: pipework and cooling towers) can achieve extended life spans, estimated about 20 years for the case of study.

3.6. Current and future scenario development

Emerging technologies evaluated in this study (HPP, MW) have been intensively investigated and developed in the last decade. In spite of the research effort and investment, although they are

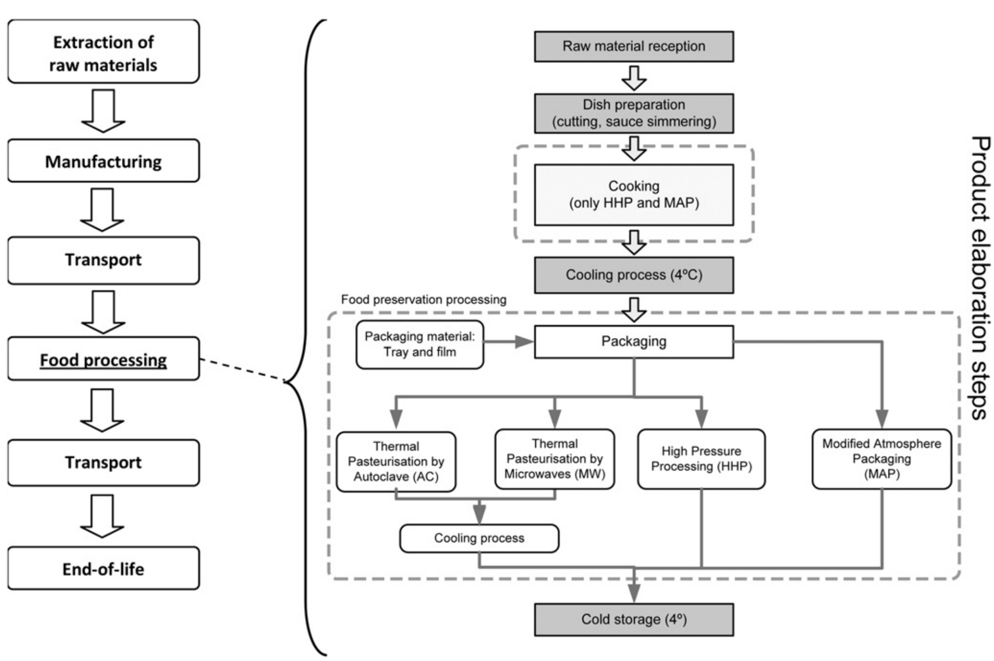

Fig. 2. System boundaries of the evaluated preservation techniques. Extraction of raw materials, manufacturing, transport and end-of-life is referred to the equipment involved. Discontinuous lines indicate the product elaboration steps related to food preservation within the limits of the study. Cooking step was added for the high pressure processing and modified atmosphere packaging methods.

already available, most of them have not yet been widely implemented in the food sector at industrial scale. Nevertheless, novel processing techniques are expected to gradually replace established ones since they may produce similar products with improved characteristics. For these reasons the current state may not be very relevant. As an attempt to evaluate the environmental impact in a future state with larger adoption of the selected emerging technologies, a predictive scenario of a possible future state in 2020 has been introduced.

The European Council in 2007 adopted ambitious energy and climate change objectives for 2020 to reduce greenhouse gas emissions by 20%, to increase the share of renewable energy to 20%, and to make a 20% improvement in energy efficiency. Different measures are being adopted in the electricity and transport sectors that set national sectorial targets. To that end, like its European counterparts, Spain has defined quantifiable and attainable objectives.

Following the energy trends scenarios expected in Spain for 2020 (Oscariz et al., 2008) differences within the system boundaries on a time perspective have been considered, mainly in terms of the electricity mix and fossil fuel consumption. As shown in Fig. 3, the predicted source mix in power generation in 2020 exhibits significant changes in comparison to the reference scenario in 2009. In the new context a significant decrease in coal/lignite generation is expected, while renewable power generation would make an impressive development and is projected to account for 45% share of total generation in 2020.

With regards to biomass energy current trends suggest is not on track to play the important role envisioned by the previsions. According to this, no significant replacement in the steam production technology -in the way of biomass boilers installation- has been expected within the food industry in the next years. Nevertheless, a change has been considered in the shares of the different fossil fuels, since it is projected the share of natural gas in total fossil fuel consumption to increase 2.5 percentage points in 2020.

3.7. Data quality

All inputs and outputs of the life cycles evaluated were characterized, quantified and introduced into specific LCA software: SIMAPRO 7.3. Considered data were collected from two main sources:

- Detailed information for thermal pasteurization by autoclave with regards to energy, chemicals and water requirements during the preservation process was gathered from two Spanish facilities. The inventory was mainly based on site-specific data collected during 2009 through technical visits using questionnaires, interviews and internal reports. It represents average data from a typical day of production.
- Data of alternative preservation methods (MW, HPP, MAP) are mainly based on e-mails and personal communications with specialized technology suppliers. Details of microwave pasteurization, modified atmosphere packaging gases and high pressure processing equipment were provided from Sairem Ibérica (2009), Air Liquide S.A. (2009) and NC Hyperbaric (2009) respectively. Additional information of the four techniques was gathered from the equipment and experiments at AZTI-Tecnalia's pilot plant. Most of the inventory details were collected in 2009.
- The rest of the complementary information, such as material production, energy supply, transportation and waste management data were obtained from databases (Ecoinvent 2.0), sectorial reports and scientific papers.

