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Implementation of PEF Treatment at Real-Scale Tomatoes Processing Considering LCA Methodology as an Innovation Strategy in the Agri-Food Sector

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Abstract: In Europe, science and innovation are boosting the agri-food sector and, in parallel, are helping to decrease greenhouse gas emissions (GHG) and European dependency on non-renewable resources. Currently, it is well-known that this sector contributes to the consumption of energy and material resources, causing significant environmental impacts that require a complex and comprehensive environmental evaluation in order to manage them effectively. This becomes even more complicated when new technologies are reaching the level of technological maturity needed to be installed in the production lines. To address this scientific challenge, the life cycle assessment (LCA) has been used in this paper to evaluate the potential of pulsed electric fields (PEF) technology at an industrial scale to facilitate the steam peeling of tomato fruits. Considering the thermo-physical peeling stage, the LCA has shown that PEF technology is environmentally friendly, because when PEF technology is applied, all the considered environmental indicators improve between 17% and 20%.

Keywords: pulsed electric fields (PEF); life cycle assessment (LCA); sustainable food production; tomato processing

1. Introduction

Agriculture is one of the most ancient and important sectors in the world. According to Eurostat [1], in 2015, just in Europe (EU-28), more than 178 million hectares were utilized as agricultural areas, including arable land (60%), permanent grassland (33%), permanent crops (7%), and other agricultural land, such as kitchen gardens (<1%). The fresh vegetable production area occupied around 18% of the total permanent crops area, and specifically, the tomato production area accounted for over 10% of the aforementioned fresh vegetable production area. In terms of global production, around 130 million tons of tomatoes are produced each year, of which around 42 million tons/year are eventually processed. In the EU-28, 16.6 million tons of tomato fruits are produced per year, representing 12% of the total global production [2]. Despite these statistics, the geographical distribution is very heterogeneous because Italy and Spain are the largest tomato producers, representing two-thirds of the total European production.

Millions of tons of tomato are processed every year to produce products for which the manufacturing requires peel removal, such as peeled tomatoes (whole, diced, or sliced), juices, sauces, and ketchup. Peeling is, therefore, the first unit operation performed during the industrial transformation of tomatoes prior to further processing, and as such, its performance is crucial for maximizing the efficiency of the overall process as well as for preserving the quality of the fresh product [3].

Hot lye peeling is one of the most popular industrial methods of peeling tomato fruits. It involves the chemical pre-treatment of tomatoes by immersing the fruits in a hot lye (NaOH) solution at a high concentration (8–25%), which depolymerizes the external layer of tomato skin, facilitating its splitting and removal by peel eliminators (washing, core scrubber, and pinch bed/rollers) [3–6]. Although this peeling method is reported to be highly effective in producing high-quality products with high peelability [4], its usage presents several problems, such as high-water and energy consumption and especially the disposal of large amounts of peeling effluent discharge characterized by high salinity and high organic content [4,7].

In order to reduce or avoid chemical contamination in wastewater and other negative environmental impacts, food processors have adopted pressurized steam peeling coupled with cold water or vacuum cooling and pinch rollers, as an alternative peeling technique [3,6,7]. During such processing, tomatoes are exposed to low- or high-pressure steam (50–200 kPa) for a few seconds (10–60 s), which causes the tomato skin to weaken (biochemical mechanism), vapor to form under the skin with the consequent increase of internalized pressure, and the peel to crack (thermal and mechanical mechanisms), all of which are required for effective peeling [3,7]. Although this method does not cause the serious environmental problems that lye peeling causes, it may lead to lower product quality, and it requires a lot of water, high pressure, and energy, which increases the cost of the final product [4,6].

For these reasons, current research is focusing on new sustainable peeling alternatives that can effectively peel tomatoes with minimum losses and a higher-quality end product, while also causing fewer environmental problems and reducing water and energy consumption. In recent years, the application of unconventional technologies as a pre-treatment for the peeling process—such as infrared radiation heating, ohmic heating, ultrasounds, and enzyme use—has been investigated intensively [4,5,7].

Among these technologies, manufacturers are showing a growing interest in the application of pulsed electric fields (PEF) as a tool in food processing. The effect of PEF pre-treatment is the permeabilization of the cell membranes, which can improve the mass transport of intracellular compounds (e.g., water, juices, and solutes) in several processes of food industry (e.g., drying and extraction) [8] upon the application of an electric field of moderate intensity ($E < 10$ kV/cm) and relatively low energy ($W_T < 10$ kJ/kg) [9]. Many investigations have proven that PEF can enable energy-efficient dehydration of plant food matrices [8], as well as enhance the extraction yield of juice and bioactive compounds from a wide range of plant food materials and food processing by-products [9,10].

From an environmental point of view, the agri-food sector is responsible for one-quarter of the impact in different environmental categories [11,12]. In light of the relevance of the agri-food sector in human feeding, the economy, and the environmental, a lot of effort and research have been developed in recent years to increase the sustainability of production not only at the cultivation stage, but also at the food processing stage.

With this purpose, the life cycle assessment (LCA) has been applied as a powerful tool to evaluate the environmental impact of a food product along its life cycle. There are several valuable studies available in the literature that use this methodology to assess the environmental implications of conventional fruit or vegetable products' value chains. In this sense, Longo et al. [13] used the LCA to assess the energy and environmental performance impacts of organic and conventional apples. Baudino et al. [14] applied the LCA method and also analyzed the strengths, weaknesses, opportunities, and threats by means of SWOT and TOWS analysis, in order to improve the production chain of kiwi fruit and baby kiwis in Italy. Accorsi et al. [15] focused their study on applying the LCA to glass and plastic bottles of extra-virgin olive oil, and Mouron et al. [16] compared the environmental impacts of losses of fresh potatoes with those of French fries. More focused on cultivation modes, other studies have also assessed the environmental implications of both open-field and greenhouse crops, considering a variety of fruits and vegetables, tomatoes among them [11,17]. Specifically with regard to tomato production, there are also studies that have focused on the environmental burdens associated with the cultivation of tomatoes, in greenhouses [18–21], open-fields [22], or both [23,24]. Generally, the environmental burdens associated with greenhouse cultivation are much greater than the impacts associated with the open-field approach. Furthermore, the LCA of different tomato-based products has been previously studied by other authors. For example, Manfredi et al. [25] analyzed tomato puree production, and De Marco et al. [26] focused their research on mashed tomato package manufacturing. In both cases, the results strongly depended on the boundaries set to carry out the analysis as well as the life cycle stages considered.

