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Comparative life cycle assessment of ohmic and conventional heating for fruit and vegetable products: The role of the mix of energy sources

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ABSTRACT

The study aims at comparing the environmental performances of the indirect heat exchanger and the ohmic heater for foodstuff decontamination. By means of a Life Cycle Assessment, adopting ReCiPe 2016 midpoint (H) method, applied to the sterilization of diced tomatoes and to the pasteurization of diced peaches for a standard company respectively in Italy and in Australia, it emerged that environmental impact of ohmic heating is higher than the indirect one. Having the ohmic heater the electric energy as the main contributor, a sensitivity analysis is added to investigate the impact of the mix of primary sources. Relevant savings in global warming potential are achieved when the French energy mix is used (77.1% on tomatoes and 87.7% on peaches) or when 100% of the energy source comes from photovoltaic panels (79.7% and 88.5% respectively). Finally, the combined use of the two technologies has been investigated, resulting to be an intermediate solution compared to the others.

1. Introduction

It is well known that the exploitation of resources and energy is particularly high in the food sector, and more specifically in food processing, with consequent effects on the environmental impact (Smith and Lal, 2022). The growing attention towards the environmental issues has been the driving force behind various changes, including the development of new preservation technologies alternative to the conventional ones (Silva and Sanjuàn, 2019) used in the decontamination step, which is one of the most demanding in terms of energy consumption (Pardo and Zufía, 2012; Cacace et al., 2020). It is the case of ohmic heating, a non-conventional thermal technology for the decontamination of food products, which is particularly appreciated for high value foodstuff having pieces (Gratz et al., 2021). The process uses electricity instead of the thermal energy coming directly from the combustion of fossil fuels and it can play a key role in the transition towards a decarbonized industry (Muhammad et al., 2019; Vignali et al., 2022). The rise of the temperature in an ohmic heater is obtained by Joule effect and it occurs inside the product, that acts as a resistance when it is placed between two electrodes and crossed by electrical current (Pelacci et al., 2021). The internal heat generation guarantees a uniform temperature distribution, because the solid and the liquid parts take the same time to warm up (S. Ramaswamy et al., 2014; Cho et al., 2017). The shorter treatment time limits the thermal damage to the sensorial and organoleptic properties and the absence of hot walls avoids burns on the external surfaces of the product, so that the quality is preserved (Sakr and Shuli, 2014; Kumar, 2018; Alkanan et al., 2021). Thanks to reduced product fouling, the ohmic heater has less cleaning requirements than traditional heat exchangers (Varghese et al., 2014). Moreover, the energy efficiency of the process is always greater than 90% (Sakr and Shuli, 2014; Rossi and Rezaharsamto, 2020; Sagita et al., 2022). and today it is difficult to have further increasements of such values to optimize the electricity consumes of the technology. Despite all these advantages, nowadays the use of ohmic heating is limited to those applications that involve heterogeneous foods or products containing solid pieces that cannot be treated in an indirect heat exchanger (Rossi and Rezaharsamto, 2020). This is mainly due to an economic reason: in terms of initial investment, an ohmic heater is more expensive than an indirect heat exchanger and the cost of the electricity is typically higher than that of the fossil fuels (Kaur and Singh, 2016; Alkanan et al., 2021).

The aspect of the ohmic technology on which literature studies have been focusing the most is the preservation of the nutritional properties achieved in several food matrices. The most successful area for the application of the ohmic technology is fruit and vegetable processing

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(Kaur et al., 2016). It is also used for the thermal treatment of meat (Bozkurt and Icier, 2010), milk (Srivastav et al., 2014), liquid egg (Icier and Bozkurt, 2019) and fish products such as shrimps (Lascorz et al., 2016). Literature studies comparing ohmic heating with conventional heating highlight the advantages that favoured the development of this non-conventional thermal process.

Nowadays another aspect that needs to be considered when two processes are compared is the environmental sustainability. According to the decarbonization plan, which must be completed by 2050 (European Commission), ohmic heating could be taken into account as a valid alternative to conventional heating processes powered by fossil fuels. In the assessment of the environmental performances of electric-based technologies a key role is related to the energy mix supplied from each country, or to the use of renewable energy at the production site (Ćorović et al., 2022). On the other hand, the impact of the equipment manufacturing in the food sector has been demonstrated as extremely low if compared with that of the consumption phase and, for these reasons it could be neglected in this type of study (Stefanini et al., 2022). The best method to compare several technologies from the environmental point of view is the Life Cycle Assessment (LCA), as suggested many years ago from the European commission (European Commission, 2003). The LCA allows to evaluate the potential environmental impacts generated within the entire life cycle of a product, which, in its most comprehensive form, includes all the phases from the extraction of the raw materials to the final disposal of the product. However, it is possible to restrict the analysis to specific life cycle stages when they are of particular importance and when in the context of comparative LCAs several alternative solutions for the same stage can be evaluated (Moni et al., 2020). Although over the years in the food sector the agricultural phase has been considered the one of highest concern in terms of environmental sustainability, nowadays the attention is turning to the processing stage, and specifically the processes for the reduction of the microbial load (Pardo and Zufía, 2012). This is due to the development of new thermal and non-thermal technologies aimed at obtaining safe and high-quality products with the longest possible shelf life (Calero et al., 2022; Pardo and Zufía, 2012). In these terms the processing phase becomes of crucial importance. Despite this, in many LCA studies it is seen as a “black box” inside which the various stages are not considered separately (Silva and Sanjuàn, 2019). The need to overcome such data gaps and optimize food processing not only at a technological level but also from an environmental perspective is also guided by the significant portion of the energy demand attributed to this phase (Sanjuán et al., 2014). Among the different food processing operations, thermal treatments are the most energy-intensive (Calero et al., 2022) and in an LCA study on processed tomatoes bleaching, concentration and pasteurization turned out to be the main contributors to the majority of the midpoint impact categories (De Marco, Riemma and Iannone, 2018). For these reasons thermal treatments can be considered hotspots on which to concentrate efforts for environmental impact reduction, an aspect that justifies the focus of the present study on the decontamination phase of processed fruit and vegetable products.

As far as the impact assessment is concerned, nowadays several impact assessment methods for the calculation of each environmental issue are available and, according to the method chosen for the analysis, the results can be different. This issue is well known especially in the food sector in which some experimental studies have been developed to investigate over the numerical results given by the adoption of several impact assessment methods applied to the same food product (Borghesi et al., 2022).