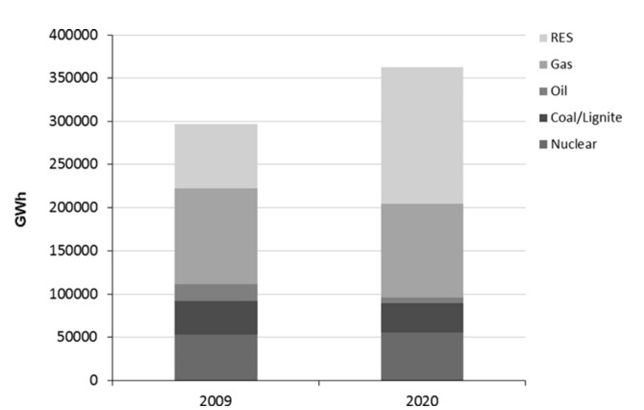

Fig. 3. Gross power generation in Spain by source in GWh. SOURCE: Oscariz et al., 2008 (RES = Renewable Energy Sources).

4. Life cycle inventory

For the life cycle inventory, a brief summary of the principal processes and estimated input data for the production and processing stage are shown in Table 2. Energy and material demands during manufacturing stage was estimated according to the weight of the machinery required for every preservation technology and the composition of its main components. Mass allocation was performed in those phases related with equipment (extraction of materials, manufacturing, transport, end-of-life), so the environmental impact of this stages was divided between the total amount of food items potentially treated in the expected lifespan of the equipment.

For electricity from a grid, average Spanish electricity mix production 2020 was estimated as presented by Oscariz et al. (2008) and also from Ecoinvent 2.0 references. Typical mineral extraction and manufacturing processes for steel and metals were inventoried based on readily available data from the Ecoinvent 2.0 database.

Polypropylene (PP) based tray and film were considered as packaging materials, being suitable for most of the evaluated treatments. An additional co-extruded ethylene vinyl alcohol (EVOH) layer is included to provide the gas barrier proprieties in the case of modified atmosphere packaging. Ethylene vinyl acetate copolymer (EVA) data was used as a proxy for EVOH according to Humbert et al. (2009).

Table 2
Summary of main inventory data per FU (1 kg of product).

Inputs from Technosphere	AC	MW	HPP	MAP
Manufacturing stage:				
Input of steel for food processing machinery (g)	0.55	0.45	9.1	0.1
Input of steel for cooling system (g)	0.35	0.35	0.15	–
Processing stage:				
Pre-cooking:				
Gas: (Wh)	–	–	76.5	76.5
Preservation treatment				
Electricity (Wh)	5.5	320	200	104
Process water (tonne)	–	–	0.5	–
Steam (kg)	1.05	–	–	–
Compressed air (l)	9.1	–	0.7	–
Gas: (N_2/CO_2) (l)	–	–	–	1.5
Cooling process				
Electricity (Wh)	26.6	26.6	9.55	–
Process water (kg)	3.1	3.1	1.4	–
Hydrogen peroxide (g)	2	2	–	–
Packaging materials:				
Polypropylene (g)	51.5	51.5	51.5	51.5
Ethyl Vinyl Alcohol (g)	–	–	–	5

Average national recycled percentages (77%) were handled concerning steel waste (Ecoacero, 2009) while electricity consumption for mechanical dismantling was estimated from Althaus et al. (2004). The remaining waste materials after the useful life period of the equipment were supposed to be disposed of in landfills modeled from Ecoinvent 2.0 database.

In the case of autoclave pasteurization, a heat treatment reaching a temperature of 90 °C for 35 min was estimated for product preservation. Injected steam was assumed as the heat medium, produced from natural gas (50%) and fuel oil (50%) according to references of steam production average in the ready-to-eat industry (EC, 2006). A closed-loop refrigeration system, including a water cooling tower, has been considered for the pre-cooling stage, while a specific freezer was taken as final cooling unit. Water losses due to evaporation were accounted, together with hydrogen peroxide consumption, used as process water disinfectant.

Similar thermal treatment was assumed for microwaves pasteurization than that for autoclave, although one third less time was considered to reach the same operational conditions (35 min, 90 °C). Electricity consumption was estimated assuming average ratio 0.32 kWh/kg. The same refrigeration scheme was accounted as for autoclave pasteurization (AC).

For high pressure processing a pressurization treatment of 500 MPa for 8 min was estimated for the case study according to supplier recommendations and literature reviewed. Electricity consumption was considered for start-up stage and continuous performance (0.2 kWh/kg). Water requirements were accounted for cooling system (1.4 l/kg) and filling pressure vessel (0.5 l/kg).

A standard gas mixture for food purposes of CO_2/N_2 (80:20) was considered adequate for the modified atmosphere packaging of the analyzed item, and a gas/product ratio of 1.5 according to manufacturer data. The assumed composition of the co-extruded multilayer packaging material (PP/EVOH/PP) was: PP (90%)/EVOH (10%). Co-extrusion process was taken from Ecoinvent 2.0 database.

5. Life cycle impact assessment

Among the different LCA impact assessment methods available with Simapro™ software (PRè, 2011), the ReCiPe midpoint method (Goedkoop et al., 2009) was chosen. Following the default list of impact categories elaborated by Guinée et al. (2001), four impact categories were selected among the so-called “baseline impact categories”: Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential (GWP), and Photochemical Oxidant Formation Potential (PO).