Nevertheless, there are a lack of studies on tomato production combining the application of PEF technology and the evaluation of its environmental impacts from the LCA perspective. Pardo and Zufia [27] evaluated the environmental impacts of some traditional and novel food preservation technologies from a LCA perspective. These techniques were autoclave pasteurization, microwaves, high hydrostatic pressure (HPP), and modified atmosphere packaging, and they were applied to different ready-to-eat meals based on fish and vegetables. More recently, Aganovic et al. [28] used the LCA methodology, as well as energy balances, to compare a conventional thermal preservation technology with two innovative alternatives—PEF and HPP. This study was carried out in a tomato and watermelon juice processing line, and it concluded that no huge differences in environmental impact were found over the three aforementioned technologies, considering "gate to gate" system boundaries.

Within these premises, one of the purposes of this paper, which was carried out in the frame of the European project "FieldFOOD", is to assess the potential of PEF technology at the industrial level to facilitate the steam peeling of tomato fruits. Furthermore, the study aims to perform a LCA study to estimate how the environmental impacts generated by peeled tomato production are influenced by applying PEF technology. Potential environmental benefits and bottlenecks are identified in order to address the main technological challenges.

2. Materials and Methods

2.1. The PEF-Assisted Tomato Peeling Process

2.1.1. Integration of PEF Technology in a Tomato Processing Line

With a view to facilitate the peelability of tomato fruits and reduce energy consumption during the thermo-physical peeling phase, a PEF system (pulse generator, treatment chamber, and control and monitoring system) was integrated into the processing line of the FPD Srl Company (Fisciano, Italy) [29], which is described in more detail later on. Briefly, a specifically designed PEF treatment chamber was installed in line at the washing phase, which was identified as the best location for PEF pre-treatment of raw tomato fruits before the thermo-physical peeling phase. The PEF treatment chamber consisted of two modules hydraulically connected in series; each one was made of two stainless steel parallel plate electrodes, with an area of 100 cm^2 and a gap distance of 15 cm. A high voltage cable connected the electrodes of the PEF chamber to a high-voltage pulsed power (20 kV-500 A) generator (Modulator PG, ScandiNova, Uppsala, Sweden) able to generate monopolar square wave pulses (3–25 µs, 1–450 Hz). The actual voltage and current signals in the treatment chamber were measured using a high-voltage probe (Tektronix, P6015A, Wilsonwille, OR, USA) and a Rogowsky coil (2–0.1, Stangenes, Inc., Palo Alto, CA, USA) connected to a 300 MHz digital oscilloscope (Tektronix, TDS 3034B, Wilsonwille, OR, USA). The maximum electric field intensity (E, kV/cm) was evaluated as the peak voltage divided by the inter-electrode gap. The total specific energy input (W_T, kJ/kg) was calculated according to Equation (1):

$$W_T = \frac{f}{\dot{m}} \int_0^{\infty} U(t) \cdot I(t) dt \quad (1)$$

where, f is the pulse frequency (Hz), U(t) and I(t) represent the voltage across the electrodes and the current intensity through the product at time t, respectively, and $\dot{m}$ is the mass flow rate of the treated product.

2.1.2. On-Site Tests

Industrial trials were carried out to evaluate the performance of the thermo-physical peeling phase and the entire processing line in terms of energy requirements and the quality of peeled tomatoes with and without the application of the PEF pre-treatment of raw tomato fruits. Tomatoes (*Solanum lycopersicum*) of the "*Taylor*" variety, field-grown in the Apulia region of Southern Italy in the 2016 season, were used for the peeling tests. The fruits, having an almost cylindrical shape (about 4.1 ± 0.2 cm in diameter, 7.4 ± 0.8 cm in length), were harvested at the red-ripening stage, transported to the FPD Company, and processed within one day.

Comparative industrial trials (with and without the PEF pre-treatment) were carried out at the operative throughput (35 t/h of tomatoes) of the FPD processing line. The steam pressure (P) in the scalder was changed between 60 and 120 kPa with a fixed residence time (13 s), while the vacuum was maintained at a relative pressure of −36 ± 5 kPa. Trials were also carried out with different field strengths (E = 0.2–0.5 kV/cm) and energy inputs (W_T = 0.2–0.5 kJ/kg) and with a fixed pulse width of 20 µs. These PEF parameters were chosen on the basis of preliminary experiments and analyses to preserve the fruit integrity and improve its peelability by reducing peel resistance (data not shown).

At the end of the thermo-physical peeling section, tomatoes were manually checked to evaluate the peeling performances. Optimal processing conditions were identified for steam peeling with and without the PEF pre-treatment of raw tomatoes as the minimal processing conditions in terms of steam pressure (P), field strength (E), and energy input (W_T), enabling the achievement of fully peeled tomatoes with firm and appealing surface integrity.

2.2. LCA Methodology

Overall, LCA is useful for analyzing the environmental impact caused by any type of process, service, or product [30] and is widely used by the authors in previous studies [31–33]. In other words, LCA studies cover the environmental aspects and potential impacts throughout a product's life (i.e., cradle-to-grave), from raw material acquisition, production and use phases, to waste management. Its objective is to evaluate and compare the environmental burdens associated with a product, process, or activity by (1) identifying the energy and materials used and wastes released to the environment and (2) evaluating and implementing opportunities to achieve environmental improvements [34].

The most up-to-date structure of the LCA methodology is proposed by the ISO 14040:2006 guidelines [35]. In addition, it is referenced in the International Life Cycle Data system (ILCD), which is a guidance for greater consistency and quality assurance. The assessment procedure is divided into four basic steps: (1) goal and scope definition; (2) inventory analysis; (3) impact assessment, and (4) interpretation. These phases have a dynamic character and are closely related among themselves.

