Accepted Manuscript

Pilot scale thermal and alternative pasteurization of tomato and watermelon juice: An energy comparison and life cycle assessment

Kemal Aganovic, Sergiy Smetana, Tara Grauwet, Stefan Toepfl, Alexander Mathys, Ann Van Loey, Volker Heinz

PII: S0959-6526(16)31356-7

DOI: [10.1016/j.jclepro.2016.09.015](https://doi.org/10.1016/j.jclepro.2016.09.015)

Reference: JCLP 7975

To appear in: *Journal of Cleaner Production*

Received Date: 15 February 2016

Revised Date: 2 September 2016

Accepted Date: 2 September 2016

Please cite this article as: Aganovic K, Smetana S, Grauwet T, Toepfl S, Mathys A, Van Loey A, Heinz V, Pilot scale thermal and alternative pasteurization of tomato and watermelon juice: An energy comparison and life cycle assessment, *Journal of Cleaner Production* (2016), doi: 10.1016/j.jclepro.2016.09.015.

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Pilot scale thermal and alternative pasteurization of tomato and watermelon juice: an energy comparison and life cycle assessment

Kemal Aganovic^{a}, Sergiy Smetana^a, Tara Grauwet^b, Stefan Toepfl^a, Alexander Mathys^c, Ann Van
Loey^b, Volker Heinz^a*

Authors are affiliated to:

a) German Institute of Food Technologies (DIL) e.V.

Prof.-von-Klitzing-Str. 7

D-49610 Quakenbrück, Germany

b) Laboratory of Food Technology

Leuven Food Science and Nutrition Research Center (LFoRCe)

Department of Microbial and Molecular Systems (M²S)

Katholieke Universiteit Leuven

Kasteelpark Arenberg 22 box 2457

B-3001 Heverlee, Belgium

c) ETH Zurich

Laboratory of Sustainable Food Processing

Institute of Food, Nutrition and Health

Schmelzbergstrasse 9

CH-8092 Zurich, Switzerland

*Author to whom correspondence should be addressed during submission process

Fax: +49 (0)5431.183-114

Telephone: +49 (0)5431.183-447

E-mail: k.aganovic@dil-ev.de

Abstract

The energy balance and life cycle assessment (LCA) of conventional (thermal) and alternative (pulsed electric fields (PEF) and high pressure processing (HPP)) technologies for preservation of tomato and watermelon juice have been evaluated. A comparison between technologies was performed at an equivalent level of microbial inactivation whilst considering the same production capacity on a pilot scale using industrial scale equipment. The data included in the study, such as selected processing conditions, energy consumption, water use, cleaning agents and maintenance, were experimentally collected. For the LCA two main systems were identified: (1) the first system reviewed only the processing stage of juice production (from “gate to gate”), and (2) the second included the expansion of the boundaries to the agricultural production stage and waste treatment during juice preparation and processing (from “farm to gate”).

Comparable energy uptake was observed when the same technology for two different juices was compared. In terms of energy consumption, the highest specific energy uptake was recorded for HPP, resulting in an energy consumption of 0.20 kWh/l of juice. Slightly less energy was required by PEF processing with 0.12 kWh/l, followed by thermal with 0.04 kWh/l of juice. As to the environmental impact, expected differences were observed between the technologies based on the differences in energy consumption. Even though the differences of processing stage were assigned to the use of energy, the largest environmental impact was associated with the 250 ml PET bottles production (~85%). Considerable differences were outlined between the two juices for the “farm to gate” analysis, where tomato juice had a higher impact compared to watermelon juice. From the sensitivity analysis, different strategies for diminishing the impact were identified. They are associated with raw material production (field tomatoes), waste amount decreasing (type of watermelons selection) and relevant packaging selection (HDPE vs. PET).

Keywords

Tomato; watermelon; HPP; PEF; LCA; pasteurization

Highlights

- Comparison based on microbial equivalence and same production capacity
- Highest energy uptake recorded for HPP, followed by PEF and thermal
- Environmental impact differences related to energy consumption of each technology
- Largest environmental impact is associated with 250 ml PET bottles production

1. Introduction

With substantial growth of world's human population, there is a higher demand for food which consequently results in more energy needed by the agro-food sector. In Europe, around 26% of the EU's final energy consumption in 2013 was needed to cultivate, process, pack and distribute food to final consumers. After crop cultivation, food processing is considered as the most intense phase of the food system, followed by logistics and packaging, accounting all three together for nearly half of the total energy used in the food system (Monforti-Ferrario Fabio et al., 2015). Energy consumption during industrial food processing (conversion of raw materials to end-products) encompasses several energy means such as heat (e.g. blanching, drying, preservation), electrical energy (conveyors, pumping), cooling (during processing or storage), lights and some others (Dalsgaard and Abbotts, 2003). In order to make their activities more energy efficient and sustainable, food industry is constantly looking into new solutions either through usage of renewable energy or utilization of energy in a more efficient way by modification of existing or introduction of new processes. In last few decades several food processing technologies for gentle preservation of food and more efficient energy utilization were investigated and discussed. Those technologies rely on other energy sources such as mechanical, electrical, electro-magnetic or others, compared to conventional, well-established ones using mostly thermal energy. Among several investigated technologies for food preservation, high pressure processing (HPP) and pulsed electric fields (PEF) have been described as the most promising ones (Knorr, 1999; Knorr et al., 1994; Pardo and Zufía, 2012; Pereira and Vicente, 2010; Rodriguez-Gonzalez et al., 2015; Toepfl et al., 2006).

So far great progress was made for better understanding the basic principles of PEF and HPP, kinetics of microbial and enzyme inactivation, as well as their impact on food quality

attributes (Deeth et al., 2007; Hendrickx and Knorr, 2001; Knorr et al., 2011; Raso et al., 2006; Tewari, 2007). At the same time development of alternative food processing technologies was driven by consumers' trend for minimally processed food with improved quality attributes compared to thermal counterparts (Devlieghere et al., 2004). This was at least the case in more developed countries. Although technological innovations and changes from "conventional-to-novel" often come with economic and success risks, at the same time they could represent long-term perspective for sustainable development and competitive production. As a result of intensive research and technological achievements, as well as increased consumer awareness and needs, today, more than 250 high pressure (HP) and over 40 PEF units operate in food industry. Around 65 HP units are owned by juice producers and around 25 machines operate in toll processing (Tonello Samson, 2015; Toepfl, 2015).