Additionally, Water Depletion (WD) category from ReCiPe 2010 methodology was also considered, since water consumption has been identified as one of the most challenging aspects which food industries have to face in the current context and it has an important relevance in the studied region, and Cumulative Energy Demand (CED) (Jungbluth and Frischknecht, 2004) was chosen as an energy flow indicator. Impact categories related to toxicity were not involved due to the lack of consensus in the international community on how to deal with them in LCIA (Martínez-Blanco et al., 2009).

For classification step, collected data are classified into different categories in accordance to their potential impact on the environment. Then, characterization is performed in order to quantify the potential contribution of an input or output to every specific impact. Furthermore, normalization stage allows to compare the relative importance of each impact category using the same scale, according to their specific contribution in the area and time covered by the study. In the present work, the situation in Europe (data from year 2008) was taken as the reference scenario.

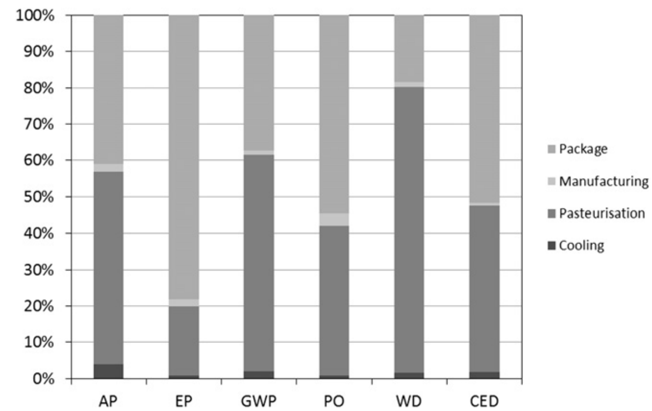

Fig. 4. Environmental impact potentials for thermal pasteurization by autoclave (AC) per FU.

Figs. 4–7 show the results obtained for every preservation technology analyzed individually, divided in different subsystems according to the reference scenario. Figs. 8 and 9 show the results obtained from the characterization and normalization phases Table 3.

6. Interpretation of results and discussion

6.1. Contribution analysis for every technology

LCAs performed individually to every technology revealed that within the specific boundaries of the study the main contributions to the environment are produced in the food processing stage during preservation treatment application, representing between 50 and 80% of the total impact in almost all the categories. This can be attributed to the large energy and water resources demanded during the preservation treatment. Since heat and electricity production steps often implies hydrocarbon combustion processes, this stage involves most of the air emissions to the atmosphere affecting categories such as climate change or acidification potential.

As can be observed in Figs. 4–7, package also implies a considerable share of the total evaluated impacts. The production stage of the packaging system has been identified to be the principal cause for part of the major impacts. Previous studies have pointed out the importance of this aspect in the life cycle of processed foods (Davis et al., 2009; Calderón et al., 2010; Andersson et al., 1998). In present study, according to its technical feasibility, similar composition and characteristics of the package system have been considered for

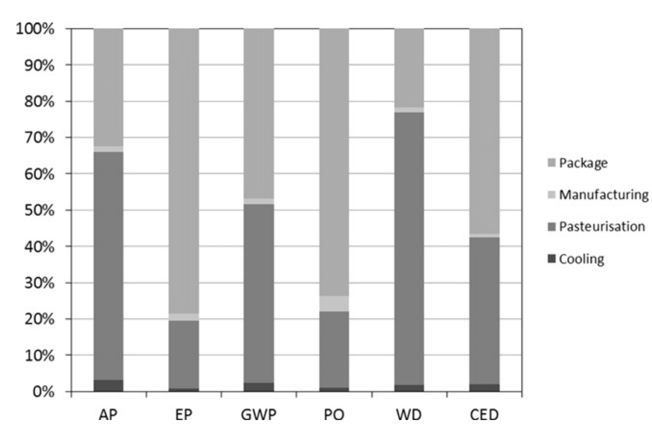

Fig. 5. Environmental impact potentials for thermal pasteurization by microwave (MW) per FU.

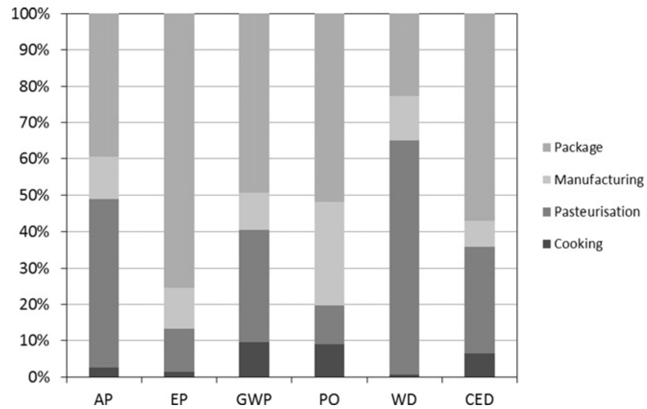

Fig. 6. Environmental impact potentials for pasteurization by high hydrostatic processing (HPP) per FU.

most of the evaluated techniques, with exception of MAP, where a multi-layer composition of the tray and film has been accounted. However, the application of different preservation technologies and the development of novel products, may imply the selection of different packaging options for every situation. According to the results obtained, this parameter must be carefully considered since the type of packaging may play an important role when aiming to improve the sustainability of the food preservation method.