2.2.1. Goal and Scope

Some innovative techniques have great potential applications at the industrial level because they enhance energy efficiency, environmental and cost optimization, and food quality. In these cases, an analysis from each of those points of view should be carefully conducted in order to give a factual and holistic perspective on the impact generated. In this vein, the main goal of this study is to evaluate the environmental impact of the PEF technology following the LCA methodology. The improvements associated with the incorporation of this novel technology in the industrial production line of peeled tomatoes are mainly focused on the energy efficiency generated from the steam reduction during the PEF pre-treated tomatoes' processing.

Regarding the scope of the analysis, a preliminary analysis was performed considering all of the stages involved in the life cycle of the tomato product processed by the PEF technique. It was concluded that there is no effect associated with the application of PEF outside of the processing line. For this reason, the LCA performed in this study is focused on the stages carried out in the tomato processing; this is an analysis from a gate-to-gate perspective.

Finally, the objective of this analysis is to compare the PEF and the conventional processing in order to quantify the environmental improvements associated with the incorporation of the innovative technology. For easy understanding of results and practical aspects, the functional unit is defined as 1 kg of processed tomato, so all results and comparisons will refer to this unit.

2.2.2. Study System Description and Boundaries

A successful and comprehensive study of the environmental effects of the incorporation of PEF technology requires a description of the system and boundaries indicating when the treatment is applied and when it is not. From a cradle-to-grave point of view, some stages are common to both the conventional and PEF tomato processing treatments, such as tomato cultivation, transport, use, and disposal, and they remain unchanged. However, the innovative PEF technology involves modifications to some stages of the tomatoes processing. The discussion of the results is then focused on those stages of the processing by means of the gate-to-gate study performed in this paper.

The first case study is the conventional process, which is set as the baseline. It starts by washing the tomatoes that come from the field by using recycled water from other parts of the plant, such as the cooling tower. Then, air blowing is used to facilitate soil removal from the fruits. Then, clean tomatoes are separated from solid wastes—leaves, branches, and soil—which are used as compost for rural land. It is worth noting that these wastes are not considered in the LCA study as credits for by-products. The following stage is sorting, during which tomatoes are classified according to size and characteristics. The sorting is done both manually and by an optical selector in order to separate unripe tomatoes. Moreover, tomatoes that are in poor condition or those that do not fulfill the minimum characteristics required are discarded and used as animal feed; again, this waste is not considered as credits for by-products under the LCA rubric, even though such use constitutes a benefit from an environmental point of view.

The next stage is thermo-physical peeling and it is composed of steam blanching, vacuum processing, mechanical peeling, and peel separation. For simplification, all of these steps are considered to be a single operational unit because of the difficulty in quantifying their inputs/outputs separately. Natural gas burning is the energy source used to generate the steam. The tomatoes are rapidly heated in a scalder by pressurized steam (60–180 kPa, 12–60 s), before being vacuum cooled and conveyed onto pinch rollers to facilitate complete peel removal. Peels are combined with the discarded tomatoes that will be used as animal feed. Water used to generate steam is not reused; it is released to the municipal sewage system.

Once the tomatoes are peeled, they are placed into cans (together with their own juice) with different capacities: 0.5 kg, 1.0 kg, 3.0 kg, 3.5 kg, and 5.0 kg. This process is carried via an automatic filling system, which includes a filler and seamer. Sterilization is the next step during which steam is generated by burning natural gas, just as in the peeling process. At this stage, condensed water is recirculated in the steam generator with small or negligible losses. In order to obtain one kg of peeled and canned tomatoes, 1.78 kg of raw tomatoes are necessary because peeled tomatoes are required to meet specific characteristics to be canned and the tomatoes received from the field include the aforementioned solid waste (branches, leaves, stones, etc.). Finally, the packaging stage makes the cans ready to be conveyed or transported for retail purposes. The cans are labelled with a paper tag containing the product description and brand. The packaging consists of a corrugated carton tray, wrapped with a plastic LDPE (low-density polyethylene) film.

In the second case study, where the PEF pre-treatment is used in the processing line, only the washing and peeling stages are affected by the incorporation of this technology. In contrast to the conventional process, air blowing is not used in the washing system, and therefore, the electricity consumption of this stage decreases considerably. Furthermore, the PEF treatment reduces the amount of steam used in the thermo-physical peeling stage up to 20%, as well as minimizing the amount of natural gas needed to produce the steam. This is the most relevant improvement resulting from the PEF technology, because not only is less energy is consumed, but it is also easier to peel the tomatoes.

So from the above description, it can be said that even though a whole preliminary study has been carried out to identify the impacts associated with the incorporation of a PEF treatment in the total life cycle chain, from a cradle-to-grave perspective, all the variations are located at the processing line. For this reason, the current LCA study is only focused on the stages performed in a real manufacturing company (food processing and packaging) for the two case studies—the baseline and the innovative line integrating the PEF technology. The above is schematized in Figure 1.

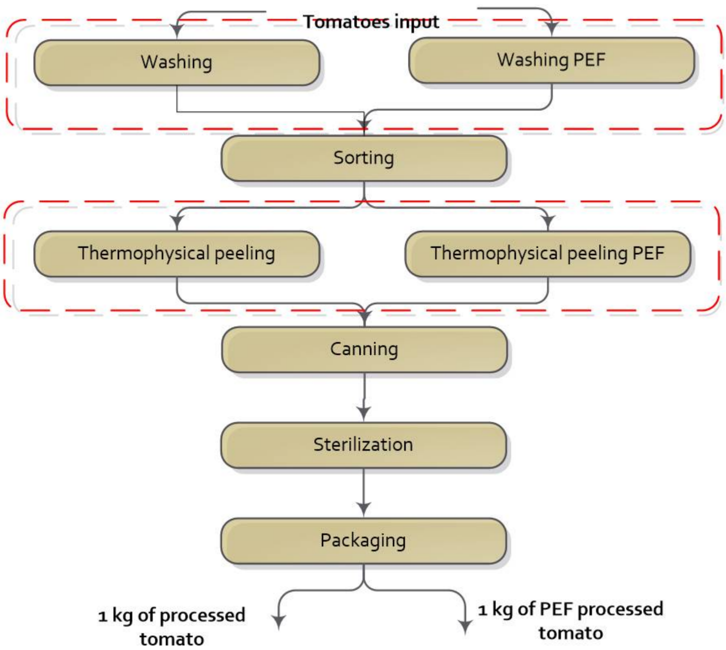

Figure 1. Study system description and boundaries. The dashed red line identifies the innovative pulsed electric fields (PEF) line modifications with respect to the baseline life cycle assessment (LCA) study.