Among the LCA studies of ohmic heating, literature shows only a few comparing the environmental impact of the ohmic technology with that of the conventional ones. An LCA and energy comparison of ohmic heating and appertization of chopped tomatoes with juice gave evidence to the fact that the energy consumption and the CO_2 emissions of the ohmic heater were less than those of the retort process (Ghnimi et al., 2021). A “from cradle to grave” LCA is carried out using a mass-based functional unit (FU) represented by 1 kg of chopped tomatoes with juice and all stages of product manufacturing have been included in the analysis. The appertization line is significantly different from the one with the ohmic heating system also in terms of packaging used. The tin production phase is the environmental hotspot of the appertization system, while the tomato production is the phase with the highest environmental load in the system with the ohmic heater. From a comparative LCA study on the conservation techniques for semi-finished peaches it was found out that the ohmic technology was responsible for a higher environmental impact than that of the low-pressure superheated steam drying with far-infrared system. The industrial stages common to the two processes are not included in the analysis and the results are referred to 1 kg of dried packaged semi-finished product (Iannone R., Riemma and De Marco, 2020). Among the non-conventional decontamination processes, ohmic heating is proved to be one of the most sustainable. In particular, for the global warming potential it is preferred over deep-freezing for the conservation of semi-finished apricots. This is due to the fact that not only is deep freezing an energy-intensive process, but it also implies additional consumptions due to the subsequent storage at −20° (De Marco and Iannone, 2017). The same product is the object of a comparative LCA analysis for the evaluation of the best preservation technology between quick freezing, low pressure superheated steam drying with far-infrared radiation and ohmic heating. The results showed ohmic heating as the most sustainable with the packaging phase generating the highest environmental impact, in contrast to the results related to the other two systems in which the most impactful phase is the processing phase. Moreover, an improved scenario characterized by a reduction in the packaging weight and by a substitution of the 40% of grid-electricity with electricity produced by photovoltaic panels has been considered. The results show a difference in the emissions that for the global warming impact category ranges between −14% and −24% according to the system (De Marco, Miranda, Riemma and Iannone, 2016). A study on non-conventional methods for the pasteurization of orange juice highlights that microwave and ohmic heating have a higher energy efficiency than that of the conventional UHT process, while the greenhouse gas emissions vary according to the energy mix, depending on the location of the industrial plant (Atuonwu, 2018). An emerging topic among the LCA studies on food processing concerns the selection of the FU that could also be representative of the nutritional value of the food (Silva and Sanjuàn, 2019). In literature there is a lack of studies that integrate the benefits of the ohmic process on the nutritional properties of the food products with the environmental impact of the technology. To combine these two aspects a nutritional LCA (*n*-LCA) could be performed. The approach to bring nutrition into the LCA consists of integrating food nutrients into the FU, to which all the input and output of the process, and therefore the environmental results, are referred. According to Saarinen et al. (Saarinen et al., 2017) an *n*-LCA can follow two different approaches: the first one refers the environmental results to a mass-based FU in which every single nutrient is considered separately. The second one considers as the FU multiple nutrients chosen according to a nutrient index. However, such methodology rises a question about the function of food, which is not just a source of nutrients, but it also provides satiety (Ridoutt, 2021). This consideration about the uncertainty of the latter approach can justify the use of a mass as the FU. This is the choice made for this study, where the environmental results are provided with the same mass of the products rather than with the same amount of nutrients.

Based on these premises, this study investigates the environmental impact of the ohmic technology in comparison to that of the conventional one, represented by the indirect heat exchanger, using the instrument of the LCA carried out on two different applications: the sterilization of diced tomatoes and the pasteurization of diced peaches.

2. The LCA methodology and the application to some food processing contexts

The experimental part of this study involves the application of the LCA to assign a quantitative value to the environmental impact associated to the different technologies considered. The LCA is a support tool for decision-making and for technological development because it allows to point out the most critical aspects on which improvements need to be made.

The software used for the LCA analysis is SimaPro 9.3 consistent with the standards ISO 14040 (ISO 14040, 2006) and ISO 14044 (ISO 14044, 2006). The structure of the analysis follows four steps: goal and scope definition, inventory analysis, impact assessment and interpretation of the results. In the first step it is identified the goal of the study, its applications, the audience and the characteristics of the system and its boundaries. Moreover, it is defined a FU, that is the quantity of product to which all the inputs and outputs must be referred. The following step, commonly referred as to Life Cycle Inventory (LCI), consists of the collection of the data related to the processes included in the system boundaries. Processes can be selected from the libraries available on SimaPro. The libraries used for the LCI are the "*Ecoinvent 3-allocation cut-off by classification-unit*". No allocation of the Ecoinvent data has been used because all the input-output flows are specific to the system under analysis and are not in common with other processes. As far as the types of data are concerned, they can be primary, if they come from measurements made on site, secondary, if they are taken from literature, and tertiary, if they are estimated from data of similar processes. For this analysis primary data, supplied by a food equipment producer (CFT) have been used to identify the main input and output of each analysed phase. Secondary data about energy sources, water consumptions, waste products and cleaning and sterilization in place substances have been taken from Ecoinvent v 3.8 database by considering each time the country or region of application. Uncertainty analysis about the consistency of these data have been performed showing relatively low uncertainty.

In the Impact Assessment it is possible to calculate the environmental impact produced by each flow of materials and energy crossing the system using several methods that can be selected from the library called "Methods" (Borghesi et al., 2022). For this case study the Global method ReCiPe 2016 Midpoint (H) has been selected. The method includes seventeen impact categories, but the environmental impact values have been calculated only for the following six impact categories, which have been considered the most significant for the system under study: global warming, terrestrial acidification, freshwater eutrophication, land use, fossil resource scarcity, water consumption. The relevance of these categories was established by conducting a literature analysis on Scopus Database. 365 studies were found using the keywords "LCA" + "food" + "treatment". 80 of them included the additional keyword "global warming", 69 the keyword "eutrophication" and 50 "acidification". Fewer results related to the impact categories of land use, fossil resource scarcity and water consumption were found, but they were nevertheless selected because they are representative of the potential environmental problems connected to the case study.

The last step of the LCA, which is the interpretation of the results, consists of the identification of the most significant variables, the evaluation of the completeness of information and the consistency of the results with the goal and scope defined at the beginning of the study.

2.1. The sterilization of diced tomatoes

2.1.1. Description of the process

Among the vegetable products that are subject to transformation processes after the harvesting phase, tomatoes are some of the most important. The 50% of the product harvested in Italy is destined to become diced (De Marco, Riemma and Iannone, 2017). When the tomatoes arrive in the factory, after the operations of washing and sorting, they are peeled, cut and separated from the juice. With a mixing operation, a specific quantity of liquid part is added to the solid pieces to reach a final concentration of 7%. After the mixing phase, the product is sterilized at the temperature of 110 °C. The sterilization process can be conducted with an indirect heat exchanger or with an ohmic heater. The use of the ohmic heater gives the possibility to obtain a product that can be reprocessed in subsequent stages, without significant losses of quality. So, after being sterilized, the diced tomatoes are stocked in aseptic packaging, that can contain up to 200 kg of product, and then reprocessed when needed. Before the product is sent to the new processing stages, it is pasteurized, so, for a second time, it is thermally treated in the ohmic heater. The sterilization systems analysed are part of an industrial line produced by CFT and located in Italy. The line operates on three daily 8-h shifts for five days a week, from Monday to Friday. The operations of cleaning in place (CIP) and Sterilization in place (SIP) are carried out on Saturday, while on Sunday the line is not in operation for the whole day. The average flow rate of processed product is 5000 kg/h. During the first hour of production on Monday the line operates at a reduced flow rate and in this phase waste product is generated.