Unlike the rest of the evaluated techniques, high pressure processing (HPP) showed relevant values in the manufacturing stage derived from the mineral extraction and steel production processes. This is mainly due to the fact that it has restricted capacity and limited production rates (units treated/hour) and it involves complex high-tech equipment and innovative design which might be potentially improved.

6.2. *Analysis of comparative results between different technologies*

As can be seen in Fig. 8, according to the results obtained with the ReCiPe method, modified atmosphere packaging (MAP) showed the lowest overall values for most of the considered impact categories when compared with the other analyzed techniques. Although this was expected, mainly due to the very low energy requirements gathered in the packaging and gas injection processes, a specific clarification must be made at this point. While a similar shelf life period (about 60 days in cool storage conditions) may be reached by the application of the other preservation technologies evaluated in this work, just a limited shelf life extension of approximately 30 days can be potentially achieved by MAP method, as reported by Murcia et al. (2003). Furthermore, the efficacy of this method varies significantly depending on the food properties (i.e. pH) or previously applied mild heat treatments (i.e. cooking, gelification, etc.) so these factors must be taken into account together when selecting MAP as the adequate preservation method for a target product. From a shelf-life point of view, the other studied technologies are comparable.

In general terms, results reveal that alternative technologies may lead to environmental impact reductions in comparison to traditional thermal processes. This is attributed to two principal causes. First, their capacity to preserve foods by avoiding severe heating/cooling successive conditions, which contribute to considerable water and heat consumption minimization. Second, as can be observed in Fig. 9 their energy consumption source is based on electricity, with an important contribution of renewable resources instead of direct combustion of fossil fuels required for heat generation in the conventional thermal treatments.

In the same way, as shown in Fig. 9, higher results of emerging technologies can be noticed specifically for acidification potential. This is mainly attributed to the sulfur dioxide emissions derived from hard coal and lignite combustion, which contribute in part to the Spanish electricity mix.

Through the normalization treatment, the results concerning the relative high environmental loads of every technology became clearer. According to Fig. 10, eutrophication potential, global warming potential and acidification potential resulted to be the more significant environmental impact categories affected within the limits of the study, indicating where efforts have to be oriented in order to reduce the overall impact of the preservation methods.

HPP has significant impact in global warming and acidification categories, attributed to electricity consumption; and especially higher than the rest in eutrophication potential, derived from materials extraction stage and disposal of furnace wastes after steel alloys production, which reflects the relevance of the manufacturing stage in this technology.

Thermal pasteurization technologies (AC, MW) showed high environmental load in almost all the impact categories, related directly or indirectly to the fossil fuel combustion processes involved in the thermal energy generation phase. Specifically, global warming potential has been identified as one of the most affected categories by environmental burdens derived from food preservation treatments, being results from thermal pasteurization by autoclave (AC) about 20% higher than equivalent pasteurization techniques (MW, HPP) due to the important heat and steam requirements of this process.

In the case of water depletion, it must be pointed out that non-thermal treatments (MAP, HPP) have lower consumption when compared to thermal pasteurizations (AC, MW). Although global impact factors and normalization filter do not reflect the importance of this aspect, this is a very sensitive category within the food processing sector, since regional features of climate may influence greatly the importance of water resources availability. However, this point may be potentially reflected in future regionalized LCA approaches.

7. Improvement actions

Analyzing the impact sources identified through the life cycle of every technology, and based on a technical and environmental point of view, a few of potential improvements may be proposed, as an attempt to point out several opportunities to reduce the environmental impact of processed food products.

Adequate preservation technology selection, meeting with quality, safety and nutritional requirements of the target product

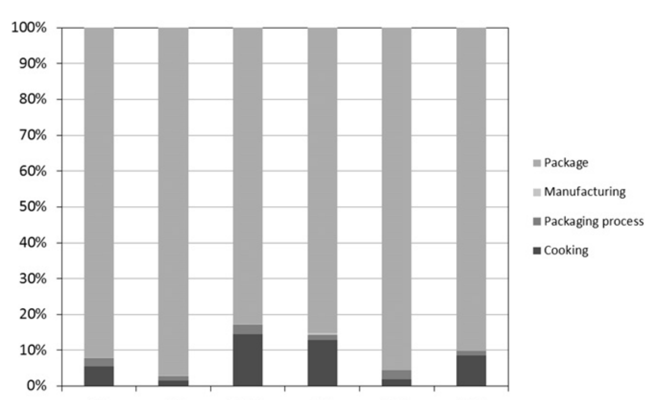

Fig. 7. Environmental impact potentials for pasteurization by modified atmosphere packaging (MAP) per FU.

