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Environmental impact analysis of HPP and PCT decontamination technologies: an LCA comparison

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Abstract
High Pressure Processing (HPP) and Pressure Change Technology (PCT) are two non-conventional food stabilization technologies that guarantee high quality products with longer shelf lives. This study analyses whether these two technologies are also able to give benefits in terms of environmental impact. A Life Cycle Assessment (LCA) is applied to the case of pineapple juice packaged in two different types of plastic bottles. The packaging material is a parameter that can influence the properties of the food product, its shelf life and the environmental impact. The results confirm that both technologies have a reduced environmental impact, especially when the most sustainable packaging material is used. Therefore, HPP and PCT are proved to be sustainable solutions in the production of high-quality food, with PCT better than HPP in this preliminary study in all the considered LCA impact categories. Moreover, they can play an important role in the reduction of food waste.

Keywords: high pressure processing; pressure change technology; Life Cycle Assessment; environmental sustainability

1. Introduction

Nowadays the development of new technologies in the food industry is driven by the need to meet the high-quality standards required by the consumers and the reduction of the environmental impact, which is now an issue of global importance. Two technologies, well known for their effectiveness in maintaining unaltered the nutritional and organoleptic properties of the food and in increasing its shelf life, are High Pressure Processing (HPP) and Pressure Change Technology (PCT). They are both non-conventional stabilization technologies that use pressure instead of heat to inactivate the pathogenic and spoilage microorganisms (Vignali, Gozzi, Pelacci, & Stefanini, 2022). In order to investigate the presence of any environmental benefits, brought about by these two processes, in addition to the reduction of food waste thanks to longer shelf lives, this study carries out a Life Cycle Assessment (LCA). The next section describes the state of the art of the topic, highlighting the gaps in the literature and the main purpose of the work. Then, section 3 illustrates the methodology used to carry out the LCA analysis; finally, results are discussed in section 4, before drawing the main conclusions of the work.

2. State of the art

Among the non-thermal treatments to stabilize food products, such as Pulsed Electric Fields, Ultraviolet Light, Sonication and Super Critic Carbon Dioxide, two alternatives use pressure: the High Pressure Processing (HPP) and the Pressure Change Technology (PCT). Both the technologies have advantages: HPP provides for good retention of nutrients, organoleptic properties and food fresh-like characteristics (Stefanini, Ronzano, Borghesi, & Vignali) since the process is carried out at room temperature, while, thanks to PCT, a fast and uniform inactivation of vegetative microbial forms can be reached. As a disadvantage there is the fact that they both have limited effects on microbial spores. Moreover, HPP, being a batch process that can be applied only to packaged products, brings to limited plant productivity, while PCT, on his side, cannot be applied to heated products, since the increase of temperature reduces the gas solubility in liquid products (Vignali, Gozzi, Pelacci, & Stefanini, 2022). Table 1 resumes their main characteristics, such as their functioning, the effects on microorganisms, enzymes and vitamins, as well as their applications.

According to a brief literature analysis carried out on Scopus Database, HPP resulted in a consolidated process studied by researchers and used by some food companies: more than 2000 works have been found using the keywords "High Pressure Processing". On the other hand, PCT is a very emerging topic, since only 7 works have been found with the search "Pressure Change Technology" in the abstract, title and keywords. Figure 1 illustrates that over the years both technologies are gaining interest. It must be noticed that the search is carried out in July 2022, but at the end of the year the number of publications might be higher.