Besides improving products' quality and safety, great benefit of alternative technologies is seen in the potential to generate added-value products from agricultural crops. Food waste is responsible for around 5% of total energy use in the EU food system. The vast amount of food waste (100 million tons in 2014) was generated at the manufacturing and household level (Monforti-Ferrario Fabio et al., 2015). Considering the amounts of energy involved in food production and waste disposal, reducing the food waste is of great importance for energy improvement of the whole food chain. Thus, application of alternative technologies, in particular for seasonal products (such as watermelons, tomatoes and similar) for shelf life extension without compromising product quality would allow utilization of large, often excess amounts of products during the harvest period and conversion into high quality products with prolonged shelf life.

To assess the environmental impacts of different processing technologies, the use of Life Cycle Assessment (LCA) seems to be the most suitable way (Guinée et al., 2011). This approach allows not only the analysis of direct environmental influences, but also the estimation of indirect impacts, which might occur along the supply chain of a product or a technology. Quite often outsourced elements of the supply chains have the highest impacts (Roy et al., 2009). LCA provides results of different impact categories assessment and integration of the impacts into single units (Goedkoop et al., 2013; Goedkoop and Spriensma, 2001; Jolliet et al., 2003). In this way, LCA allows reviewing the technological process as a complete system and as a part of more complex supply chain.

As opposite to quality evaluation and processing impact comparison of alternative technologies where numerous studies are available, their environmental impact was not so

often in the focus, resulting in a lack of studies on this topic. The study performed by Pardo and Zufia (2012), assessed LCA of different technologies (autoclave pasteurization, microwaves, high hydrostatic pressure and modified atmosphere packaging) for production of a ready-to-eat meal based on fish and vegetables. Due to different product and processing conditions considered, the results of the study are difficult to compare with our current study. Nevertheless, together with few other authors, they pointed out the importance of processing stage in the whole life cycle (Andersson et al., 1998; Davis and Sonesson, 2008). The LCA study performed on cooked tuna-tomato dish reported fish harvesting and supply as the most important stage (Zufia and Arana, 2008). Calderón et al. (2010) investigated canned ready meal where production showed the highest environmental impact, together with significant contribution of gas and electricity used at industrial level. In the study of Davis et al. (2010) the environmental impact of PEF and HPP as compared to thermal pasteurization of carrot juice was addressed. It has been concluded that the energy used for pasteurization was relatively small compared to total life cycle energy use, resulting in no significant differences between technologies in general.

The objective of the present study was to perform energy balance comparison and life cycle assessment of conventional (thermal) and alternative (PEF and HPP) technologies for pilot scale preservation of tomato and watermelon juice on industrial scale units. The pilot scale production capacity was chosen based on the batch-nature of the smallest industrial high pressure unit, often used by small start-up companies as well as for toll processing of beverages. The study was based on collected experimental data (processing conditions resulting in an equivalent level of microbial inactivation and expected shelf-life of the juices; measured energy consumption of PEF and HPP), while considering the same production capacity for each technology. Results of the study could be used to identify the most impacting elements of the system and, therefore, imply where potential improvements could be made towards more sustainable food production, regardless if involving thermal or alternative technologies.

2. Materials and methods

2.1. Tomato and watermelon fruits and juice preparation

Tomatoes (*Solanum lycopersicum*, var. *Arvento*) and watermelons (*Citrullus lanatus* var. *Rayada*) were obtained from the local store in Germany. Tomatoes were grown in the

Netherlands and watermelons in Spain. The juice was produced at German institute of food technologies. Tomatoes and watermelons were first washed and subsequently crushed using cutter equipped with vacuum (30L VK 5000 express, Kilia Wertstoff-Technik GmbH, Germany). In the case of watermelons, before the chopping the flesh was separated from rind. After the chopping, vacuum was applied to the freshly prepared juice for air removal injected during chopping.

2.2. Pasteurization of tomato and watermelon juice

Processing conditions for thermal and alternative pasteurization of tomato and watermelon juice, resulting in equivalent microbial inactivation were experimentally selected and are described in our previous work (Aganovic et al., 2014; Aganovic et al., 2015). An overview of the selected conditions resulting in at least 5-log inactivation of *Escherichia coli*, *Lactobacillus plantarum* and *Listeria innocua* in tomato and watermelon juice is presented in table 1.

Table 1. An overview of selected processing conditions for thermal, PEF and HPP resulting in at least 5-log inactivation of indicator microorganisms

	Thermal	PEF	HPP
Tomato juice	74 °C, 30 s	$T_{in}=30\text{ °C}$ 9.8 kV/cm; 188 kJ/kg	600 MPa, 5 min
Watermelon juice	74 °C, 45 s	$T_{in}=35\text{ °C}$ 11 kV/cm; 175 kJ/kg	600 MPa, 5 min

For the trials, pilot and industrial scale equipment was used. Thermal treatments were carried out using a continuous pilot-scale plate heat exchanger type S4A-IT10-16-TL-Liquid (Sondex, Hamburg, Germany). The heat exchanger consisted of 16 plates with a filling volume of 0.188 L per plate and maximum heat transfer rate of 12 kW. For the PEF treatment a continuous, pilot-scale unit (HVP 5 kW, DIL, Quakenbrueck, Germany) was used and for the HP treatment, a small industrial scale HP unit with a volume of 55 L was used (Wave 6000/55 Hiperbaric, Burgos, Spain). The system operates at room temperature with maximal pressure of 600 MPa and a pressure build-up rate of around 170 MPa/min.

2.3. Energy evaluation and measurement

Energy required for thermal pasteurization was calculated, whereas the energy consumption during PEF and HP process was experimentally measured, for the previously selected processing conditions (Table 1). Besides comparing the technologies at the same level of microbial inactivation, comparable production capacity was taken into account. Due to its batch nature, HP process was taken as a starting point to define the capacity. Based on an empirically measured filling efficiency of the HP vessel 36.5% for 250 ml plastic bottles, and considering a handling and treatment time of 10 min per run, a production capacity of 120 l/h was calculated. Consequently, the same production capacity was considered for continuous PEF and thermal processes. It is important to note that energy required for preparation of the juice (e.g. washing, chopping, sieving) was not included in this part of the study, but in the overall life cycle assessment (section 3.2).

2.3.1. Thermal processing

Thermal processing is one of the most common preservation methods used in food industry for inactivation of pathogenic vegetative microorganisms associated with public health hazards (Augusto et al., 2014; Wilbey et al., 2014). Specific energy (E) needed for heating, mostly involves energy required to be transferred to a material with a specific heat capacity (C_p), at a certain mass flowrate ($\dot{m}$) to cause a temperature change (ΔT) (Eq.1).

$$E = C_p \cdot \dot{m} \cdot \Delta T \quad \text{Eq. (1)}$$

Energy for cooling can be also calculated using equation 1, as one third of the total energy needed to cause the temperature change (Kessler, 1988). From the sum of total energy for heating and cooling, a 70% heat recovery was considered. This is because our study was designed for a relatively small pilot-scale production of 120 l/h, compared to actual industrial production capacities of few thousands l/h, where heat recovery rates can be even higher. Potential heat losses during the holding time were neglected in this calculation.