2.2.3. Environmental Indicators

The method used to calculate the environmental impacts in this study is called ReCiPe. This is one of the most recent and harmonized midpoint indicator approaches for life cycle impact assessment. ReCiPe includes 18 midpoint impact categories [36] from which eight have been selected as the most relevant indicators according to the specific characteristics of the processes considered in this study: climate change (CC), ozone depletion (OD), terrestrial acidification (TA), freshwater eutrophication (FEu), human toxicity (HT), freshwater ecotoxicity (FEc), water depletion (WD), and fossil depletion (FD) [37,38].

A closer look will be taken at climate change, as it is a major global problem and its reduction is one of the main achievements expected out of this project. It will be measured in kg of CO_2 equivalents, referring to the functional unit of this analysis. The ozone depletion potential accounts for the destruction of the stratospheric ozone layer by anthropogenic emissions of ozone-depleting substances and uses CFC-11 (trichlorofluoromethane) as a reference compound. The terrestrial acidification potential is a measure of emissions that cause acidifying effects to the environment. It is expressed as kg of SO_2 equivalents that provide an equivalent estimate of air pollutant emission. The major acidifying emissions are nitrogen oxides (NO_x) and sulphur dioxide (SO_2). Eutrophication of fresh water can be defined as the over-enrichment of watercourses with ammonia, nitrates, nitrogen oxides, and phosphorous. Its occurrence can lead to damage of ecosystems, increased mortality of aquatic fauna and flora, and loss of species dependent on low-nutrient environments. Eutrophication potential is expressed using the reference compound kg of PO_4 equivalents. The measure of human toxicity assesses the effect of a chemical on the function of environmental persistence (fate), its accumulation in the human food chain (exposure), and the toxicity (effect) of the chemical. It is measured in kg of 1,4 dichlorobenzene (1,4-DB eq.). The emission of some substances, such as heavy metals, can have significant impacts on the ecosystem. Freshwater ecotoxicity is an assessment of toxicity based on maximum tolerable concentrations in freshwater aquatic ecosystems and it is expressed using kg 1,4-DB eq. Finally, the last two indicators are water depletion and fossil fuel depletion. They represent the amount of water and fossil fuels (volatile materials, such as methane or liquid petrol, or non-volatile materials such as coal) consumed, both directly and indirectly. They are quantified in m^3 of water and kg of oil eq., respectively.

2.2.4. Life Cycle Inventory (LCI)

After goal, scope, system description and boundary definitions, the next step in the LCA is the life cycle Inventory (LCI). The LCI considers all the energy, resources, and materials consumed (inputs) and generated (outputs) during the different production and manufacturing processes. Depending on the system limits, the associated inputs/outputs are identified, and the data gathering can be focused on the requirements set by the selected process stages. The energy and materials involved in the analysis are referred to by the previously established functional unit in order to identify and quantify all inputs/outputs from each stage under the same reference.

Because data gathering for LCA studies can be a demanding task, the following actions must be considered to ensure its adequacy:

- Identify potential data collection challenges and precautionary measures to maintain the integrity of the study (e.g., incomplete surveys, improper data entry, data representativeness, etc.).
- Determine and create, if necessary, a method for collection, storage, and retention of data.
- Monitor and support data collection activities.

To do so, a data gathering protocol was developed to perform the LCI. Firstly, an initial study of both the innovative PEF technology and the production lines involved in the analysis were reviewed to identify the needed data. A LCI was developed for the conventional processes within the peeled tomato production line, and, another LCI was established in order to identify and quantify the modifications caused by the introduction of the PEF technology.

The data collection requires special attention to obtain an accurate LCI, and consequently, reliable LCA results. The data for the LCI was collected mainly from two sources: from experimental data provided by the on-site tests, associated with the inputs and outputs for the production line stages, both with and without the incorporation of the PEF technology; and from specialized literature and in-house knowledge, in order to internally validate the data obtained. This data gathering protocol is based on an iterative process that guarantees that all of the associated environmental burdens are represented in order to evaluate the performance of the PEF technology in the value chain. Finally, once the data collection is finished, it necessitates an exhaustive amount of work to synthesize and analyze to ensure its representativeness, its congruency, and to detect any deviation. If problems are detected, new data needs and requirements can be redefined in order to cover all of the relevant processes.

As a result of the previously described data gathering protocol, all the material and energy flows were identified and quantified, with and without the PEF technology. Data is divided in such a way that Table 1 contains general information about the global process, and Figure 2 shows information referred to in the different stages of the process.

If a material or energy flow is less than 1% of the cumulative mass of all of the inputs and outputs, depending on the type of flow, it may be excluded due to practical issues. This cut-off criteria is used to ensure that all relevant environmental impacts were represented in the study.