Table 1. Functioning, effects and application of HPP and PCT

	HPP	PCT
Applications	Prepacked liquid and solid foods (e.g. fish, meat, juices, cheese)	Only liquid foods (e.g. juices, milk, wine)
Functioning	The pre-packed products is loaded into a vessel, in which a pressure medium, usually water (Rastogi, 2013), is pumped isostatically up to the desired pressure (100-900 MPa) (Elamin, Endan, Yosuf, Shamsudin, & Akhmedov, 2015). After holding the product for the required time (1-30 minutes), the pressure is released and the packaging is dried before being refrigerated (Farkas & Hoover, 2000)	The liquid product is mixed and pressurized (25-50 MPa) with an inert gas (Argon or Nitrogen). During the holding time (1-5 minutes), the diffusion of the dissolved gas through the cell membranes occurs reaching saturation. Then, a flash decompression causes the degassing: the increase of the gas volume disrupts the cells of microorganisms (Vignali, Gozzi, Pelacci, & Stefanini, 2022)
Effects	Breakdown of ribosomes, death of vegetative microorganisms (Qazalbash, Aadil, Madni, & Bekhit, 2018). Unfolding of proteins or enzymes. The lethal effect is achieved during holding time.	Damages to the microbial cell structures Few impacts on enzyme activity and nutritional compounds. The lethal effect is achieved at the dynamic decompression step (Aschoff, et al., 2016)
State of use	Consolidated	Emerging

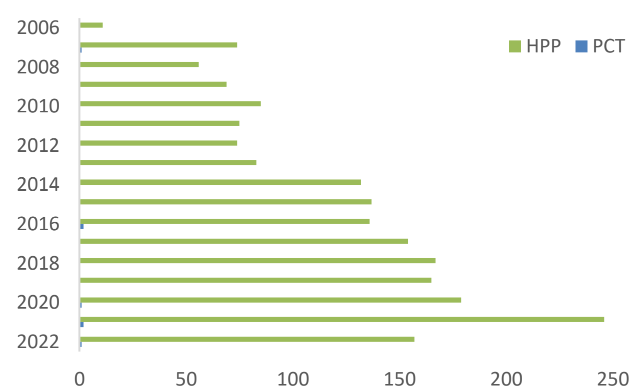


Figure 1. The number of publications over years on Pressure Change Technology (PCT) and High Pressure Processing (HPP).

To date, the environmental impacts of HPP are studied in some articles (Nabi, et al., 2021) (Jambrak, Nutrizio, Djekić, Pleslić, & Chemat, 2021), and some authors compare them with those of other stabilization technologies. For instance, HPP resulted less environmental impactful than thermal pasteurization or Modified Atmosphere Packaging (Cacace, Bottani, Rizzi, & Vignali, 2020) according to many impact categories such as global warming, stratospheric ozone depletion, fine particulate matter emissions, terrestrial acidification and ecotoxicity potentials. Instead, there are no works that analyze the sustainability of PCT or compare it with other technologies from an environmental perspective.

Besides these premises, this article aims at comparing the environmental performances of HPP and PCT, investigating the main hotspots of both technologies. The methodology used is the Life Cycle Assessment (LCA), recognized by the European Commission as the best tool to estimate the potential environmental impacts throughout the life cycle of a product or process (European Commission, 2021). In the article, the evaluation is performed for a system which includes the product treated with the two alternative technologies and its packaging: pineapple juice packaged in two types of plastic bottles, one made of 100% virgin PET and the other one made of 50% r-PET, has been considered. Since the packaging material is a parameter that could affect the environmental results, this study also aims to quantify the benefit brought by the use of a recycled material rather than one produced from the extraction of new raw materials.

3. Materials and Methods

3.1. Life Cycle Assessment

The quantification of the environmental impact is carried out with the LCA. The principles and framework of the LCA are defined by the regulation ISO 14040 (ISO 14040, 2006), while the methodological guidelines are set by the regulation ISO 14044 (ISO 14044, 2006). The LCA consists of four steps: goal and scope definition, inventory analysis, impact assessment and interpretation of the results. The first step defines the aim of the study, the system boundaries and the functional unit (FU), to which all the input and output data, and therefore the results, are referred. In the inventory analysis all the data are collected and normalized to the functional unit. For the impact assessment several methods can be chosen and the results are dependent on the method used. The analysis is carried out with the software SimaPro 9.4 with Ecoinvent 3.8 as the database for the inventory analysis.

3.1.1. Goal and scope definition

As mentioned, the aim of the study is to investigate the sustainability of HPP and PCT technologies. The two processes are compared considering their material and energy consumption. The FU of the study is 1 kg of pineapple juice. The juice can be filled in bottles and then stabilized with HPP, or it can be cold pasteurized with PCT and then filled into bottles of two different materials: 100% virgin PET and 50% virgin PET / 50% r-PET. The graphical representation of the system boundaries is reported in Figure 2.