2.1.2. Goal and scope definition

The study is applicable to the industrial context and in particular it addresses the food sector, responsible for a large share of the global environmental impact and, therefore, committed to the environmental challenges set by the Sustainable Development Goals. The goal of the research is to compare the environmental impact of the two sterilization processes applied to the diced tomatoes. The system boundaries set the type of the analysis, which is in this case a "gate to gate" analysis restricted to the sterilization phase conducted with the two alternative technologies (Fig. 1). This choice is justified by the rules of the comparative LCA that allow to exclude from the analysis the life cycle stages common to the two systems (Silva and Sanjuàn, 2019). A quantity of 1 kg of product with the same level of log-reduction of the microbial load, alternatively achieved with the two decontamination systems, is chosen as the FU in order to reflect the function of the processes under analysis. Furthermore, given that the product is packaged in the same type of packaging regardless of the decontamination process applied, the packaging is not included in the FU.

2.1.3. Inventory analysis

The primary data collected for the ohmic and conventional pasteurization processes, all referred to the FU, are reported in Table 1 and Table 2. Data include not only the consumptions for the sterilization of the product, but also those for the CIP and SIP operations.

With the material and energy flows collected in the LCI it is created a process assembly for each system considered. The following step of the LCA analysis is the Impact Assessment that consists of the evaluation of the environmental impact associated to the process assembly using the methods mentioned in Paragraph 2.

2.2. The pasteurization of diced peaches

2.2.1. Description of the process

Fruit is a perishable product and to extend its shelf life it must be stabilized microbiologically. By stopping the microbial reactions, that are responsible for the deterioration of the product, fruit can be used as an ingredient for other recipes, and it can go through further processing. The objects of this analysis are diced peaches, that need to be pasteurized to be then used as an ingredient for fruit salads without liquid parts. The pieces can be modeled as cubes with a side of 25 mm. Peaches are acid products (pH = 3) and they are very perishable because of their high content of ethylene (Iannone R., Riemma and De Marco, 2020), responsible for the fruit ripening. Therefore, a thermal treatment must be used to stabilize them. For the stabilization process a liquid part is necessary, especially when an indirect heat exchanger is used. The liquid part is functional to the transfer of the heat to the solid parts which,

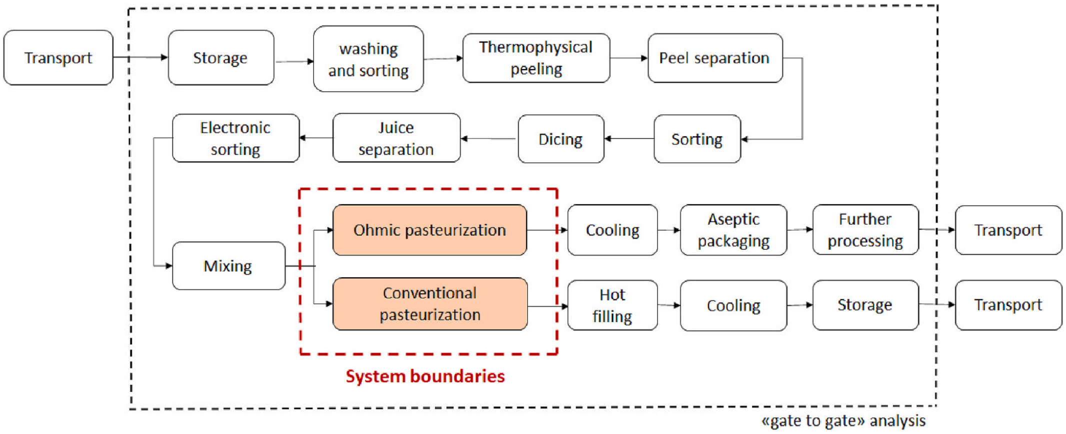

Fig. 1. System boundaries (diced tomatoes).

Table 1
Material and energy flows entering the sterilization system with the indirect heat exchanger.

Input	Ecoinvent Dataset	Value
Heat for the product sterilization [MJ]	Heat, district or industrial, natural gas {RER}| market group for | Cut-off,U	4,20E-01
Waste product [kg]	Tomato, processing grade {IT}| tomato production, processing grade, open field	5,00E-03
Electric energy for pump operation [kWh]	Electricity, medium voltage {IT}| market for | Cut-off,U	1,40E-03
Heat for CIP & SIP [MJ]	Heat, district or industrial, natural gas {RER}| market group for	9,17E-03
Water [kg]	Tap water {Europe without Switzerland}| market for | Cut-off,U	2,50E-02
Sodium Hydroxide (NaOH) [kg]	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off,U	6,33E-04
Nitric Acid ($NaOH_3$) [kg]	Nitric acid, without water, in 50% solution state {RER}| market for nitric acid, without water, in 50% solution state | Cut-off,U	3,80E-04

Table 2
Material and energy flows entering the sterilization system with the ohmic heater.

Input	Ecoinvent Dataset	Value
Electric energy for product sterilization [kWh]	Electricity, medium voltage {IT}| market for | Cut-off,U	9,80E-02
Waste product [kg]	Tomato, processing grade {IT}| tomato production, processing grade, open field | Cut-off,U	3,33E-03
Electric energy for pump operation [kWh]	Electricity, medium voltage {IT}| market for | Cut-off,U	1,00E-03
Heat for CIP & SIP [MJ]	Heat, district or industrial, natural gas {RER}| market group for | Cut-off,U	6,17E-03
Water [kg]	Tap water {Europe without Switzerland} | market for | Cut-off,U	1,67E-02
Sodium Hydroxide (NaOH) [kg]	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off,U	4,56E-04
Nitric Acid ($NaOH_3$) [kg]	Nitric acid, without water, in 50% solution state {RER}| market for nitric acid, without water, in 50% solution state | Cut-off,U	2,17E-04

through the mechanisms of conduction and convection, heat up slowlier than the juice. In an indirect heat exchanger, the solid parts are no more than the 70%, while in an ohmic heater they can reach the 80%.