2.3.2. Pulsed electric fields

Energy needed for PEF process encompasses electricity consumed by the pulse generator, thermal energy needed for preheating of the product prior to the treatment, as well

as energy needed for pumping and cooling of the product. The PEF process occurs due to product's conductivity and ability of electrical current to flow through it due to charged molecules. However, due to product's resistivity, certain amount of electrical energy is converted to heat as Joule heating (Heinz et al., 2001). This part of energy is important to consider in an energy balance, as part of this heat can be used for preheating of the product before PEF, using already treated product (Fig. 2).

To measure electricity consumption during PEF operation a PowerClamp meter (PeakTech Prüf- und Messtechnik GmbH, Ahrensburg, Germany) was used. From the measured electrical current (I), power (P) was calculated using equation 2, with U as the three-phase voltage of 400 V and $\cos\varphi$ as the power factor characteristic for the machine:

$$P = \sqrt{3} \cdot U \cdot I \cdot \cos \varphi \quad \text{Eq. (2)}$$

In addition, the energy needed for preheating of the product was calculated as in equation 1, under consideration that PEF treated product can be used to almost fully preheat the cold non-treated product and thus achieve up to 90% recovery. The energy needed for final cooling of the product was calculated as one third of the energy needed for cooling, according to equation 1.

2.3.3. High pressure processing

The PowerClamp meter was connected on the electrical power supply and electrical current during operation of the high pressure (HP) unit was recorded. Electrical power consumption (P) was calculated using the equation 2 and was used to illustrate the energy consumption during one high pressure cycle (Fig. 4).

2.4. Software

For visual representation of flowcharts of juice pasteurization, eDraw Max (ver. 7.9.4, 2015, Sheung Wan, Hong Kong) was used. The LCA study was performed using professional SimaPro8 software (ver. 8.0.1 Analyst) and adapted Ecoinvent 3.1 database processes.

2.5. LCA methodology

The presented study is based on a standardized LCA approach (ISO 14040, 2006; ISO 14044, 2006), which allows reviewing the technological process as a complete system and as a part of more complex supply chain. LCA was based on IMPACT 2002+ methodology (Joliet et al., 2003), which allows the analysis of results according to the main mid-point impact categories (e.g. global warming, land occupation, non-renewable energy use) and synthesis of those into a single result category for a relative comparison (according to the impact of an average European).

2.5.1. Type of LCA

LCA studies are traditionally divided into two main groups: attributional and consequential analyses (Baumann and Tillman, 2004). There are numerous publications available discussing the benefits of both approaches (Earles and Halog, 2011; Ekvall and Finnveden, 2001; Luo et al., 2009; Schmidt and Weidema, 2008; Thomassen et al., 2008). As the aim of this paper was to assess and compare conventional and alternative preservation technologies, we followed the recommendations proposed by Hospido et al. (2010) for LCA of novel food products and processing technologies. Accordingly, “prospective attributional LCA” was recommended, which assess the current state of a product or a technology to analyze the change of the impact if another state is achieved. At the same time it does not indicate the change of system properties of the environment if the whole production is changed to the new option.

2.5.2. Functional unit

The aim of the study was to assess environmental performance and compare three technologies applicable for two types of juices (tomato and watermelon): traditional (thermal) and alternative pasteurization (PEF and HPP). As the investigated technologies operate in different modes (thermal and PEF in continuous, and HPP in batch mode) the use of mass-based functional unit (FU) was predefined (Hospido et al., 2010; Schau and Fet, 2008). It was suitable to indicate the physical relations of production, processing and waste treatment stages. Therefore, the FU was defined for this study as 1 kg of pasteurized juice, bottled and ready for sale.

2.5.3. System boundaries

According to the objective of the paper, two main system views were identified: (1) the first reviewed only the processing stage of juice production from “gate to gate” (similarly to the work of Pardo and Zufía (2012)), and (2) the second system from “farm to gate” (“cradle to gate”) included the expansion of the boundaries to the agricultural production stage and waste treatment (generated during processing). For the latter approach, different scenarios were applied, as specific data on the agricultural stage were not available. In this way the specific impacts and hotspots of the processing stage were accounted, including the review of the complete supply chain of the two juice productions.

2.5.4. Scenarios

Evaluation of changes in results by alterations in raw material supplies, location of processing plant, packaging and waste treatment options were assessed. Raw resources were initially supplied from the Netherlands (tomatoes) and Spain (watermelons). Potential alterations of supply areas were accounted for both juices, as well as possible changes in agricultural growing techniques. The baseline scenario included juice production in Germany with the use of typical mix of energy and water from the grid (based on Ecoinvent 3.1 database). The study relied on a number of scenarios used for sensitivity analysis of tomato juice production: SC1-0: baseline scenario of HP processed juice; SC1-1: German electricity mix; SC1-2: minimal distance between farm and processing site; SC1-3: field tomatoes growing; SC1-4: HDPE bottles; SC1-5: natural gas for heating. The sensitivity of watermelon juice production relied on: SC2-0: baseline scenario of HP processed juice; SC2-1: 50% less waste at processing; SC2-2: minimal distance between farm and processing site; SC2-3: HDPE bottles.

2.5.5. Data

Foreground data for processing stage of juice production was collected during the technological production at pilot scale at the German Institute of Food Technologies (DIL e.V., Germany). Data on energy consumption, water use, cleaning agents and maintenance, included in the study, was experimentally collected in the period 2012–2015. Foreground

primary data on processing was directly measured for all three technologies. Background data on input resources production (energy, agricultural commodities, water, detergents etc.) was assumed to be similar and was therefore based on average data from Ecoinvent 3.1 and literature sources adapted for the study conditions.

2.5.6. Life Cycle Inventory (LCI)

The inventory for LCA included directly measured and calculated data for processing stage and average data for the background processes (Table 2). For a fair comparison the LCA study relied on as much similar conditions as possible, i.e. for the same raw materials, with similar pre-processing conditions (washing, chopping, sieving), same packaging (250 ml PET bottles of 18.5 g weight with HDPE covers of 3.08 g weight), similar bottling and equipment cleaning techniques (1% solution of alkali cleaners in combination with chlorine disinfection). The selection of raw materials was done according to the real conditions of experimental settings.