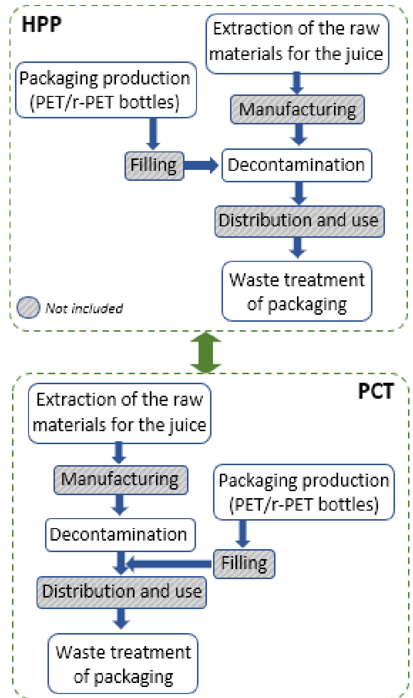


Figure 2. System boundaries of the LCA

3.1.2. Inventory analysis

The data collected are mainly secondary data taken from literature. All the sources, the numerical values of the input and output and the Ecoinvent datasets selected for each material and energy flow are reported in Table 2. Since an average quantity of 3 kg of pineapple is required for 1 kg of fresh pineapple juice and, considering that the density of the product is approximately 1,045 kg/l (Vollmer, et al., 2020), a quantity of 2,87 kg of pineapple is necessary to produce 1 kg of FU. In this phase, the disposal scenarios of the pineapple and of the PET and r-PET bottles were also modelled. According to the cut-off approach the benefit provided by the use of a recycled material is considered at the beginning of the life cycle, so the disposal scenario of the two types of bottles is the same. In this way, double counting is avoided. According to Corepla sustainability report (Corepla, 2020) 47% of plastic waste is recycled, 48% is sent to incineration and the rest 5% is landfilled. As far as the waste treatment of pineapple juice is concerned, data are taken from Ispra municipal waste report (ISPRA, 2021). In 2021, the biological treatment of the organic fraction of urban waste includes 48,1% composting, 46,8% of integrated aerobic and anaerobic treatment and 5,1% anaerobic digestion. Since there is no dataset for the integrated aerobic and anaerobic treatment, the respective percentage is equally divided between composting and anaerobic digestion, so the scenario modelled with SimaPro is represented by 71,5%

composting and 28,5% anaerobic digestion.

3.1.3. Impact assessment

The impact assessment is carried out with the ReCiPe Midpoint 2016 (H) method, which is a global method commonly used in papers that compare different technologies (Pardo & Zufía, 2012). Overall, it reports 18 different impact categories, but in this study only six, very similar to those included in the European EPD method (EPD, 2022), have been considered i.e. global warming, terrestrial acidification, freshwater eutrophication, land use, fossil resource scarcity and water consumption potentials.

4. Results and Discussion

In this section the main results are presented. First of all, it can be noted that, in the life cycle of a PET bottle treated with HPP, the decontamination phase (composed of process water, electricity and compressed air consumption) is responsible for only 5-30% of the impact, depending on the categories (Figure 3). A similar result is obtained also for PCT (Figure 4). The main cause of impact in both scenarios, according to the assumptions of the study, is the production of pineapple juice. This result is in accordance with the literature, where it is known that the agricultural phase generates higher environmental impacts (Cheng, Wang, & Yu, 2022), regardless of the stabilization treatment used then on the food product. Comparing now the decontamination technologies, the differences between HPP and PCT are the consumption involved in the treatments. Process water and compressed air have a low impact during the HPP, instead of electricity that contributes up to the 10% of the total impact. On the other hand, the electricity used in PCT seems to have a negligible impact, while argon impacts 5% of the total. Overall, PCT appears as the best solution according to the global warming, terrestrial acidification, land use, water consumption and fossil resource scarcity potentials.