In the industrial plant, after the reception and quality control phases, the peaches are stocked in refrigerated conditions to prevent the fruit from ripening and to keep the quality of the product as close as possible to that in the harvesting phase. The first processing phases include washing and calibration, followed by pitting and peeling. Thanks to the subsequent sorting phase, residues of kernels and skins are detected and discarded. At this point the peaches are ready to be cut into cubes: when the fruit is cut, some juice is released. The liquid part is separated and then mixed with the solid part in a percentage dependent on the type of pasteurization system used. So, the pasteurization phase is preceded by a mixing phase to reach the desired solid-liquid ratio. The pasteurization is carried out at a temperature of 98 °C and then the product is packaged in aseptic containers. The packaging phase is not included in the system boundaries. However, it must be said that the reduction of the 10% of the liquid results in a saving of packaging and, therefore, in a reduction of the environmental impact.

The pasteurization systems analysed are part of an industrial line produced by CFT and located in Australia. The operating conditions are the same as those of the line for the sterilization of diced tomatoes described in Paragraph 2.1.1.

2.2.2. *Goal and scope definition*

The goal of the study is to compare the environmental impact of the ohmic and the conventional heating systems for the pasteurization of diced peaches. It is conducted a "gate to gate" LCA analysis and in the system boundaries only the pasteurization processes are included. The FU is 1 kg of product and the reasons behind this choice are the same ones explained in Paragraph 2.1.2 (see Fig. 2).

2.2.3. *Inventory analysis*

The primary data collected for the ohmic and conventional pasteurization processes, all referred to the FU, are reported in Table 3 and Table 4.

3. Life cycle impact assessment

3.1. *Environmental results for the sterilization of diced tomatoes*

In the Impact Assessment the environmental impacts of the processes analysed are calculated with the method mentioned in Paragraph 2. The results are reported in Table 5.

The results highlight that the maximum value of the environmental impact is attributed to the ohmic heating sterilization process for all the impact categories included in the ReCiPe 2016 Midpoint (H) method. The gap between the impact results of the two technologies is particularly relevant for the categories "Terrestrial acidification" and "Freshwater eutrophication". For these two categories the numerical value of

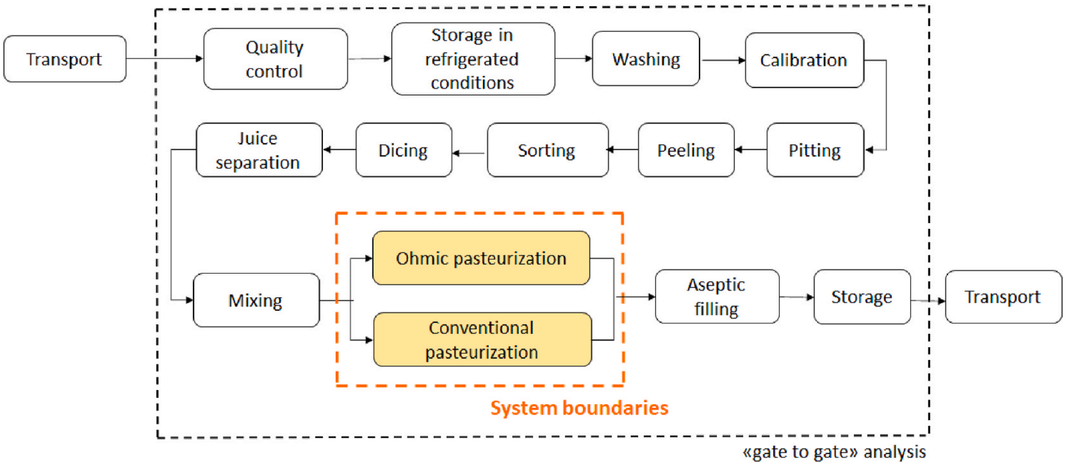

Fig. 2. System boundaries (diced peaches).

Table 3
Material and energy flows entering the pasteurization system with the indirect heat exchanger.

Input	Ecoinvent Dataset used	Value
Heat for the sterilization of the product [MJ]	Heat, central or small-scale, natural gas {RoW}| market for heat, central or small-scale, natural gas| Cut-off,U	2,30E-01
Waste product [kg]	Peach {RoW}| peach production | Cut-off,U	5,00E-03
Electric energy for pump operations [kWh]	Electricity, medium voltage {AU}| market for | Cut-off,U	1,40E-03
Heat for CIP & SIP [MJ]	Heat, central or small-scale, natural gas {RoW}| market for heat, central or small-scale, natural gas | Cut-off,U	9,17E-03
Water [kg]	Tap water {RoW}| market for | Cut-off, U	2,50E-02
Sodium Hydroxide (NaOH) [kg]	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off,U	6,33E-04
Nitric Acid ($NaOH_3$) [kg]	Nitric acid, without water, in 50% solution state {RoW}| market for nitric acid, without water, in 50% solution state | Cut-off,U	3,80E-04

Table 4
Material and energy flows entering the pasteurization system with the ohmic heater.

Input	Ecoinvent Dataset used	Value
Electric energy for the product sterilization [kWh]	Electricity, medium voltage {AU}| market for | Cut-off,U	6,00E-02
Waste product [kg]	Peach {RoW}| peach production | Cut-off,U	3,33E-03
Electric energy for pump operations [kWh]	Electricity, medium voltage {AU}| market for | Cut-off,U	1,00E-03
Heat for CIP & SIP operations [MJ]	Heat, central or small-scale, natural gas {RoW}| market for heat, central or small-scale, natural gas | Cut-off,U	6,17E-03
Water [kg]	Tap water {RoW}| market for | Cut-off, U	1,67E-02
Sodium Hydroxide (NaOH) [kg]	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off,U	4,56E-04
Nitric Acid ($NaOH_3$) [kg]	Nitric acid, without water, in 50% solution state {RoW}| market for nitric acid, without water, in 50% solution state| Cut-off,U	2,17E-04

Table 5
Values of the environmental impact of the ohmic and conventional heating technologies (tomatoes).

Impact category	Unit	Ohmic heating	Conventional heating
Global warming	kg CO_2 eq	4,61E-02	2,54E-02
Terrestrial acidification	kg SO_2 eq	8,23E-05	2,46E-05
Freshwater eutrophication	kg P eq	1,62E-04	0,257E-04
Land use	m^2a crop eq	1,14E-05	0,108E-05
Fossil resource scarcity	kg oil eq	1,85E-03	0,808E-03
Water consumption	m^3	4,76E-05	1,98E-05

the impact of the conventional technology is respectively 16% and 9% of that of the ohmic technology. Moreover, the CO_2 emissions of the conventional process are the 55% of those of the ohmic process (see Fig. 3).