Table 2. Main inputs in the production of juice used in the study (from “farm to gate”) per FU (FU is defined as 1 kg of pasteurized juice, bottled and ready for sale)*

Inputs		Type of juice processed					
		Tomato			Watermelon		
		Thermal	PEF	HPP	Thermal	PEF	HPP
		Raw material production ^a					
Farm to gate	Electricity, MJ	0.7956			0.054		
	Heat, MJ	8.886			-		
	Transportation, tkm	0.3804			Ship 0.9284; road trucks 0.2216		
	Water, kg	2.0			53.9		
	Fertilizers (complex), kg	0.005			0.0112		
	Raw resource amount, kg ^b	1.11			2.0		
Gate to gate		Pre-processing ^b					
	Electricity, MJ	0.2628	0.2628	0.288	0.1739	0.1739	0.1966
	Water, kg	2.22			1.0		
		Processing ^b					
	Electricity, MJ	0.1368	0.4327	0.6516	0.1307	0.4291	0.6516
	Composting, kg	0.11			1.0		

* The table includes only those data which were different for the compared products

^a Estimated from Ecoinvent 3 database

^b Measured values (German Institute of Food Technologies DIL e.V.)

The study relied on a number of assumptions, aimed to compare different processing technologies on “a fair basis”. The waste material from raw materials processing (seeds, peelings) was treated as compost up to the point of compost application on the field. The impact of the infrastructure and equipment construction was lower than 1% compared to the impact of other elements of the supply chain and was therefore not included in the study. Labelling of the bottles was excluded from the study as well, as there is a variety of possible

labelling types and neither of the options affects the scores in a significant way. The LCA study did not include the recycling options for the PET bottles, as there was no specific relevant information on the recycling options for thermal, PEF or HPP treated juices. Moreover, the impacts would be similar for different technologies. The possible additional variations at the processing stage (shape of the bottles, filling rate) were not considered in the study as their variations affected the results in a minimal way and therefore can be neglected. According to the real data of the raw materials used for trials, it was assumed that tomatoes were grown in the Netherlands in greenhouse conditions, while watermelons were harvested from the field in Spain. All the pre-processing and processing activities took place in Germany (Quakenbrueck, Lower Saxony).

3. Results and discussion

3.1. Energy evaluation and comparison

Results of the energy assessment are discussed below in separate sections for each technology. An overview of the energy requirements for the pasteurization of two juices is presented in table 3.

3.1.1. Thermal processing

Calculated specific energies for thermal pasteurization of tomato and watermelon juice were 4.56 kWh and 4.36 kWh respectively (Table 3). The minor difference in energy is explained by the slightly different heat capacity of the juices.

Figure 1. An example of thermal pasteurization line of tomato juice with 120 l/h capacity, from product tank to the filling tank, including heater (HW) and heating section (1), recovery section (2) and cooling section (3)

An illustration of line for thermal pasteurization of tomato juice, including heating (1), recovery (2) and cooling section (3) is presented in Fig. 1. Based on a long tradition of thermal processing and knowledge obtained on microbial and enzymatic inactivation kinetics, as well as heat transfer models for different foods, significant process and equipment improvements have been achieved so far. This resulted in high level of optimization of thermal processes with the ability to recover 70-95 % of heat, by heating of the incoming cold product with already heated product. The rate of heat recovery depends in a first place on the production capacity and the heat exchanging surface. By increasing the surface, energy for heating can be reduced down to one sixth, and for cooling down to one third of the total energy required (Kessler, 1988).

3.1.2. Pulsed electric fields (PEF) processing

The specific energy uptake for PEF preservation of tomato and watermelon juice in our study was measured to be 14.42 kWh and 14.30 kWh, respectively (Table 3). The difference in required energy is a result of the different specific energy inputs needed to achieve the desired level of microbial inactivation (188 kJ/kg for tomato and 175 kJ/kg for

watermelon juice) and the different juice characteristics (e.g. conductivity, specific heat capacity, pH etc.). PEF inactivation of microorganisms is based on the application of very short high-voltage pulses to induce irreversible electroporation of microbial membranes in a product with certain conductivity contained between electrodes. In that context, major processing parameters are electric field strength, specific energy as well as starting and final temperature. The process requires application of electric fields of sufficient strength between 10 to 20 kV/cm. The specific energy input can be considered as a dose parameter. However, due to product's resistivity, the electrical energy is converted to heat as Joule heating (Heinz et al., 2001). This part of energy is important to consider in an energy balance, as part of this heat can be recovered for preheating of the product before PEF (stage 1 and 2 in Fig. 2).

As illustrated in Fig. 2, prior to PEF processing, the juice is heated up to a certain temperature. The heating is necessary only at the starting phase, whereas after a certain processing time a 90-95% heat recovery can be achieved by pre-heating the juice with already PEF treated juice. From an economical perspective, by increasing the inlet temperature of the juice before the PEF treatment, more heat could be derived from the final product resulting in more effective heat recovery and in the end less energy required for final cooling. In that sense, by pre-heating the juice to moderate temperatures (e.g. 40-60 °C) and applying lower amounts of electrical energy (e.g. 60-100 kJ/kg), a more efficient process could be designed, while achieving the same level of microbial inactivation.

Figure 2. An example of PEF tomato juice pasteurization with 120 l/h capacity, from product tank to filling tank, including heater for starting (HW), pre-heating/recovery section, PEF (9.8 kV/cm; 188 kJ/kg, with two treatment chambers), and cooling section

It should be mentioned that this thermal-assisted setup should be mainly considered for less heat-sensitive products and/or products where relatively high specific PEF energy inputs are required to achieve the desired level of microbial inactivation (e.g. low acidic products such as vegetable juices, dairy products or products where inactivation of bacterial endospores is required). However, final temperature of the product should not exceed the range where quality advantage of the final product would be compromised. It should be noted that exposure of the product to high temperatures during PEF occurs only for very short treatment times. However, the PEF treated product, heated due to the Joule heating, should be cooled down as fast as possible in order to reduce the thermal effect.

3.1.3. High pressure processing (HPP)

Energy evaluation of one HP cycle involving 600 MPa for 5 min resulted in 3.63 kWh of energy consumed. Considering loading and unloading time (1.5 min), filling efficiency of the HP vessel (36.5%), compression time (3.5 min) and holding time (5 min), six cycles per hour have been calculated, resulting in an energy consumption of 21.72 kWh for the production of 120 l of juice.

An industrial HP process involves underwater pressurization of the product at room temperature to a certain pressure (mostly 400-600 MPa) and holding it pressurized for a specific time (mostly 1-5 min). Such high pressures induce changes in functionality of cell membranes resulting in inactivation of vegetative cells, as well as some enzymes (Heinz and Buckow, 2009). Typical industrial machines consist of a yoke, a HP vessel, one or more high pressure intensifiers, plugs for closing the vessel and wedges for securing the plugs. The pressure transmitting medium (water) is contained in a separate tank and at start of a cycle is pumped from one side of the vessel and air is released on the other (Fig. 3).