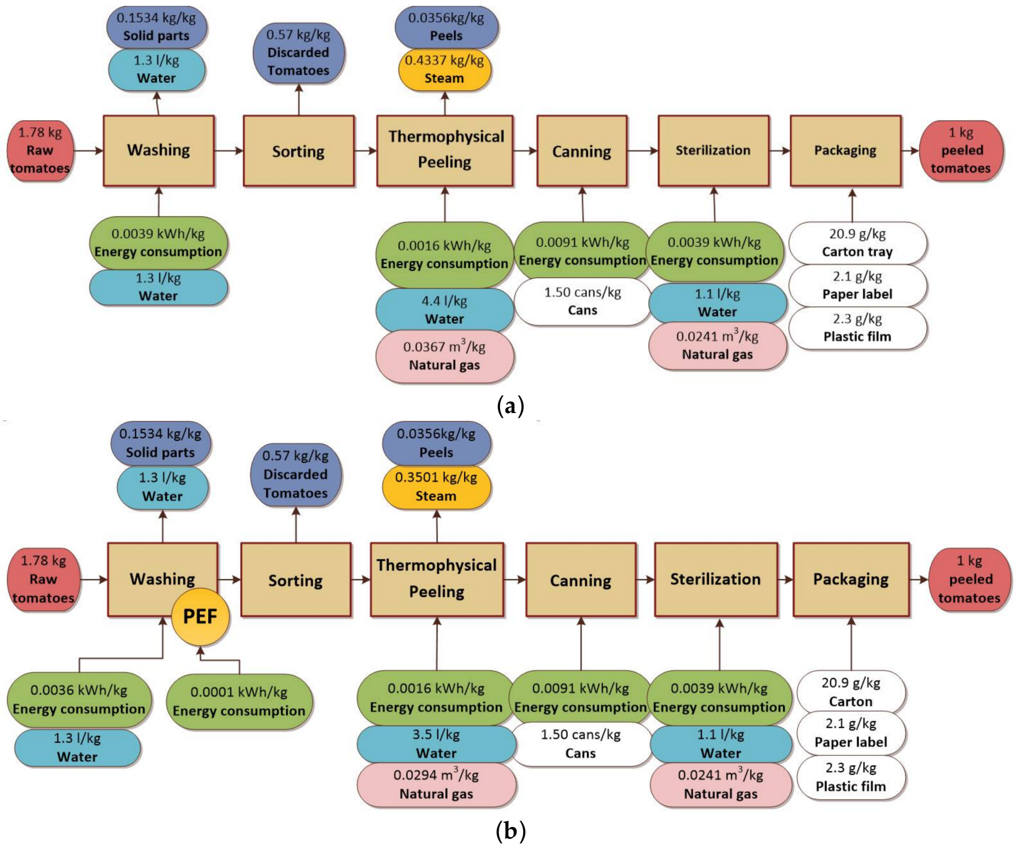

Figure 2. Flow chart of FPD srl's tomato processing line of without (**a**) and with (**b**) the integrated PEF system.

Table 1. Most representative life cycle inventory (LCI) parameters of the tomato processing line.

Parameter	Value per kg Processed	Units
Processing time	3.5	h
Final product produced	1	kg/kg
Tomatoes fed to the plant	1.78	kg/kg
Daily operating hours	18	h/day
Working days	70	days/year

From the flowcharts, it can be observed that only the consumption in some stages change when the PEF treatment is applied. Concretely, electricity savings are registered in the washing and peeling stages. On the other hand, although the PEF equipment requires electricity consumption to operate, it is a very low-energy intensive treatment for this specific application. All of the above data collected in the LCI allows the reporting of credible environmental indicators associated with the conventional manufacturing process of the peeled tomato production line as compared to the innovative process with the PEF incorporation.

Complementary to the LCI elaborated from data measured in a real processing plant and the in-house datasheet and models, the Ecoinvent database, developed by ETH (Swiss Research Institute), was used to complete the analysis. It includes information related to energy generation, mineral resource extraction, basic industrial processes, waste treatment, and transport. The new Ecoinvent 3.0 version (Zurich, Switzerland) [39] was used, with data in "allocation" mode (each transformation has an allocated impact). Furthermore, in order to run the simulations and make the calculations, Simapro 8.4 (Amersfoort, The Netherlands, the new, latest version [40]) was used. This software is a flexible and well-designed tool for LCA studies based on ISO 14040. Both tools were fundamental to carry out the present study.

3. Results and Discussion

3.1. Technical Results of PEF Integration

As a preliminary study before the LCA analysis, the effect of steam peeling alone on the peelability of the tomato fruit was also tested. The results achieved from visual tests, in terms of peel performance, showed that a minimum steam pressure of 100 kPa was necessary to achieve fully peeled tomatoes according to the standard product quality of FPD Company (McMurray, PA, USA).

The application of the PEF pre-treatment at different field strengths (E) and energy inputs (W_T) confirmed the ability of the PEF technology (on its own) to reduce the resistance of tomato peels to removal, which was assessed by measuring the textural properties (hardness and peel strength) of the fruits immediately after the electrical treatment (data not shown). The higher the PEF treatment intensity (E, W_T), the lower the peel resistance. The combination of the PEF pre-treatment with steam peeling was shown to be effective for facilitating peel removal. In particular, when tomatoes were exposed to the PEF pre-treatment at 0.45 kV/cm and 0.40 kJ/kg, a steam pressure of 80 kPa was enough to achieve similar peeling ease and product quality as steam peeling alone (at 100 kPa), demonstrating that the PEF treatment caused an overall 20% reduction of energy consumption in the peeling phase. It is likely that the application of the PEF pre-treatment at very mild processing conditions was enough to promote the mass transfer of water inside the fruit leading to a greater availability of water under the tomato skin, as compared with untreated tomatoes. As a consequence, during the steam heating of the fruits, a greater pressure difference across the tomato skin, due to vaporization, facilitated the formation of cracks on the tomato peel before the tomatoes were exposed to the pinch rollers system.

The results obtained from this study demonstrate the potential of PEF as a pre-treatment method to improve the efficiency of the industrial processing of tomato fruits by facilitating peel removal and saving energy.

3.2. LCA Environmental Results

This section contains the results obtained from the LCA performed for this study. Results are divided into two different sections: the first section contains the results referring to the conventional processing and the second section contains the results obtained after analyzing the tests performed with the PEF technology at the industrial level. As mentioned above, the processing line contains the stages of the life cycle chain that were modified due to the PEF incorporation; and therefore, those stages are studied in more detail.

3.2.1. Results from the Conventional Processing System

The results take into account the life cycle of 1 kg of conventionally manufactured peeled tomatoes from their reception at the industrial company to the end of the processing and packaging line. At this last point, the product has finished processing and it is ready to be transported to the point of sale. The absolute values of the most relevant indicators are collected in Table 2. In addition, Figure 3 depicts the share distribution of the different stages.

Table 2. Absolute environmental impacts of the gate-to-gate life cycle study of producing 1 kg of packaged peeled tomatoes by a conventional process. Units: CC (kg CO_2 eq.), OD (kg CFC-11 eq.), TA (kg SO_2 eq.), FEu (kg P eq.), HT (kg 1,4-DB eq.), FEc (kg 1,4-DB eq.), WD (m^3), and FD (kg oil eq.).