It is possible to analyse the input data of the ohmic process to enquire about the contribution of each input to the total environmental impact. Fig. 3 shows that for all the impact categories the predominant contribute is that of the electric energy. Such contribution is always over 90%, except for the categories “Land use” and “Water consumption”. It is maximum for the category “Fossil resource scarcity”, where it reaches 96%, and such result is in contrast with the expectation that the use of electricity allows fossil fuel savings. The high contribution of the electric energy to the total environmental impact leads to some considerations about the transition towards processes powered by electricity, in substitution to those powered by fossil fuels, which is taking place in accordance with the decarbonization plan. In this case study such substitution is even environmentally pejorative.

3.2. *Environmental results for the pasteurization of diced peaches*

The comparison between the ohmic and conventional pasteurization of diced peaches points out that ohmic heating is the process with the highest environmental impact, as shown by the results in Table 6.

Ohmic heating is always responsible for the highest environmental impact except for the impact categories “Land use” and “Water consumption”. As far as global warming is concerned, the use of the ohmic heater does not provide for a reduction in the CO_2 emissions, which are 63% higher than those of the indirect heat exchanger.

By carrying out the data analysis, it is obtained the graph in Fig. 4, which shows how the electricity consumed by the ohmic heating process is the input with the heaviest weight on the total environmental impact for all the categories, except for “Land use” and “Water consumption” where the waste product makes the largest contribution to the total impact.

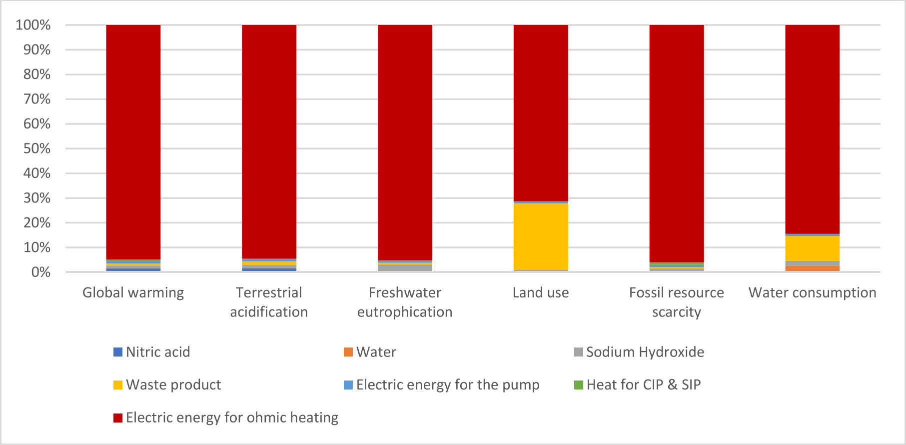

Fig. 3. Contribution of each input to the total environmental impact of the ohmic heating technology (diced tomatoes).

Table 6
Values of the environmental impact of the ohmic and conventional heating technologies (peaches).

Impact category	Unit	Ohmic heating	Conventional heating
Global warming	kg CO$_2$ eq	6,34E-02	2,36E-02
Terrestrial acidification	kg SO$_2$ eq	2,08E-04	0,456E-04
Freshwater eutrophication	kg P eq	1,02E-04	0,0396E-04
Land use	m^{2}a crop eq	1,88E-03	2,49E-03
Fossil resource scarcity	kg oil eq	1,54E-02	0,758E-02
Water consumption	m^3	8,73E-04	0,114E-04

For both the case studies the results of the LCA show that the conventional technology is still preferable from an environmental point of view, even though it is powered by fossil fuel. This means that nowadays the ohmic technology cannot explicate its potentials in the reduction of the environmental impact because in most of the countries the transition towards cleaner energy mixes has not been completed yet.

4. Discussion and sensitivity analysis

4.1. Sensitivity analysis

The results of the Impact Assessment show that the major contributor to the total environmental impact of ohmic technology is the electricity consumed to power the system. The reason behind this result is that the technology is energy-intensive, requiring, at the average flow rate of 5000 kg/h, 490 kWh and 300 kWh respectively for diced tomatoes and diced peaches. Moreover, such quantity of energy is produced with a mix of primary sources that are in the considered countries mainly not renewable. Although the ohmic technology is characterized by high conversion efficiencies, the energy input remains too high to bring environmental benefits unless changes are made upstream on the energy mix.

4.1.1. Analysis of the results under the hypothesis of industrial plant located in France

Since the environmental impact of the electric energy depends on the mix of primary sources used for electricity production, it is interesting to see how the results of the LCA change considering a different location of the industrial plant, and, therefore, a different energy mix. This new scenario can be modeled in the SimaPro software through the variation of the dataset entries referring to electricity, as reported in Table 7.

Assuming that the industrial plant that carries out the

Table 7
Input flows of electric energy referred to the FU.

Input	Ecoinvent Dataset	Value
Electric energy from the national grid (for the sterilization of diced tomatoes) [kWh]	Electricity, medium voltage {FR}| market for | Cut-off,U	0,098
Electric energy from the national grid (for the pasteurization of diced peaches) [kWh]	Electricity, medium voltage {FR}| market for | Cut-off,U	0,06

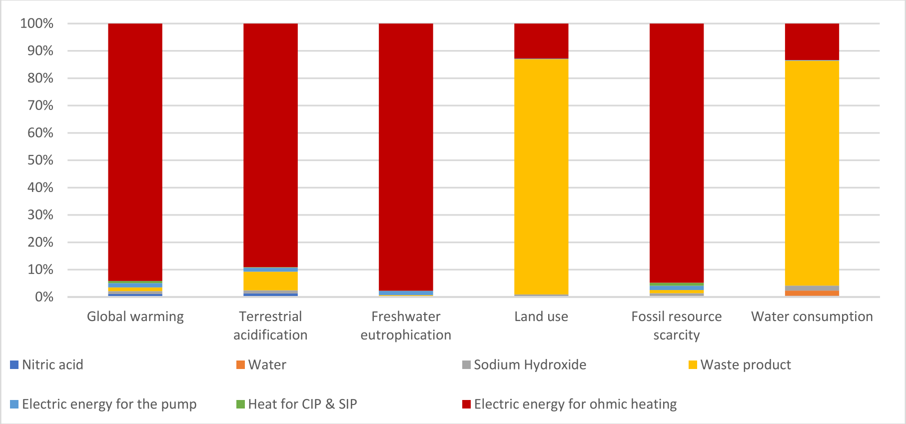

Fig. 4. Contribution of each input to the total environmental impact of the ohmic heating technology (diced peaches).

Table 8
Values of the environmental impact of the ohmic and conventional heating technologies (France).