Figure 3. HPP process chart including high pressure vessel, pressure intensifier, water tank, oil path and its cooling section (adopted with permission of Hiperbaric, Spain)

To generate the compression, electrical energy is used by the pressure intensifier(s) pump driven by hydraulic oil. For the selected high pressure cycle conditions, most of the electrical energy was consumed for pressure build-up (1.7 kWh) and keeping the pressure constant over 5 min (1.5 kWh). Less energy was needed for moving the machine parts (closing the plugs and wedging, 0.3 kWh), and for opening and pumping the water back (0.1 kWh) (Figure 4).

Three main parameters with direct impact on energy consumption during a HP process are pressure, total cycle time and vessel filling efficiency. Filling efficiency represents a relationship between the vessel volume and the maximum volume of the packed product that can be produced in one charge, expressed in percent. It is understandable that the work needed for compression accounts for the highest energy amount, followed by holding under pressure. Total cycle time includes handling time (loading/unloading), time needed for compression and

holding time, and has a direct impact on the production capacity. Consequently, the total energy depends first on the required pressure, followed by the treatment time necessary to achieve a certain effect (e.g. level of microbial inactivation). Accordingly, pressure or time reduction will result in reduction of total energy utilization. Reducing the holding time, not only reduces the direct energy consumption, but also allows more cycles per hour. Moreover, an optimal state and condition of the machine (better condition of intensifiers, fittings, seals, no leaks etc.) would result in less energy dissipation during a high pressure cycle. In other words, the work of the high pressure pump is less required (e.g. energy peaks occurring during holding time in step 6 in Fig. 4). Today, large industrial HP machines are available in vessel volumes up to 525 liters and up to 4000 kg/h capacity, operating in batch to semi-continuous way, equipped mostly with more than two, possibly up to 12 pressure intensifiers. The most often used treatment conditions for juice preservation involves 500-600 MPa and 2-3 min holding time (Tonello-Samson, 2014).

Figure 4. Energy consumption during high pressure cycle (600 MPa, 5 min) including different steps and pressure build-up. Power is indicated in blue full line and pressure in dashed red line. Different steps are given in numbers: 1. Moving the product, vessel and plug in; 2. Filling the vessel with water; 3. Closing the plug; 4. Wedging; 5. Pressure build-up; 6. Holding time; 7. Opening and pumping the water back

For an energy-efficient HP cycle, it is beneficial to maximize the filling ratio in order to utilize the compression energy in a more efficient way. For the juices, this could be done by using larger vessels, larger volumes of the bottles or optimization of the bottle shape, resulting in better filling efficiency (e.g. hexagonal instead of round bottles). Nowadays, most of the juice producers operate at a filling ratio from 40 to 45% (Tonello Samson, 2015).

After pressurization, the energy used for compression is mostly lost along with decompression. However, there is a great potential to recover up to 50% of the compression energy by synchronization of the compression and decompression phase in twin-vessel systems in order to compress the vessel at atmospheric pressure (Rodriguez-Gonzalez et al., 2015).

An overview of the energy consumption for thermal, PEF and high pressure pasteurization of tomato and watermelon juice based on a 120 l/h production and for selected inactivation conditions is given in table 3. The given rates of energy consumption were considered for life cycle assessment of different pasteurization technologies for the processing stage.

Table 3. Overview of energy consumption for thermal, PEF and HPP pasteurization of tomato and watermelon juice based on 120 l/h production capacity

	Thermal (kWh)	PEF (kWh)	HPP (kWh)
Tomato juice	4.56	14.42	21.72
Watermelon juice	4.36	14.30	21.72

3.2. Life cycle impact assessment and technologies comparison

Pasteurization technologies were first analyzed in the scope of “processing stage LCA” similarly to the publication of Pardo and Zufía (2012). Due to the similarities of resources consumption at the processing stage for different juices (Table 3), the assessment was performed for tomato juice only. The comparison revealed an expected differentiation between the technologies based on the differences in energy consumption (Fig. 5). Other inputs and outputs like consumed water, types of bottles used, cleaning procedures, were intentionally levelled to obtain a “fair comparison” ground. As production of raw materials was not considered at this stage, the highest impact of HPP was observed among the three compared technologies. This was independent of the product type. Even though the differences of processing stage were assigned to the use of energy, the largest environmental impact was associated with the 250 ml PET bottles production (~85%).

Figure 5. Processing stage LCA technologies comparison (FU 1 kg of pasteurized tomato juice, bottled and ready for sale, raw materials production is excluded, scope - from gate to gate; zero values of aquatic acidification and eutrophication excluded; 1 kPt = impact of 1 European per year)

Further, a LCA of complete supply chains was conducted in order to reveal the impact and potential changes in supply chains triggered by alterations of the processing. Moreover, the identification of the “hotspots” and the best case scenarios were set as the aims of LCA comparison for this research. Obtained results (Fig. 6) indicated only minor differences at the processing stage (energy use for processing), while surprisingly, considerable differences were outlined between the two products. Despite the high level of waste generation during watermelon juice production (around 50%), its overall impact was around 40% lower than the impact of tomato juice production. Production and preservation of watermelon juice (including PET bottles production) was responsible for 46-49% of the environmental impacts for all three technologies. Production and preservation of tomato juice resulted in around 30% of the environmental impact allocation (from “farm to gate”).

Figure 6. Results of LCA comparison for different technologies (FU 1 kg of pasteurized juice, bottled and ready for sale, scope - from farm to gate; zero values of aquatic acidification and eutrophication excluded; 1 kPt = impact of 1 European per year)

The highest impacts of juice production (from “farm to gate”) were associated with energy use for the production of tomatoes in greenhouses in the Netherlands (around 50% of overall impact) and with transportation of watermelons from Spain to Germany (around 30% of the overall impact). In all of the cases the environmental impacts were closely associated with energy used for raw materials production, transportation and processing. It explains the high impacts in categories of global warming, non-renewable energy use and respiratory inorganics (Fig. 7). Comparatively, high impact of tomatoes production in the categories of terrestrial ecotoxicity, global warming, non-renewable energy use and respiratory inorganics is related to the use of coal for greenhouses heating (country energy mix). The only category, where watermelon juice production had higher weighted impact compared to tomato juice production was land occupation, which is related to the high amount of waste generated (50% of weight).

Figure 7. Product comparison midpoint characterization factors for different technologies (FU 1 kg of pasteurized juice, bottled and ready for sale, scope - from farm to gate; zero values of aquatic acidification and eutrophication excluded; 1 kPt = impact of 1 European per year)

3.3. Comparison of the results with previous studies

Sensitivity analysis included the comparison of the results with similar studies available in the literature. It is necessary to mention that there is a lack of LCA studies including processing technologies. To the best of our knowledge, only two studies considered HPP and PEF technologies (Davis et al. 2010; Pardo and Zufía 2012). However, the comparison with available literature data has a very “shallow” character as multiple processing aspects were different in other studies.