	Total	Washing	Sorting	Thermo-Physical Peeling	Canning	Sterilization	Packaging
CC	1.50	4.42×10^{-3}	9.93×10^{-4}	2.21×10^{-2}	1.39	1.59×10^{-2}	6.70×10^{-2}
OD	1.54×10^{-7}	5.93×10^{-10}	1.50×10^{-10}	1.59×10^{-8}	1.22×10^{-7}	1.06×10^{-8}	4.54×10^{-9}
TA	3.52×10^{-2}	1.83×10^{-5}	4.76×10^{-6}	1.32×10^{-4}	3.47×10^{-2}	9.14×10^{-5}	2.95×10^{-4}
FEu	7.38×10^{-4}	4.86×10^{-7}	1.21×10^{-8}	7.44×10^{-6}	6.99×10^{-4}	5.12×10^{-6}	2.65×10^{-5}
HT	9.95×10^{-2}	8.51×10^{-5}	9.83×10^{-6}	2.16×10^{-4}	9.55×10^{-2}	1.60×10^{-4}	3.60×10^{-3}
FEc	2.21×10^{-4}	3.30×10^{-6}	3.29×10^{-7}	1.54×10^{-6}	1.98×10^{-4}	4.75×10^{-7}	1.71×10^{-5}
WD	7.60	2.04×10^{-2}	1.15×10^{-4}	0.12	7.20	9.03×10^{-2}	0.17
FD	0.47	7.25×10^{-4}	2.02×10^{-8}	3.54×10^{-2}	0.39	2.37×10^{-2}	2.02×10^{-2}

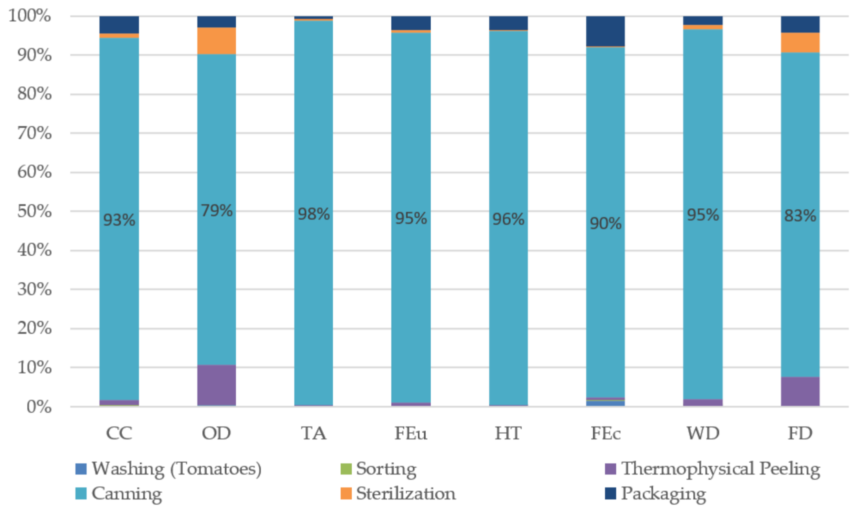

Figure 3. Contribution analysis of the most relevant environmental impacts of producing 1 kg of packaged peeled tomatoes by a conventional process.

The greatest contributor to all of the relevant environmental indicator categories is the canning stage. Canning is responsible for more than 90% of the total environmental impact caused by the manufacturing process on each environmental indicator, except for the fossil depletion and ozone depletion indicators, to which it only contributes 83% and 79%, respectively. Regarding the latter indicator, the canning stage's impact on it is mainly due to the manufacturing of the tin cans used as the containers of the peeled tomatoes. Concretely, the electricity (15%) and fuel consumption (13%) of that manufacturing process are the greatest contributing flows.

As a complementary analysis, Table 3 contains the relative impact of the same system but excluding the contributions associated with the canning stage in order to clarify the impact of the rest of the stages on the relevant environmental indicators.

Table 3. Relative environmental impacts of the gate-to-gate life cycle study of producing 1 kg of packaged peeled tomatoes by a conventional process (excluding the canning stage).

	Washing	Sorting	Thermo-Physical Peeling	Sterilization	Packaging
CC	4.0%	0.9%	20.0%	14.4%	60.7%
OD	1.9%	0.5%	50.0%	33.4%	14.3%
TA	3.4%	0.9%	24.4%	16.9%	54.5%
FEu	1.2%	<0.1%	18.8%	13.0%	67.0%
HT	2.1%	0.2%	5.3%	3.9%	88.4%
FEc	14.5%	1.5%	6.8%	2.1%	75.2%
WD	5.1%	<0.1%	30.9%	22.5%	41.4%
FD	0.9%	<0.1%	44.2%	29.7%	25.2%

The ozone depletion and fossil depletion indicators are dominated by the impact of the thermo-physical peeling stage (50% and 44.2%, respectively), mainly because of the steam generation. The remaining seven indicators were more influenced by the packaging stage, which contributed 41.4% and 88.4% to water depletion and human toxicity, respectively. In addition, thermo-physical peeling is also responsible for 30.9% of the water depletion, 24.4% of the terrestrial acidification impact, and 20.0% of the CO_2 eq. emissions considered in this study. Since one of the advantages of using the PEF treatment is the reduction in the steam consumption, it was expected to obtain relevant improvements in these impact categories.

These results are in accordance with findings reported by other authors. For example, Del Borghi et al. [41] assessed the sustainability of different tomato product supply chains by means of the LCA methodology, all of them produced in Italy. They concluded that for most of the impact categories, the packaging stage had a higher contribution than food processing stage. For example, according to that study, 4.9×10^{-8} kg of CFC-11 are released during the packaging stage of one kg of peeled tomato and 2.6×10^{-8} kg of CFC-11 are emitted during food processing. However, the most contributory stage of the peeled tomato life cycle chain is the tomato cultivation phase, mainly due to the high consumption of fossil fuel. Cellura et al. [11] carried out a LCA of a variety of crops, tomatoes among them. In this study, tomatoes were processed to be marketed as raw fruits. The authors concluded that the most relevant environmental impacts were related to the consumption of raw materials for greenhouse cultivation and packaging (including canning). The impact associated with the life cycle of tomato products strongly depends on the inputs/outputs considered in each stage, as well as the kind of product manufactured. Finally, another study performed by Garofalo et al. [42] analyzes under the same LCA methodology a whole-peeled tomato production process, which is very similar to the conventional process case study of this paper. The authors reported that the most relevant environmental impacts were caused during the processing stage, especially the waste as managed by that processing company, followed by the packaging and cultivation steps. Concretely, the CO_2 emissions associated with the processing of 1 kg of peeled tomato (without canning/packaging) is 0.126 kg, which is greater than the value calculated in the current study (0.043 kg CO_2). This value in this paper is more similar to the value reported by Karakaya and Özilgen [43] (0.092 kg CO_2), although it is also lower than their value. Even though the analysis carried out in these papers have many similarities with the current analysis, the present paper does not include treatments for waste management or the recycling of some materials. For example, the impact associated with the manufacturing of the tin used for the cans where the product is contained is very high because it is assumed that this material is not extracted from recycled materials. Even though the use of recycled materials is arguably relevant, the aim of this study is to evaluate the integration of a new technology in the peeling process. Because the same kind of raw material is used to quantify the impacts associated with both the conventional and PEF processes, this material will not be responsible for any variation registered in the considered environmental indicators.