Impact category	Unit	Ohmic heating of diced tomatoes	Conventional heating of diced tomatoes	Ohmic heating of diced peaches	Conventional heating of diced peaches
Global warming	kg CO_2 eq	1,06E-02	2,54E-02	7,85E-03	2,36E-02
Terrestrial acidification	kg SO_2 eq	3,12E-05	2,57E-05	3,40E-05	4,56E-05
Freshwater eutrophication	kg P eq	3,02E-06	1,08E-06	2,29E-06	3,96E-06
Land use	m^{2}a crop eq	9,02E-04	8,08E-04	1,88E-03	2,49E-03
Fossil resource scarcity	kg oil eq	2,81E-03	9,31E-03	2,00E-03	7,58E-03
Water consumption	m^3	4,45E-04	1,96E-04	9,58E-04	1,14E-03

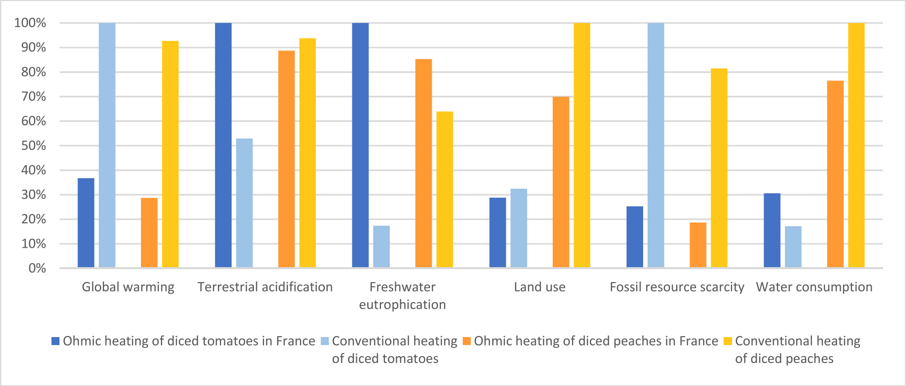

Fig. 5. Comparison of the environmental impact of the ohmic and conventional heating technologies for both diced tomatoes and peaches in France.

decontamination process with the ohmic heater is located in France, the results of the LCA change according to what is reported in Table 8.

Fig. 5 represents the comparison between the two decontamination processes for both diced tomatoes and diced peaches within the new scenario. The comparative histogram highlights the positive effect of the use of the French energy mix on some impact categories, such as global warming. This reduction of the CO_2 emissions can be attributed to French wide use of the nuclear source, which allows to lead the energy conversion without CO_2 emissions (Saidi and Omri, 2020).

In order to see how the impact of the ohmic technology changes according to the location of the industrial plant, a sensitivity analysis has been carried out. It consists of the introduction of a set of parameters that express the dependence of the electric energy from its country of origin. Eight different countries have been considered: Italy, Australia, France, Germany, United States, China, Norway and India. The results applied to diced tomatoes is represented in Fig. 6 and similar results are obtained for the case of diced peaches. A general overview of the results shows that India, Australia and China are the countries in which the consumption of electricity causes the biggest environmental impact for the majority of the impact categories. Such result is consistent with the fact that the primary source used in the highest percentage by these three countries is coal (International Energy Agency, 2020a). France and Norway are the most virtuous ones because of the wide use of hydroelectric energy, in the case of Norway (International Energy Agency, 2020c), and of nuclear energy, in the case of France (International Energy Agency, 2020b). However, the effect of the production of energy from hydroelectric sources by Norway has an effect on “Water consumption” in which the environmental impact generated by Norway is significantly higher than that of the other countries.

4.1.2. *Analysis of the results under the hypothesis of electric energy supplied by photovoltaic panels*

Assuming that the industrial plant is equipped with photovoltaic panels, it can be analysed the scenario in which the electric energy supplied to the ohmic heater comes in part or in whole from the photovoltaic source. Economic aspects are not included in the analysis.

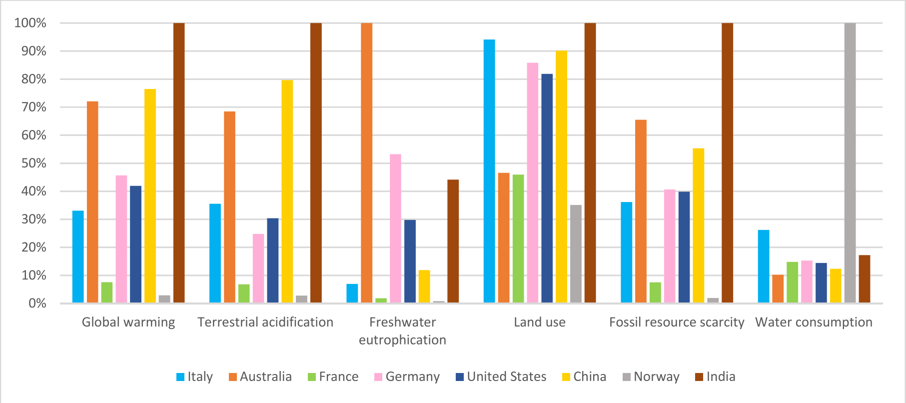

Fig. 6. Comparison between the environmental impact of the ohmic heating of diced tomatoes in different countries.

Table 9
Input flows of electric energy referred to the FU.

	Input	Ecoinvent Dataset	Value
Sterilization of sliced tomatoes	Electric energy from the national grid [kWh]	Electricity, medium voltage {IT}| market for| Cut-off,U	0,049
	Electric energy from photovoltaic panels [kWh]	Electricity, low voltage {IT}| electricity production, photovoltaic, 3 kWp slanted-roof installation, multi-Si, panel, mounted| Cut-off,U	0,049
Sterilization of diced peaches	Electric energy from the national grid, [kWh]	Electricity, medium voltage {AU}| market for | Cut-off,U	0,03
	Electric energy from photovoltaic panels [kWh]	Electricity, low voltage {AU}| electricity production, photovoltaic, 3 kWp slanted-roof installation, multi-Si, panel, mounted| Cut-off,U	0,03

In the first case analysed it is made the hypothesis that the photovoltaic plant can provide only the 50% of the total amount of electric energy necessary to the ohmic system. During the LCI it is created a new process in which the electric energy is divided into two components, as reported in Table 9.

As it can be noticed from Fig. 7, the use of 50% of electricity produced locally from renewable sources is not sufficient to make the ohmic process preferable than the conventional one from an environmental point of view. From the results of the LCA, reported in Table 10, it can be stated that for both diced peaches and diced tomatoes the maximum value of the environmental impact is that of the ohmic heating system for the majority of the categories.

In the second case analysed it is made the hypothesis that the photovoltaic plant provides the whole amount of the electric energy necessary to the ohmic system.