However, in both scenarios (Figures 3 and 4), the PET bottle resulted impactful from an environmental point of view, e.g. up to 30% on the fossil resource scarcity potential.

Besides this result, the comparison of the impacts of HPP and PCT using PET or r-PET bottles is interesting. Figure 5 illustrates that the use of r-PET generates benefits regardless of the treatment used. In particular, the use of PCT with r-PET bottle allows a reduction of the impact of 10% in comparison to HPP with PET bottle.

Table 2. Data collection

Life cycle stage	*Input*	*Unit of Measurement*	*Value*	*Source*	*Dataset*
Product	Pineapple	kg	2,87	Primary data	*Pineapple {GLO}| market for*
Packaging	PET bottle	g	22	(Stefanini, Borghesi, Ronzano, & Vignali, 2021)	*Polyethylene terephthalate, granulate, bottle grade {GLO}| market for* *Injection moulding {GLO}| market for* *Blow moulding {GLO}| market for*
	r-PET bottle	g	22	(Stefanini, Borghesi, Ronzano, & Vignali, 2021)	*Polyethylene terephthalate, granulate, amorphous, recycled {Europe without Switzerland}| market for polyethylene terephthalate, granulate, amorphous, recycled* *Polyethylene terephthalate, granulate, bottle grade {GLO}| market for* *Injection moulding {GLO}| market for* *Blow moulding {GLO}| market for*
	Bottle cup	g	2,68	(Stefanini, Borghesi, Ronzano, & Vignali, 2021)	*Polyethylene, high density, granulate {Europe without Switzerland}| polyethylene, high density, granulate, recycled to generic market for high density PE granulate*
	Bottle label	g	0,8	(Stefanini, Borghesi, Ronzano, & Vignali, 2021)	*Polypropylene, granulate {GLO}| market for* *Extrusion, plastic film {GLO}| market for*
HPP	Electricity	Wh	173,5	(Cacace, Bottani, Rizzi, & Vignali, 2020)	*Electricity, medium voltage {IT}| market for*
	Water	kg	0,228	(Cacace, Bottani, Rizzi, & Vignali, 2020)	*Tap water {Europe without Switzerland}| market for*
	Compressed air	l	0,74	(Cacace, Bottani, Rizzi, & Vignali, 2020)	*Compressed air, 600 kPa gauge {RER}| compressed air production, 600 kPa gauge, >30kW, average generation*
PCT	Electricity	kJ	26,3	(Gómez-López, et al., 2021)	*Electricity, medium voltage {IT}| market for*
	Inert gas (Argon)	g	20	(Vollmer, et al., 2020)	*Argon, liquid {RER}| market for argon, liquid*

Figure 3. HPP environmental impacts.

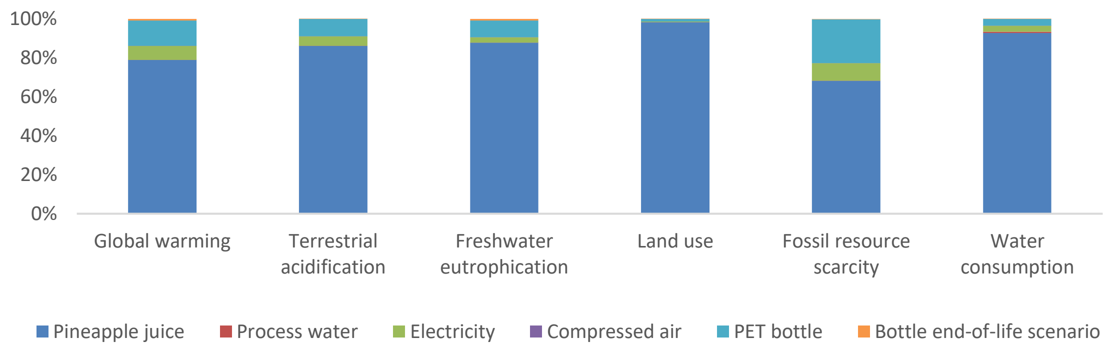


Figure 4. PCT environmental impacts.