3.2.2. Results from the PEF Processing System

For the purpose of comparison, additional tests were performed under the same operational conditions as the tests characterized in the previous section, but this time, integrating PEF equipment. The PEF treatment was applied during the washing stage in order to improve the efficiency of the processing procedure. When the PEF technology is incorporated in the process, the electricity consumption of the cleaning stage is considerably smaller, and at the same time, it reduces the amount of steam and natural gas used in the thermo-physical peeling. This fact is the most relevant improvement obtained as a result of the incorporation of the PEF technology, because not only is less energy consumed but also it is easier to peel the tomatoes. The rest of the stages remain unchanged with the addition of the PEF treatment.

The absolute impact values for each environmental indicator are shown in Table 4 and the relative impact of the most significant environmental indicators are depicted in Figure 4.

Table 4. Absolute environmental impacts of the cradle-to-gate life cycle study of producing 1 kg of packaged peeled tomatoes by a PEF process. Units: CC (kg CO_2 eq.), OD (kg CFC-11 eq.), TA (kg SO_2 eq.), FEu (kg P eq.), HT (kg 1,4-DB eq.), FEc (kg 1,4-DB eq.), WD (m^3), and FD (kg oil eq.).

	Total	Washing PEF	PEF Treatment	Sorting	Thermo-Physical Peeling PEF	Canning	Sterilization	Packaging
CC	1.49	4.04×10^{-3}	6.39×10^{-5}	9.93×10^{-4}	1.80×10^{-2}	1.39	1.59×10^{-2}	6.70×10^{-2}
OD	1.50×10^{-7}	5.45×10^{-10}	7.93×10^{-12}	1.50×10^{-10}	1.27×10^{-8}	1.22×10^{-7}	1.06×10^{-8}	4.54×10^{-9}
TA	3.52×10^{-2}	1.69×10^{-5}	2.30×10^{-7}	4.76×10^{-6}	1.07×10^{-4}	3.47×10^{-2}	9.14×10^{-5}	2.95×10^{-4}
FEu	7.37×10^{-4}	4.25×10^{-7}	9.97×10^{-9}	1.21×10^{-8}	5.98×10^{-6}	6.99×10^{-4}	5.12×10^{-6}	2.65×10^{-5}
HT	9.95×10^{-2}	7.88×10^{-5}	1.03×10^{-6}	9.83×10^{-6}	1.77×10^{-4}	9.55×10^{-2}	1.60×10^{-4}	3.60×10^{-3}
FEc	2.21×10^{-4}	3.27×10^{-6}	4.19×10^{-9}	3.29×10^{-7}	1.27×10^{-6}	1.98×10^{-4}	4.75×10^{-7}	1.71×10^{-5}
WD	7.58	1.81×10^{-2}	3.85×10^{-4}	1.15×10^{-4}	0.10	7.20	9.03×10^{-2}	0.17
FD	0.46	6.05×10^{-4}	1.98×10^{-5}	2.02×10^{-8}	2.84×10^{-2}	0.39	2.37×10^{-2}	2.02×10^{-2}

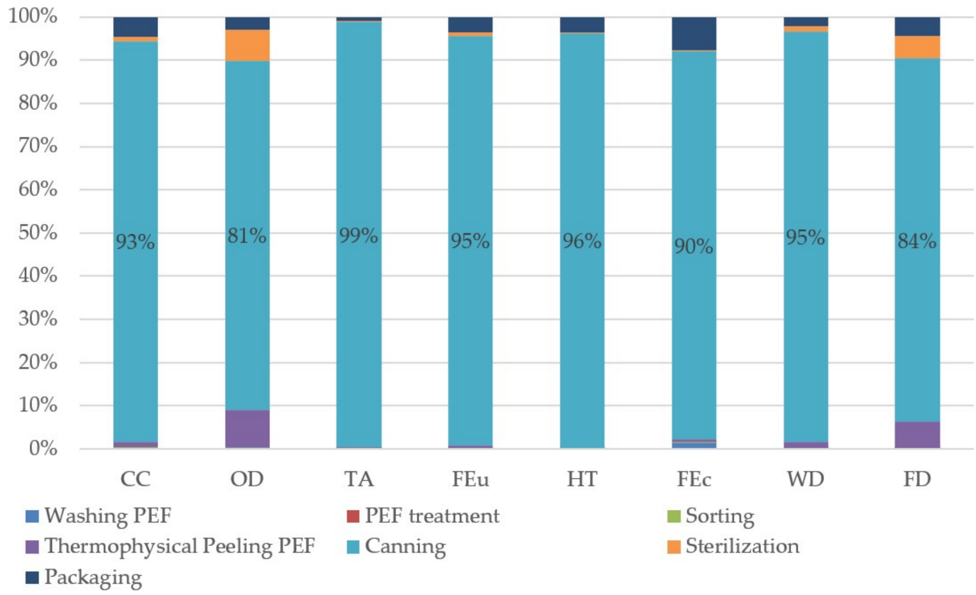

Figure 4. Contribution analysis of the most relevant environmental impacts of producing 1 kg of packaged peeled tomatoes by PEF process.

If this last figure is compared with the results depicted in Figure 3, where the impacts from the conventional process are considered, it can be seen that both present a similar distribution. As in the conventional case, canning is the most contributing stage in all the environmental indicators considered when the PEF is integrated in the processing line.