The use of 100% photovoltaic energy produces a positive effect especially on global warming, as it can be noticed from the results reported in Table 11 and in Fig. 8. Focusing on the global warming impact category, it is interesting to observe what percentage of photovoltaic energy is necessary for the ohmic system to achieve the same or a better environmental performance than the conventional system. In the case of the sterilization of diced tomatoes, improvements in the environmental results are seen when the percentage of photovoltaic energy is over 50%. With 51% of photovoltaic energy the impact of the two systems is the same (2,54E-02 kg CO_2 eq). With 70% of photovoltaic energy the impact is halved and with 100% of photovoltaic energy the reduction becomes even more relevant, as shown in Fig. 8. In the case of the pasteurization of diced peaches, the environmental results of the ohmic system becomes better than those of the conventional one when the percentage of photovoltaic energy is above 70%. With a percentage of 100% a reduction of the 62% is reached.

From the results obtained it can be stated that the electric energy locally produced from renewable sources brings good improvements to the environmental performances of the ohmic process. However, since the solution that provides for the coverage of the entire energy needs of a single machine by the photovoltaic plant is not always feasible, for both economic and land availability reasons, it is worth analysing the case of combined use of the two technologies for the decontamination of the product. In this way it is possible to have the positive effects of the ohmic heating on the quality of the product limiting the quantity of electric energy consumed.

4.1.3. Analysis of the results under the hypothesis of combined use of the indirect heat exchanger and the ohmic heater

The combination of the ohmic and conventional heating processes allows to have the benefits from the two technologies with a mitigation of the negative aspects: the indirect heat exchanger is used in the preheating phase while the ohmic heater covers the final temperature rise when the product is more exposed to the risk of burns. Literature documents that one of the most common applications of the combined use of the ohmic heater with another technology is the cooking process of hamburger patties (Ozkan and Farid, 2014): ohmic heating is used in the last step in order to ensure that the desired temperature is reached at the core of the product without having burns on the external surfaces. In the case of the diced tomatoes the product is preheated till 65 °C, the temperature below which the damage to the integrity and quality of the product is negligible. The final step of the thermal treatment, where the temperature reaches 110 °C, is led in the ohmic heater, which guarantees a high-quality product suitable for further processing after a period of storage. In the case of diced peaches, the conventional heating is used to reach the temperature of 70 °C leaving the further temperature rise till 98 °C to be conducted in the ohmic heater. This ensures that the shape and size of the pieces are not altered during the pasteurization process and that the thermal and mechanical damage is as limited as possible. In order to recreate the process on the software SimaPro, the dataset used for the analysis has been modified as reported in Table 12.

In Table 13 the environmental results are reported in comparison to those of the separate use of the ohmic and conventional heating.

Fig. 9 highlights that for both the products the single use of conventional heating is still the solution that implies the lowest environmental impact in the categories “Global warming”, “Terrestrial acidification”, “Freshwater eutrophication” and “Fossil resource scarcity”, especially as regards the pasteurization of diced peaches. In this case, despite the reduction of the electric energy consumption

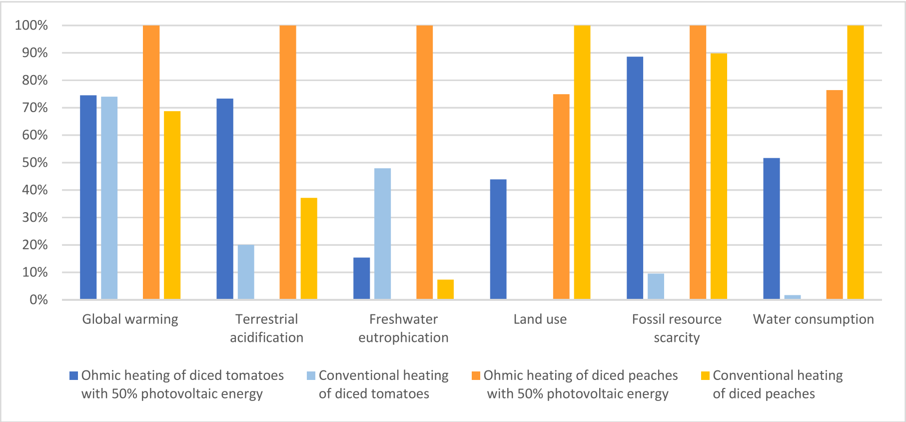

Fig. 7. Comparison of the environmental impact of the ohmic and conventional heating technologies for both diced tomatoes and peaches with 50% of electric energy from photovoltaic panels.

Table 10
Values of the environmental impact of the ohmic and conventional heating technologies with 50% of electric energy from photovoltaic panels.

Impact category	Unit	Ohmic heating of diced tomatoes	Conventional heating of diced tomatoes	Ohmic heating of diced peaches	Conventional heating of diced peaches
Global warming	kg CO_2 eq	2,56E-02	2,54E-02	3,43E-02	2,36E-02
Terrestrial acidification	kg SO_2 eq	8,99E-05	2,46E-05	1,23E-04	4,56E-05
Freshwater eutrophication	kg P eq	8,26E-06	2,57E-05	5,36E-05	3,96E-06
Land use	m^2a crop eq	1,09E-03	1,08E-06	1,86E-03	2,49E-03
Fossil resource scarcity	kg oil eq	7,48E-03	8,08E-04	8,44E-03	7,58E-03
Water consumption	m^3	5,90E-04	1,98E-05	8,72E-04	1,14E-03

Table 11
Values of the environmental impact of the ohmic and conventional heating technologies with 100% of electric energy from photovoltaic panels.

Impact category	Unit	Ohmic heating of diced tomatoes	Conventional heating of diced tomatoes	Ohmic heating of diced peaches	Conventional heating of diced peaches
Global warming	kg CO_2 eq	9,35E-03	2,54E-02	7,30E-03	2,36E-02
Terrestrial acidification	kg SO_2 eq	4,86E-05	2,57E-05	4,31E-05	4,56E-05
Freshwater eutrophication	kg P eq	6,20E-06	1,08E-06	5,29E-06	3,96E-06
Land use	m^2a crop eq	7,17E-04	8,08E-04	1,74E-03	2,49E-03
Fossil resource scarcity	kg oil eq	2,35E-03	9,31E-03	1,74E-03	7,58E-03
Water consumption	m^3	3,49E-04	1,96E-04	8,73E-04	1,14E-03

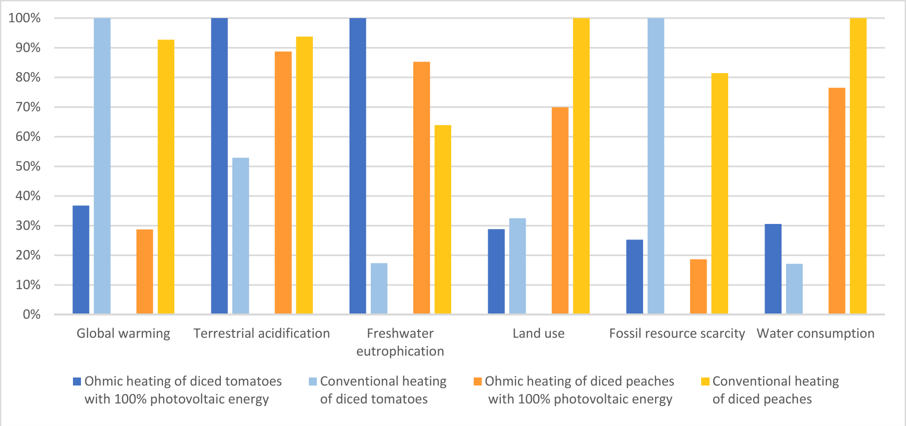

Fig. 8. Comparison of the environmental impact of the ohmic and conventional heating technologies for both diced tomatoes and peaches with 100% of electric energy from photovoltaic panels.