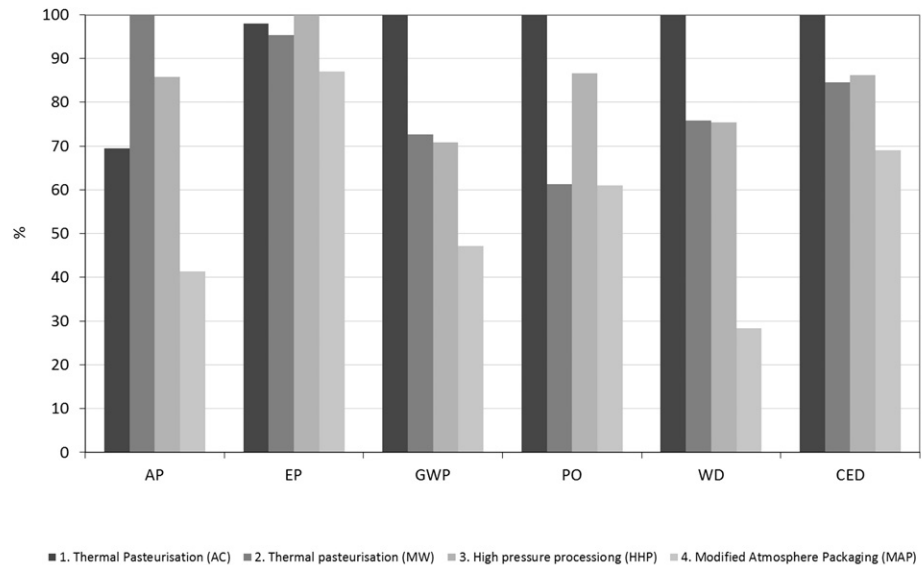

Fig. 8. Comparative environmental results obtained after characterization using ReCiPe. (Reference scenario 2020).

has been identified as an important factor affecting sustainability. Through this study, modified atmosphere packaging has shown to lead to reduced environmental impacts in comparison to pasteurization processes when a moderate shelf life of the product is required. Murcia et al. (2003) studied the efficacy of modified atmosphere packaging for prolonging the shelf-life of several ready-to-eat cooked products. In all cases studied, the potential risk of spoilage through microorganisms growth appear minimal, reporting that studied ready to eat food packed under controlled conditions could safely carry a 'use by' date of 29 days post-manufacture on the packaging.

Deeper knowledge of consumption habits may lead to more accurate shelf life requirements according to actual consumer needs. In addition to this, high barrier film together with strict temperature control and good sanitary handling would ensure microbial and organoleptical condition, thus satisfying consumer demand for minimally processed foods while providing more sustainable products.

Packaging was found to be a hot-spot for many of the impact categories investigated within food preservation system. Although packaging is an essential element of almost every food product, isolating food from factor affecting loss of quality such as oxygen, moisture and microorganisms it represents an important source of environmental burden and waste (Roy et al., 2009). Since the production stage of the packaging system is reported be the principal cause for the major impacts, increasing recycling rates, reducing weight in the primary package, and modifying both primary and secondary packaging present some optimizing opportunities for food and beverage industries to reduce the impact related to their food preservation methods (Ferrão et al., 2003; Henningsson et al., 2004; Hyde et al., 2001).

In general terms, closed-loop refrigeration circuits, heat exchanging opportunities and/or water cooling towers has been identified as efficient methods to reduce both, energy and water consumption in the conventional pasteurization step of food industries.

With regards to thermal pasteurization by autoclave, where steam is often the direct or indirect heating media, energy and water consumption can be minimized depending on the process technology considered. Saturated steam process uses important amounts of steam for venting leading to significant energy inefficiencies. Other type of retort technologies based on overpressure processes (i.e. water immersion retorting, water spray retorting) permit the combination with a heat exchanger and a pump to recirculate both sterilizing and cooling water allowing reutilization without chemical treatment for the next process. Also a storage vessel can be added as a hot water reservoir that is preheated for the next pasteurization cycle by capturing sterile water from previous process.

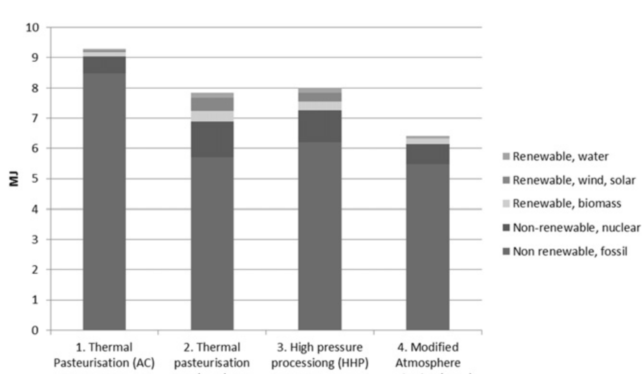

Fig. 9. Comparative environmental results obtained for cumulative energy demand per FU. (reference scenario 2020).

Table 3
Comparative characterization values for selected impact categories for 1 kg of processed food item round in the four analyzed preservation technologies (energy mix scenario 2020).

Impact categories	Unit	AC	MW	HPP	MAP
AP	g SO_2	1.12	1.31	1.24	0.68
EP	g PO_4^{3-}	0.0073	0.0080	0.0130	0.0067
GWP	g $CO_{2\ eq}$	397.3	254.2	281.8	217.3
PO	g C_2H_4 eq	8.6	5.3	7.4	5.2
WD	l	3.3	2.5	2.5	0.9
CED	J	410.4	263.3	292.9	224.2

AP = Acidification Potential; EP = Eutrophication Potential; GWP = Global Warming Potential; PO = Photochemical oxidation; WD = Water depletion; CED = Cumulative Energy Demand; AC = Pasteurization by autoclave; MW = Pasteurization by microwaves; HPP = Pasteurization by high hydrostatic pressures; MAP = Modified atmosphere packaging.