Some significant differences are found between the analysis carried out for the conventional and the PEF processes, especially in the ozone depletion indicator. By applying the novel technology, the impact associated to this indicator has been reduced in 2.07% considering the whole processing line. The reduction in the ozone depletion indicator is due to the fact that most of the improvements stem from the PEF incorporation at the thermo-physical peeling. This stage presented higher contribution in the ozone depletion indicator, so this is the environmental category with the greatest reduction. Besides, it is also remarkable the reduction incurred in the fossil fuel depletion indicator as a direct consequence of reducing the natural gas consumed for the peeling stage (−1.52%). The variations displayed in the remaining environmental indicators are smaller than 0.50%.

Since the same kind and size of cans are considered in both analysis, the absolute impact associated to the tin manufacturing does not significantly change after incorporating the PEF treatment. Table 5 contains the impact share attributable to each stage for the eight selected environmental indicators, but excluding the effect of the canning. This is meant to compare with more detail the contributions associated to the remaining stages of the processing line.

Table 5. Relative environmental impacts of the gate-to-gate life cycle study of producing 1 kg of packaged peeled tomatoes by a PEF process (excluding the canning stage).

	Washing PEF	PEF Treatment	Sorting	Thermo-Physical Peeling PEF	Sterilization	Packaging
CC	3.8%	0.1%	0.9%	17.0%	15.0%	63.3%
OD	1.9%	<0.1%	0.5%	44.6%	37.1%	15.9%
TA	3.3%	<0.1%	0.9%	20.8%	17.7%	57.3%
FEu	1.1%	<0.1%	<0.1%	15.7%	13.5%	69.6%
HT	2.0%	<0.1%	0.2%	4.4%	4.0%	89.4%
FEc	14.6%	<0.1%	1.5%	5.7%	2.1%	76.1%
WD	4.8%	0.1%	<0.1%	26.7%	24.0%	44.3%
FD	0.8%	<0.1%	<0.1%	38.9%	32.6%	27.7%

For the reasons explained above, the breakdown of the stages indicates that the contribution of the thermo-physical peeling is now smaller for all of the environmental categories, and the highest reduction occurs in the ozone depletion indicator. In addition, it can be observed that the impact associated with the electricity consumption of the PEF machine is negligible in comparison to the rest of stages. Therefore, any small savings in other upstream or downstream stages, especially in the thermo-physical peeling stage, will provide a net improvement from an environmental viewpoint.

In sum, the PEF technology was able to reduce the amount of steam consumed in the thermo-physical peeling stage, as well as the electricity consumption in the washing system. However, these savings represent a limited impact reduction in most of the environmental indicators from an overall LCA perspective. For instance, looking at one of the most frequently used indicators—climate change—the emissions of greenhouse gasses in the packaging and canning stages incur the highest impact in this indicator. Since the PEF equipment does not affect any of these stages, the total environmental variation is reduced from a LCA gate-to-gate point of view. Therefore, in order to assess only the effect of the PEF technology (as compared to the conventional one), the analysis should be focused on the thermo-physical peeling stage because the steam reduction is the most relevant achievement reached in this processing line.

Under the above premise, Table 6 shows the absolute impacts of the peeling stage when the PEF machine is used and not used in a given stage. It can be seen that all of the environmental indicators improve with the new technology. For example, the number of emissions of CO_2 eq. is reduced by 18% when the PEF technology is applied. Moreover, the fossil depletion and ozone depletion indicators are almost 20% lower in the peeled tomato manufacturing process using the innovative PEF technology.

Table 6. Absolute environmental impact of thermo-physical peeling (per kg of canned peeled tomatoes). Units: CC (kg CO_2 eq.), OD (kg CFC-11 eq.), TA (kg SO_2 eq.), FEu (kg P eq.), HT (kg 1,4-DB eq.), FEc (kg 1,4-DB eq.), WD (m^3), and FD (kg oil eq.).

	Thermo-Physical Peeling	Thermo-Physical Peeling PEF	Variation
Climate change	2.21×10^{-2}	1.80×10^{-2}	−18.72%
Ozone depletion	1.59×10^{-8}	1.27×10^{-8}	−19.76%
Terrestrial acidification	1.32×10^{-4}	1.07×10^{-4}	−19.15%
Freshwater eutrophication	7.44×10^{-6}	5.98×10^{-6}	−19.58%
Human toxicity	2.16×10^{-4}	1.77×10^{-4}	−18.14%
Freshwater ecotoxicity	1.54×10^{-6}	1.27×10^{-6}	−17.24%
Water depletion	0.12	0.10	−19.05%
Fossil depletion	3.54×10^{-2}	2.84×10^{-2}	−19.83%

4. Conclusions

Currently, pressurized steam is one of the technologies most frequently used to carry out tomato peeling on industrial scale. However, a lot of water and energy is consumed by using such technology. But when a PEF pre-treatment is applied, a tomato product of the same peelability and quality can be obtained by using a much lower pressure, thus using less steam and natural gas.

In order to analyze the environmental improvements associated with the experimental incorporation of this PEF treatment at industrial level, LCA methodology was applied to the processing line of an Italian company that manufactures peeled and canned tomatoes. Firstly, the total life cycle of the product (from cradle to grave) was analyzed, and it was found that all of the variation due to PEF incorporation was located at a few particular stages of the processing line—tomatoes washing and thermo-physical peeling. Thus, the detailed LCA was mainly focused on those stages.

In the case study analyzed in this work, when the PEF technology was applied, the amount of steam required for the thermo-physical peeling stage decreased by 20%. Moreover, is the PEF modifications did not required air blowing during the washing stage. Thus, both effects reduced the energy consumption of the process and its associated impact on several environmental indicators (climate change, ozone depletion, terrestrial acidification, etc.).

The tomato peeling and the canning stage had the highest impact on most of the environmental categories from a gate-to-gate perspective. When the total processing line is considered, the global environmental improvements are specially reflected in the benefits obtained by the ozone depletion and fossil depletion indicators because of the consumption reduction. In addition, if the study focused only on the thermo-physical peeling stage, all of the environmental indicators improved between 17% and 20% in absolute values when the PEF technology was used. Further industrial tests should be carried out on other tomatoes varieties—especially those that are difficult to peel even in conventional treatments—in order to confirm these preliminary results.

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