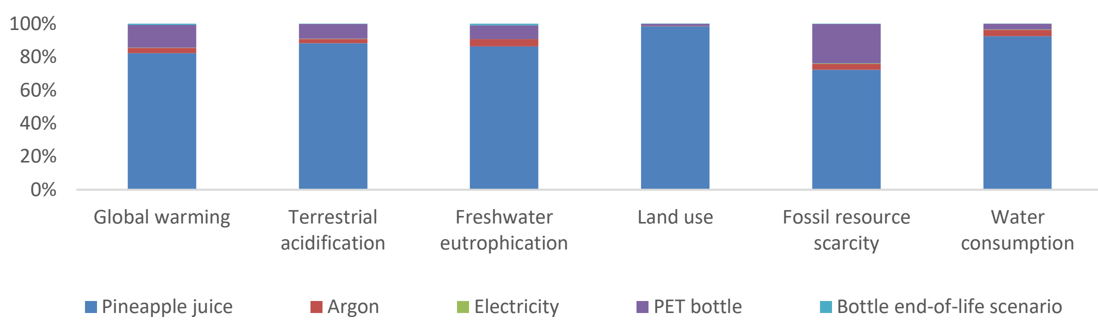
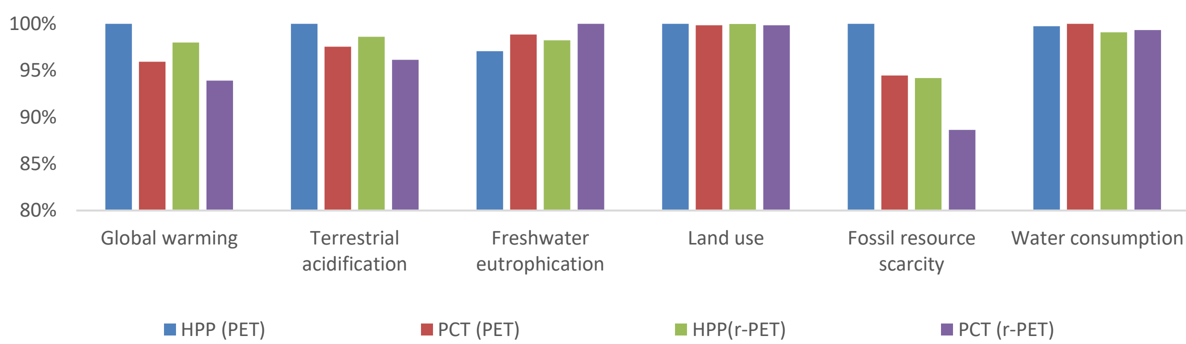


Figure 5. Comparison of the environmental impact of HPP and PCT with PET and r-PET bottles.



5. Conclusions

Today non-thermal technologies are gaining interest in the food sector for their capability to stabilize the products preserving their nutritional value. With a focus on High Pressure Processing and Pressure Change Technology this study discovered, with a brief literature analysis, that HPP is a consolidated treatment for solid and liquid value-added food, while PCT is still not well known and implemented. However, thanks to a Life Cycle Assessment carried out on pineapple juice treated with the two processes, this work highlighted that PCT allows a reduction of the environmental impact especially in the categories of global warming, terrestrial acidification, land use, water consumption and fossil resource scarcity potentials. In particular, the use of an r-PET bottle, instead of a PET traditional one, can decrease the overall environmental impact, regardless the technology used.

The main limits of the study are the lack of primary data and the omission of the aspects related to the shelf life of the product on which the amount of food waste generated depends. The development of valid correlations between the number of days of shelf life and the quantity of discarded product would also allow to estimate the environmental impact of the end of life of the juice and to fully quantify the benefits brought by each technology. For a more complete analysis, other non-thermal technologies, such as Pulsed Electric Fields (PEF), could be included in the comparison. PEF is similar to PCT in terms of effectiveness in quality preservation and in packaging optimization, an advantage that gives an additional value two these two technologies over HPP. These are the directions towards which the future developments of this research will be oriented.

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