Even though different authors used different raw materials for the processing trials, the results of the impacts were in close approximation to the ranges of the main midpoint results of our study (Table 4). However, to make a comparison with literature data, it was necessary to account for the variations in systems boundaries and LCA methodologies.

Table 4. Main midpoint impact categories results for the complete assessment (from “farm to gate”, FU 1 kg of pasteurized tomato juice, bottled and ready for sale)

Impact category	Unit	Tomato			Watermelon		
		Thermal	PEF	HPP	Thermal	PEF	HPP
Land occupation	m ² arable	0.14-0.50	0.14-0.50	0.14-0.50	0.19-0.27	0.19-0.27	0.19-0.27

Global warming	kg CO ₂ eq.	1.83-1.84	1.87-1.89	1.93-1.95	1.03-1.11	1.08-1.16	1.14-1.22
Non-renewable energy use	MJ (kWh)	22.56-25.89 (6.27-7.19)	23.14-26.76 (6.43-7.43)	23.78-27.71 (6.61-7.70)	16.49-19.58 (4.58-5.44)	17.07-20.46 (4.74-5.68)	17.71-21.41 (4.92-5.95)

Note. Ranges of results are based on the use of IMPACT 2002+ and ReCiPe methodologies

The study of Davis et al. (2010) revealed results on PEF and HPP application for carrot juice. The study presented following impacts of juice processing (FU 1 l of carrot juice): 14-15 MJ (3.89-4.17 kWh) of energy consumption, ~0.75 kg CO₂ eq. for climate change, ~0.85 g PO₄ eq. for eutrophication and ~2.2 g SO₄ eq. for acidification. Our study demonstrated generally higher results for most of the categories (Table 4). Pardo and Zufía (2012) defined only processing stage impacts for HP and thermal processing without precise specification of the equipment capacities. At the same time the authors defined two options for cumulative energy demand which differs in few orders. Nevertheless, we assumed that the energy demands used for the processing of 1 kg of ready-to-eat dish in their study were in the range of 7.8-9.2 MJ (2.17-2.56 kWh) and 8 MJ (2.22 kWh) for thermal and HPP respectively. Thermal processing resulted in ~0.4 kg CO₂ eq. (global warming potential), 0.0073 g PO₄ eq. (eutrophication potential) and 1.12 g SO₄ eq. (acidification potential). HPP had ~0.28 kg CO₂ eq. for global warming, 0.0013 g PO₄ eq. for eutrophication potential and 1.24 g SO₄ eq. for acidification potential (Pardo and Zufía, 2012). Our current study identified higher impacts in most of the categories: energy consumption and global warming potential (Table 4); acidification potential (23-26 g SO₄ eq.) and eutrophication potential (0.2-0.6 g PO₄ eq.). However, the results of our study considered impact from the complete life cycle assessment (from “farm to gate”). The energy consumption during processing was empirically measured at equal production capacity. Moreover, all three technologies were evaluated at intensities resulting in an equivalent level of safety. Taking into account the different raw materials, processing conditions and other factors considered in similar studies, it is difficult to compare obtained results with those already available in the literature. In some cases the comparison of LCA at processing stage would be possible if the full range of conditions (e.g. capacity, holding time, temperature profile) was specified in the literature. The production capacity of equipment is of special importance as it affects the product flow volume and efficiency of resource use. The lack of these parameters created difficulties for the reproduction and comparison of the studies.

3.4. Sensitivity analysis and different scenarios

In order to ensure the viability of the results of our study (and based on empirical measurements, specific for the case study) we performed a sensitivity analysis with changes of the most impactful elements of the life cycle chains. These results are presented in forms of scenarios, which were different from the main study. It was defined that changes in energy mixes, packaging material, transportation distances, as well as energy sources, did not change the comparative relative results between technologies. At the same time, the scenarios allowed identification of more environmentally sustainable options. As the baseline scenarios were based on very similar conditions of energy mixes, transportation means and water uses, there was no need to present the scenarios for each processing technology and each product. However, tomato and watermelon juices had different environmental hotspots (Fig. 8 and Fig. 9).

Figure 8. Endpoint LCA results of sensitivity scenarios indicating the variations due to the changes in the production conditions of tomato juice (HPP as baseline scenario; from “farm to gate”; 1 kPt = impact of 1 European per year; SC1-0: baseline scenario; SC1-1: German electricity mix; SC1-2: minimal transportation distance; SC1-3: field tomatoes growing; SC1-4: HDPE bottles; SC1-5: natural gas for heating)

Figure 9. Endpoint LCA results of sensitivity scenarios indicating the variations due to the changes in the production conditions of watermelon juice (HPP as baseline scenario; from farm to gate; 1 kPt = impact of 1 European per year; SC2-0: baseline scenario; SC2-1: 50% less waste at processing; SC2-2: minimal transportation distance; SC2-3: HDPE bottles)

The highest impacts related to the tomato juice were associated with the use of energy from various sources (electricity and heat) for tomato production in the Netherlands. Therefore, it was assumed that changes in energy mix for electricity or types of fuels used for the heating might change the overall results of the study. This was confirmed for the change of heating energy from the European mix to natural gas (both background processes from Ecoinvent 3 database). Use of natural gas (SC1-5) had lower impact for around 30%, compared to the mix of energy sources (includes use of coal) (SC1-0). At the same time, shift of electricity sources from European to the German mix (SC1-1) did not change the results significantly (Fig. 8). Similarly, the change of transportation distances (assuming the processing took place in a distance less than 100 km) did not change the results in a considerable way (SC1-2).

Growing tomatoes on the field (lowering the energy consumption by 90%) allowed decrease of the overall environmental impacts of tomato juice (SC1-3) by almost 50% (Fig. 8). In this case the environmental impacts of the tomato juice would have been lower than watermelon juice. Another alternative scenario (SC1-4) with potential impact was the use of high-density polyethylene (HDPE) bottles (some successful examples of their use exist on the market). The use of HDPE bottles of the same weight allowed decreasing the overall environmental impact by 10% (Fig. 8 and Fig. 9). A similar effect was achieved with the use of polypropylene (PP)

bottles. Therefore, the best case scenario of tomato juice production would be based on the use of field grown tomatoes and HDPE (or PP) bottles. It would result in a decrease by 60% of the environmental impact of baseline tomato juice production.