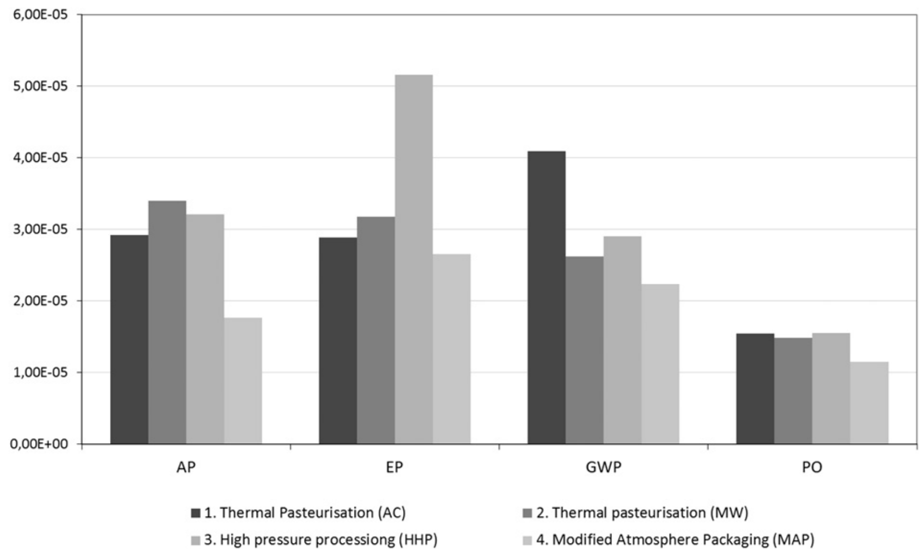

Fig. 10. Comparative environmental results obtained after normalization using ReCiPe. (reference scenario 2020).

Optimization of the fuel use efficiency by promoting adequate production planning, steam-boilers advanced control, pipe and equipment isolation, and/or fossil fuel replacement by renewable sources, such as biomass or biogas, are others improvement measures to potentially be adopted in the future by conventional thermal processes in order to reduce their energy consumption and become environmentally friendlier.

Minimization of the energy requirements of the preservation process could be also attempted by careful design and adjustment of operational parameters, according to actual market requirements while ensuring food safety. Chotyakul et al. (2011) investigated the development of a procedure to estimate a processing time ensuring that the process target would be met with a 95% probability, by careful analysis of variability in the affected parameters. Developed procedure allowed more accurate estimation of thermal processing times to achieve desirable surviving spore load probability with a specified confidence level, and also estimations of the reduction in process time gained by lowering the variability of process design parameters.

Specific effort may be needed aiming to eco-design high hydrostatic pressure process and equipment. As mentioned before, it involves complex high-tech materials and innovative design which is still under development, having the potential to be improved by taking into account environmental aspects. Recent engineering advances have contributed to the efficiency of HPP operations. New mechanical developments have allowed to improve intensifier designs and opening/closing mechanisms leading to more efficient processing times and better prestressing techniques that increase fatigue resistance of the vessels under high pressures (Norton and Sun, 2008). Other advances can represent opportunities of saving energy and process time. For example, the Tandem concept by NC Hyperbaric, where two vessels share their intensifier pumping group, has proven to increase productivity by about 15–20% compared to two classical machines due to the decrease in the needed time to raise the pressure (Hernando-Sáiz et al., 2008).

MW heating is also getting much attention of researchers in developing novel pasteurization and sterilization processes for packaged foods. The utilization of electromagnetic simulation models together with the food characteristics information is allowing to adjust and optimize microwave applicators in order to achieve more homogeneous heating and reduce losses during energy, leading to more flexible processing techniques. Discontinuities in the wave transmission system to the final device also implies losses affecting to global efficiency. This can be optimized by computer simulation, limiting perturbations and increasing the energy yield.

Finally, a special comment about combination of different preservation techniques must be made at this point. In fact, most of the ideas about new preservation methods were around well over a century ago, however, the current consumer demands for high quality foods has driven their recent development. Newer studies in food preservation are examining how different methods can work synergistically to reduce the level of additives and/or processing needed. The challenge for the future includes devising new and improved inactivation and inhibition techniques using combination treatments and multi-target interference and these innovative approaches may provide an important potential for environmental impact reduction in the future food chains that will need to be considered (Ottley, 2000).

8. Conclusions

The case study reported here is an attempt of apply LCA methodology specifically focused on food preservation methods, which are one of the dominating steps in terms of energy consumption when producing processed foods. In spite of its limitations, associated with the novel technologies involved, it is a rather complete study and the collection of site-specific data contributes to the strength of the results presented. Conclusions are specific for the target product studied, however some general improvements have been identified and environmental criteria has been provided in order to select the more adequate preservation method when designing new food products.

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References

Althaus, H.-J., Blaser, S., Classen, M., Jungbluth, N., 2004. Life Cycle Inventories of Metals. Swiss Centre for Life Cycle Inventories.

Air Liquide S.A., 2009. Personal Communication.

Andersson, K., Ohlsson, T., Olsson, P., 1998. Screening life cycle assessment (LCA) of tomato ketchup: a case study. Journal of Cleaner Production 6 (3–4), 277–288.