Watermelon juice production included field-grown raw materials. Therefore, it can be assumed that the change of the impact could be achieved with the use of more efficient agricultural techniques. As this was out of the scope of the study, such scenarios were not included in the comparison. However, it was assumed that a high impact of watermelon juice production is associated with the high transportation weight for a long distance and high waste rate (around 50% for middle sized watermelons). Performed analysis indicated only a minor impact of the transportation distance change. Reduction of the transportation distance to 100 km with the use of light commercial lorry (SC2-2, similar to the scenario with the tomato juice) lowered the overall environmental impact by 5% only (Fig. 9). Such a minor change was associated with the use of the efficient ship transportation from Spain to the Netherlands, which was considered in a baseline scenario (SC2-0).

Waste reduction (around 50%) achieved with the use of larger watermelons with thin peels allowed lowering the environmental impact of juice production by 13% (SC2-1). A similar decrease was achieved with the change of bottles (SC2-3). Altogether, the estimated changes could result in the best case scenario (less waste, lower transportation distance and different bottles), which would have 32% lower environmental impact than the baseline scenario.

In the end, for the total energy balance and environmental impact, a significant role belongs also to consumers and their decision which product they purchase (prefer one technology over another, health claims, buying locally, buying seasonally, etc.).

4. Conclusion

Evaluation of energy requirements for comparable preservation of tomato and watermelon juice using different processing technologies at a 120 l/h production capacity showed the highest energy consumption for the HP process (around 0.20 kWh/l of juice). The next most energy demanding technology was PEF (around 0.12 kWh/l of juice), followed by thermal process (around 0.04 kWh/l of juice). No huge differences in terms of energy were observed between the same technologies for the two different juices. Despite higher energy requirements for HPP and PEF to deliver comparable shelf-life of juices compared to thermal processing, their advantage is widely recognized in their potential to deliver products with an

improved quality compared to their thermal counterparts. From an energetic point of view, improvement of PEF processing can be achieved by elevated inlet temperatures. In this way higher heat recovery rate can be achieved. Here it is important to optimize the process conditions while still maintaining the potential quality benefit. In case of HPP, a more energy efficient process could be obtained by lowering the pressure and shortening the holding time, as well as by increasing the filling efficiency. This is likely to occur when larger scale HP units would be used. However, manipulation of pressure and time has to be aligned with safety aspect, delivering a targeted level of safety. Moreover the optimization should be done for each and specific product.

From the LCA perspective, no huge differences in environmental impact have been observed over the three investigated technologies with “gate to gate” system boundaries. A slightly higher impact was observed for HPP, followed by PEF and thermal. Even though the differences of processing stage were assigned to the use of energy, the largest environmental impact was associated with 250 ml PET bottles production (~85%). The largest environmental impacts of product life cycle (from “farm to gate”) were associated with raw materials production (around 20% for watermelon juice and around 64% for tomato juice) and processing (around 30% for tomato juice and around 50% for watermelon juice). The optimization strategies for diminishing environmental impact vary for different juices and are associated with raw material production (field tomatoes), waste amount decreasing (type of watermelons selection) and relevant packaging material selection (HDPE vs. PET).

However, the energy balance and the outcome of environmental impact of thermal and alternative preservation techniques might slightly change with increasing production capacity. The intensity of the ultimate processing conditions for PEF and HPP at pilot scale used in this study would most likely not be exceeded in an industrial environment. Also, the potential differences in theoretical calculation versus experimental data for thermal preservation could lead to slightly different results, especially when large scale is considered. Therefore an extended study on a wide range of products involving large industrial production capacity is recommended.

Acknowledgment

This research was financially supported by the Seventh Framework Programme (FP7) of the European Union under the Marie Curie Initial Training Network ‘HST FoodTrain’ (Grant agreement 264470). The funding sources had no involvement in study design, collected data, performed analysis and interpretation. The authors would also like to thank to Dr. Knut Franke, Dr. Carole Tonello Samson, Dr. Diego Wilches Perez, Lucia Valsasina and Chiara Longhin for their supportive contribution.

Reference list

- Aganovic, K., Grauwet, T., Kebede, B.T., Toepfl, S., Heinz, V., Hendrickx, M., Van Loey, A., 2014. Impact of different large scale pasteurisation technologies and refrigerated storage on the headspace fingerprint of tomato juice. *Innovative Food Science & Emerging Technologies* 26, 431-444.
- Aganovic, K., Grauwet, T., Siemer, C., Toepfl, S., Heinz, V., Hendrickx, M., Van Loey, A., 2015. Headspace fingerprinting and sensory evaluation to discriminate between traditional and alternative pasteurization of watermelon juice. *European Food Research and Technology*, 1-17.
- Andersson, K., Ohlsson, T., Olsson, P., 1998. Screening life cycle assessment (LCA) of tomato ketchup: a case study. *Journal of Cleaner Production* 6, 277-288.
- Augusto, P.E.D., Tribst, A.A.L., Cristianini, M., 2014. THERMAL PROCESSES | Commercial Sterility (Retort), in: Tortorello, C.A.B.L. (Ed.), *Encyclopedia of Food Microbiology* (Second Edition). Academic Press, Oxford, pp. 567-576.
- Baumann, H., Tillman, A.-M., 2004. The hitchhiker's guide to LCA: an orientation in life cycle assessment methodology and application. Studentlitteratur, Lund, Sweden.
- 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, 1196-1207.
- Dalsgaard, H., Abbotts, W., 2003. 8 - Improving energy efficiency, in: Mattsson, B., Sonesson, U. (Eds.), *Environmentally-Friendly Food Processing*. Woodhead Publishing, pp. 116-129.
- Davis, J., Moates, G., Waldron, K., 2010. 5 - The environmental impact of pulsed electric field treatment and high pressure processing: the example of carrot juice, in: Doona, C.J., Kustin, K., Feeherry, F.E. (Eds.), *Case Studies in Novel Food Processing Technologies*. Woodhead Publishing, pp. 103-115.
- Davis, J., Sonesson, U., 2008. Life cycle assessment of integrated food chains—a Swedish case study of two chicken meals. *Int J Life Cycle Assess* 13, 574-584.
- Deeth, H.C., Datta, N., Ross, A.I.V., Dam, X.T., 2007. Pulsed Electric Field Technology: Effect on Milk and Fruit Juices, *Advances in Thermal and Non-Thermal Food Preservation*. Blackwell Publishing, pp. 241-269.
- Devlieghere, F., Vermeiren, L., Debevere, J., 2004. New preservation technologies: Possibilities and limitations. *International Dairy Journal* 14, 273-285.
- Earles, J.M., Halog, A., 2011. Consequential life cycle assessment: a review. *Int J Life Cycle Assess* 16, 445-453.
- Ekvall, T., Finnveden, G., 2001. Allocation in ISO 14041—a critical review. *Journal of Cleaner Production* 9, 197-208.
- Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A.D., Struijs, J., Zelm, R.v., 2013. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. , ReCiPe 2008. First edition (version 1.08). Report I: Characterisation. Retrieved from www.lcia-recipe.net. Date accessed: 15.05.2016
- Goedkoop, M., Spriensma, R., 2001. The Eco-indicator 99. A damage oriented method for Life Cycle Impact Assessment, Third edition ed, Amersfoort. Retrieved from www.pre-sustainability.com/download/EI99_annexe_v3.pdf. Date accessed: 15.05.2016
- Guinée, J.B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., Rydberg, T., 2011. Life Cycle Assessment: Past, Present, and Future. *Environmental Science & Technology* 45, 90-96.