Butz, P., Serfert, Y., Fernández Garcia, A., Dieterich, S., Lindauer, R., Bognar, A., et al., 2004. Influence of high-pressure treatment at 25 °C and 80 °C on folates in orange juice and model media. Journal of Food Science 69 (3).

Calderón, L.A., Iglesias, L., Laca, A., Herrero, M., Díaz, M., 2010. The utility of Life Cycle Assessment in the ready meal food industry. Resources, Conservation and Recycling 54 (12), 1196–1207.

Chotyakul, N., Velazquez, G., Torres, J.A., 2011. Assessment of the uncertainty in thermal food processing decisions based on microbial safety objectives. Journal of Food Engineering 102 (3), 247–256. Elsevier Ltd.

Davis, J., Sonesson, U., 2008. Life cycle assessment of integrated food chains—a Swedish case study of two chicken meals. The International Journal of Life Cycle Assessment 13 (7), 574–584.

Davis, J., Moates, G.K., Waldron, K.W., 2009. High pressure processing – a step in the right direction towards sustainable food processing? Food Safety Magazine 15, 12–15.

Davis, H.K., 1993. Modified atmosphere packing of fish. In: Parry, R.T. (Ed.), Principles and Applications of Modified Atmosphere Packaging of Food. Blackie Academic and Professional, London, pp. 189–228.

Devlieghere, F., Vermeiren, L., Debevere, J., 2003. New preservation technologies: possibilities and limitations (Review). International Dairy Journal 14, 273–285.

Defaye, A.B., Ledward, D.A., MacDougall, D.B., Tester, R.F., 1995. Renaturation of metmyoglobin subjected to high isostatic pressure. Food Chemistry 52, 19–22.

Ecoacero, 2009 www.ecoacero.com.

European Commision, 2006. Reference Document of Best Available Techniques in the Food, Drink and Milk Industries.

Farr, D., 1990. High pressure technology in the food industry. Trends in Food Science & Technology 1, 14–16.

Fernández García, A., Butz, P., Bognar, A., Tauscher, B., 2001. Antioxidative capacity, nutrient content and sensory quality of orange juice and an orange-lemon-carrot juice product after high pressure treatment and storage in different packaging. European Food Research and Technology 213, 290–296.

Fernández, K., Aspe, E., Roeckel, M., 2009. Shelf-life extension on fillets of Atlantic Salmon (*Salmo salar*) using natural additives, superchilling and modified atmosphere packaging. Food Control 20 (11), 1036–1042. Elsevier Ltd.

Ferrão, P., Ribeiro, P., Nhambiu, J., 2003. A Comparison between Conventional LCA and Hybrid EIO-LCA: A Portuguese Food Packaging Case Study.

Goedkoop, M.J., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., Van Zelm, R., 2009. ReCiPe 2008, A Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level, first ed. Report I: Characterization.

Gomez-Estaca, J., Gomezguillen, M., Montero, P., 2007. High pressure effects on the quality and preservation of cold-smoked dolphinfish (*Coryphaena hippurus*) fillets. Food Chemistry 102 (4), 1250–1259.

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Wegener, A., Suh, S., Udo de Haes, H.A., 2001. Life Cycle Assessment – An Operational Guide to the ISO Standards. Centre of Environmental Science, Leiden, The Netherlands.

Henningsson, S., Hyde, K., Smith, A., Campbell, M., 2004. The value of resource efficiency in the food industry: a waste minimization project in East Anglia, UK. Journal of Cleaner Production 12 (5), 505–512.

Hernando-Sáiz, A., Tárrago-Mingo, S., Purroy-Balda, F., Samson-Tonello, C., 2008. Advances in design for successful commercial high pressure food processing. Food Australia 60 (4), 154–156.

Hospido, A., Davis, J., Berlin, J., Sonesson, U., 2010. A review of methodological issues affecting LCA of novel food products. The International Journal of Life Cycle Assessment 15 (1), 44–52.

Huang, L., Sites, J., 2007. Automatic control of a microwave heating process for in-package pasteurization of beef frankfurters. Journal of Food Engineering 80 (1), 226–233.

Humbert, S., Rossi, V., Margni, M., Jolliet, O., Loerincik, Y., 2009. Life cycle assessment of two baby food packaging alternatives: glass jars vs. plastic pots. The International Journal of Life Cycle Assessment 14 (2), 95–106.

Hyde, K., Smith, A., Smith, M., Henningsson, S., 2001. The challenge of waste minimization in the food and drink industry: a demonstration project in East Anglia, UK. Journal of Cleaner Production 9 (1), 57–64.

ISO14040, 2006. Environmental Management—Life Cycle Assessment—Principles and Framework.

Jungbluth, N., Frischknecht, R., 2004. Implementation of Life Cycle Impact Assessment Methods Ecoinvent Report No. 3. <www.ecoinvent.ch>.

Lado, B.H., Yousef, A.E., 2002. Alternative food-preservation technologies: efficacy and mechanisms. Microbes and Infection/Institute Pasteur 4 (4), 433–440. Retrieved from. http://www.ncbi.nlm.nih.gov/pubmed/11932194.

Lakshmanan, R., Piggot, J.R., Paterson, A., 2003. Potential applications of high pressure for improvement in salmon quality. Trends in Food Science & Technology 14, 354–363.

Martínez-Blanco, J., Muñoz, P., Antón, A., Rieradevall, J., 2009. Life cycle assessment of the use of compost from municipal organic waste for fertilization of tomato crops. Resources Conservation and Recycling 53 (6), 340–351.

MARM, 2007. Ministerio de Medio Ambiente, Medio Rural y Marino La alimentación en España, 2006.

Morris, C., Brody, A.L., Wicker, L., 2007. Non-thermal food processing/preservation technologies: a review with packaging implications. Packaging Technology and Science 20 (4), 275–286.

Murcia, M.A., Martínez-Tomé, M., Nicolás, M.C., Vera, A.M., 2003. Extending the shelf-life and proximate composition stability of ready to eat foods in vacuum or modified atmosphere packaging. Food Microbiology 20, 671–679.

Norton, T., Sun, D.-W., 2008. Recent advances in the use of high pressure processing as an effective technology in the food industry. Food and Bioprocess Technology 1 (1), 2–34.

NC Hyperbaric, 2009. Personal Communication.

Oey, I., Van der Plancken, I., Van Loey, A., Hendrickx, M., 2008. Does high pressure processing influence nutritional aspects of plant based food systems? Trends in Food Science & Technology 19 (6), 300–308.

Office of financial management, 2010. SAAM Manual.

Oliveira, M.E.C., Franca, A.S., 2002. Microwave heating of foodstuff. Journal of Food Engineering 53, 347–359.

Ottley, C., 2000. Nutritional effects of new processing technologies. Trends in Food Science & Technology 11 (11), 422–425.

Oscariz, J., Novo, M., Prats, F., Seoane, M., Torrego, A., 2008. Global Change. Spain 2020/2050. Fundación CONAMA, Madrid.

Özogul, F., 2004. The effects of modified atmosphere packaging and vacuum packaging on chemical, sensory and microbiological changes of sardines (*Sardina pilchardus*). Food Chemistry 85 (1), 49–57.

Parry, R.T., 1993. Introduction. In: Parry, R.T. (Ed.), Principles and Application of Modified Atmosphere Packaging of Food. Blackie Academic and Professional, Glasgow, pp. 1–17.

Patras, A., Brunton, N.P., Da Pieve, S., Butler, F., 2009. Impact of high pressure processing on total antioxidant activity, phenolic, ascorbic acid, anthocyanin content and colour of strawberry and blackberry purées. Innovative Food Science & Emerging Technologies 10 (3), 308–313. Elsevier B.V.

Pereira, R.N., Vicente, A.A., 2010. Environmental impact of novel thermal and non-thermal technologies in food processing. Food Research International 43 (7), 1936–1943.

PRè, 2011. SimaPro 7.3. PRè Consultants, The Netherlands.

Ramirez-Suárez, J., Morrissey, M., 2006. Effect of high pressure processing (HPP) on shelf life of albacore tuna (*Thunnus alalunga*) minced muscle. Innovative Food Science & Emerging Technologies 7 (1–2), 19–27.

Roy, P., Nei, D., Orikasa, T., Xu, Q., Okadome, H., Nakamura, N., et al., 2009. A review of life cycle assessment (LCA) on some food products. Journal of Food Engineering 90 (1), 1–10.

Sairem Ibérica, S.L., 2009. Personal Communication.

Sandén, B.A., Jonasson, K.M., Karlström, M., Tillman, A.M., 2005. LCA of Emerging Technologies: A methodological Framework. LCM2005—Innovation by Life Cycle Management. Book of Proceedings, Barcelona, Spain, September 5–7, 2005, pp. 37–41.

Sequeira-Munoz, A., Chevalier, D., Lebail, A., Ramaswamy, H., Simpson, B., 2006. Physicochemical changes induced in carp (*Cyprinus carpio*) fillets by high pressure processing at low temperature. Innovative Food Science & Emerging Technologies 7 (1–2), 13–18.

Sizer, C.E., Balasubramaniam, V.M., Ting, E., 2002. Validating high-pressure process for low-acid foods. Food Technology 56 (2), 36–42.

Tang, Z., Mikhaylenko, G., Liu, F., Mah, J., Pandit, R., Younce, F., et al., 2008. Microwave sterilization of sliced beef in gravy in 7-oz trays. Journal of Food Engineering 89 (4), 375–383.

Tukker, A., Huppes, G., Guinée, J.B., Heijungs, R., Koning, A., de & Oers, L.F.C.M., van & Suh, S., Geerken, T., Holderbeke, M., van & Jansen, B., Nielsen, P., 2006. Environmental Impacts of Products (EIPRO) – Analysis of the Life Cycle Environmental Impacts Related to the Final Consumption of the EU-25. European Commission, JRC – IPTS, Luxembourg.

Wan, J., Mawson, R., Ashokkumar, M., Ronacher, K., Coventry, M.J., Roginski, H., Versteeg, C., 2005. Emerging processing technologies for functional food. Australian Journal of Dairy Technology 60 (2), 167–169.

Wang, Y., 2003. Dielectric properties of foods relevant to RF and microwave pasteurization and sterilization. Journal of Food Engineering 57 (3), 257–268.

Zufía, J., Arana, L., 2008. Life cycle assessment to eco-design food products: industrial cooked dish case study. Journal of Cleaner Production 16, 1915–1921.