- 1 Heinz, V., Alvarez, I., Angersbach, A., Knorr, D., 2001. Preservation of liquid foods by high
2 intensity pulsed electric fields—basic concepts for process design. *Trends in Food Science &*
3 *Technology* 12, 103-111.
- 4 Heinz, V., Buckow, R., 2009. Food preservation by high pressure. *Journal für Verbraucherschutz*
5 *und Lebensmittelsicherheit* 5, 73-81.
- 6 Hendrickx, M.E.G., Knorr, D., 2001. *Ultra High Pressure Treatment of Foods*. Springer US, New
7 York (N.Y.).
- 8 Hospido, A., Davis, J., Berlin, J., Sonesson, U., 2010. A review of methodological issues affecting
9 LCA of novel food products. *Int J Life Cycle Assess* 15, 44-52.
- 10 ISO 14044. (2006). *Environmental management – Life cycle assessment – Requirements and*
11 *guidelines*. International Organization for Standardization.
- 12 ISO 14040. (2006). *Environmental Management – Life Cycle Assessment – Principles and*
13 *Framework*.
- 14 Joliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., Rosenbaum, R., 2003.
15 *IMPACT 2002+: A new life cycle impact assessment methodology*. *Int J Life Cycle Assess* 8, 324-
16 330.
- 17 Kessler, H.G., 1988. *Lebensmittel- und Bioverfahrenstechnik - Molkereitechnologie*. Kessler, N.;
18 Auflage: 3., überarb. u. erw. Aufl. (1988), Freising-Weihenstephan, Germany.
- 19 Knorr, D., 1999. Novel approaches in food-processing technology: new technologies for
20 preserving foods and modifying function. *Current Opinion in Biotechnology* 10, 485-491.
- 21 Knorr, D., Froehling, A., Jaeger, H., Reineke, K., Schlueter, O., Schoessler, K., 2011. Emerging
22 technologies in food processing. *Annual review of food science and technology* 2, 203-235.
- 23 Knorr, D., Geulen, M., Grahl, T., Sitzmann, W., 1994. Food application of high electric field pulses.
24 *Trends in Food Science & Technology* 5, 71-75.
- 25 Luo, L., van der Voet, E., Hupples, G., Udo de Haes, H., 2009. Allocation issues in LCA methodology:
26 a case study of corn stover-based fuel ethanol. *Int J Life Cycle Assess* 14, 529-539.
- 27 Monforti-Ferrario Fabio, Dallemand Jean-Francois, Pinedo Pascua Irene, Motola Vincenzo, Banja
28 Manjola, Scarlat Nicolae, Medarac Hrvoje, Castellazzi Luca, Labanca Nicola, Bertoldi Paolo,
29 Pennington David, Goralczyk Malgorzata, Schau Erwin, Saouter Erwan, Sala Serenella,
30 Notarnicola Bruno, Tassielli Giuseppe, A., R.P., 2015. Energy use in the EU food sector: State of
31 play and opportunities for improvement, in: Centre, J.R. (Ed.). *Publications Office of the*
32 *European Union, European Union*.
- 33 Pardo, G., Zufia, J., 2012. Life cycle assessment of food-preservation technologies. *Journal of*
34 *Cleaner Production* 28, 198-207.
- 35 Pereira, R.N., Vicente, A.A., 2010. Environmental impact of novel thermal and non-thermal
36 technologies in food processing. *Food Research International* 43, 1936-1943.
- 37 Raso, J., Heinz, V., Manas, P., Vercet, A., 2006. Effect of PEF on Enzymes and Food Constituents,
38 *Pulsed Electric Fields Technology for the Food Industry*. Springer US, pp. 131-151.
- 39 Rodriguez-Gonzalez, O., Buckow, R., Koutchma, T., Balasubramaniam, V.M., 2015. Energy
40 Requirements for Alternative Food Processing Technologies—Principles, Assumptions, and
41 Evaluation of Efficiency. *Comprehensive Reviews in Food Science and Food Safety* 14, 536-554.
- 42 Roy, P., Nei, D., Orikasa, T., Xu, Q., Okadome, H., Nakamura, N., Shiina, T., 2009. A review of life
43 cycle assessment (LCA) on some food products. *Journal of Food Engineering* 90, 1-10.
- 44 Schau, E., Fet, A., 2008. LCA studies of food products as background for environmental product
45 declarations. *Int J Life Cycle Assess* 13, 255-264.

- 1 Schmidt, J., Weidema, B., 2008. Shift in the marginal supply of vegetable oil. *Int J Life Cycle Assess*
2 13, 235-239.
- 3 Tewari, G., 2007. *High-Pressure Processing of Foods, Advances in Thermal and Non-Thermal*
4 *Food Preservation*. Blackwell Publishing, pp. 203-239.
- 5 Thomassen, M., Dalgaard, R., Heijungs, R., de Boer, I., 2008. Attributional and consequential LCA
6 of milk production. *Int J Life Cycle Assess* 13, 339-349.
- 7 Toepfl, S., Mathys, A., Heinz, V., Knorr, D., 2006. Review: Potential of high hydrostatic pressure
8 and pulsed electric fields for energy efficient and environmentally friendly food processing. *Food*
9 *Reviews International* 22, 405-423.
- 10 Toepfl, Stefan. 2015. Personal communication. German Institute of food technologies, Germany.
- 11 Tonello-Samson, C., 2014. Advances in high pressure processing: case studies, IFT Annual
12 Meeting & Food Expo, New Orleans, LA, USA.
- 13 Tonello Samson, C., 2015. Personal communication. Hiperbaric, Spain.
- 14 Wilbey, R.A., Batt, C.A., Tortorello, M.L., 2014. HEAT TREATMENT OF FOODS | Principles of
15 Pasteurization, *Encyclopedia of Food Microbiology* (Second Edition). Academic Press, Oxford, pp.
16 169-174.
- 17 Zufia, J., Arana, L., 2008. Life cycle assessment to eco-design food products: industrial cooked
18 dish case study. *Journal of Cleaner Production* 16, 1915-1921.

19
20