Table 12
Material and energy flows entering the sterilization system with the combination of the ohmic and conventional technologies.

Input	Value for diced tomatoes	Value for diced peaches
Heat for the product sterilization, MJ	1,84E-01	9,20E-02
Electric energy for the product sterilization [kWh]	5,80E-02	3,40E-02
Waste product, kg	5,00E-03	4,17E-03
Electric energy for pump operations, kWh	1,00E-03	1,00E-03
Heat for CIP & SIP, MJ	6,17E-03	6,17E-03
Water, kg	2,50E-02	2,00E-02
Sodium Hydroxide (NaOH), kg	4,56E-04	5,07E-04
Nitric Acid (NaOH$_3$), kg	2,17E-04	2,60E-04

introduced by the combined use of the ohmic and conventional technologies, the aspect relative to the Australian energy mix, dominated by the presence of coal as the main primary source for electricity production, is predominant and it negatively affects the environmental results.

Fig. 10 shows some improvements introduced by the combined use of the ohmic and conventional technologies over the process entirely carried out with the ohmic heater.

5. Conclusions

The study aimed at comparing the environmental performances of two technologies for the decontamination of diced tomatoes and diced peaches, carried out respectively in Italy and in Australia, using the LCA methodology with the ReCiPe 2016 Midpoint (H) as impact assessment method. The environmental aspects of ohmic heating are poorly discussed in literature, but they are of particular importance for the food industry which, like other industrial sectors, is involved in the decarbonization process and needs to guide its technological development towards a greater environmental sustainability. Life Cycle Assessment represents the optimal methodology to investigate whether the substitution of the technologies powered by fossil fuels with electric-based ones leads to an effective reduction of the environmental impact. Since the sustainability of electric-based technologies, as ohmic heating, is strongly dependent on the primary sources used for electricity

Table 13
Values of the environmental impact of the combined use of the ohmic and conventional technologies and the total use of the conventional or ohmic heating.

		Diced tomatoes			Diced peaches		
Impact category	**Unit**	**Combined use of conventional and ohmic heating**	**Conventional heating**	**Ohmic heating**	**Combined use of conventional and ohmic heating**	**Conventional heating**	**Ohmic heating**
Global warming	kg CO_2 eq	3,54E-02	2,54E-02	4,61E-02	4,41E-02	2,36E-02	6,34E-02
Terrestrial acidification	kg SO_2 eq	8,82E-05	2,46E-05	8,23E-05	1,34E-04	4,56E-05	2,08E-04
Freshwater eutrophication	kg P eq	6,52E-06	2,57E-05	1,62E-04	5,94E-05	3,96E-06	1,02E-04
Land use	m^2a crop eq	2,27E-03	1,08E-06	1,14E-05	2,27E-03	2,49E-03	1,88E-03
Fossil resource scarcity	kg oil eq	1,16E-02	8,08E-04	1,85E-03	1,18E-02	7,58E-03	1,54E-02
Water consumption	m^3	5,95E-04	1,98E-05	4,76E-05	1,01E-03	1,14E-03	8,73E-04

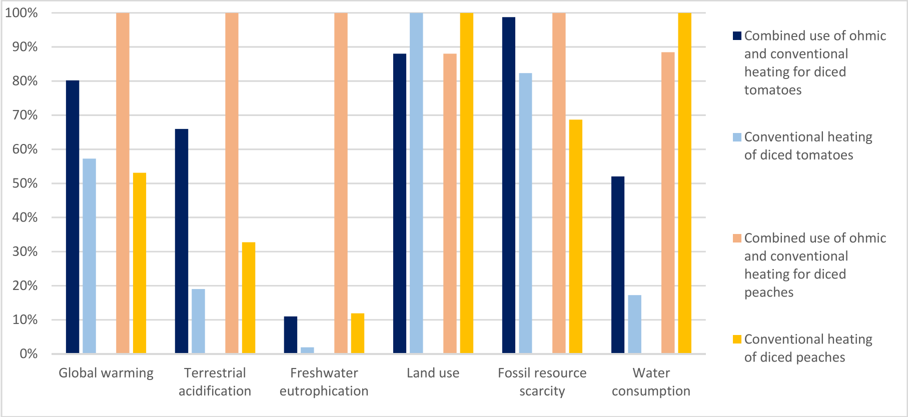

Fig. 9. Comparison between the environmental impact of the combined use of ohmic and conventional heating technologies and the total use of conventional heating.

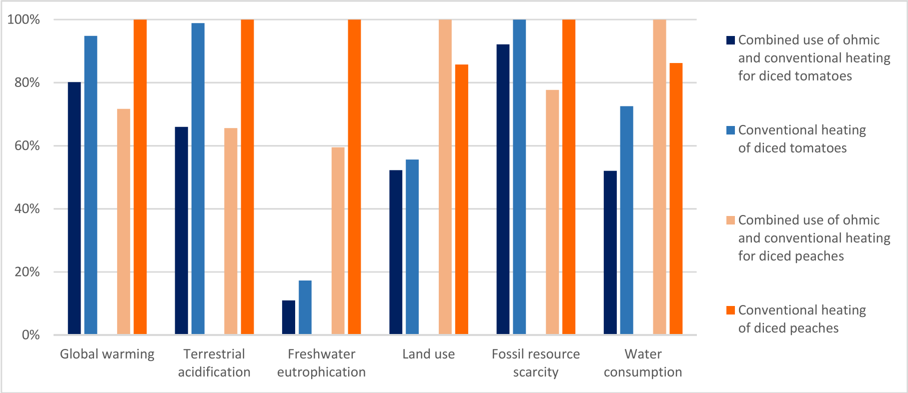

Fig. 10. Comparison between the environmental impact of the combined use of ohmic and conventional heating technologies and the total use of ohmic heating.

production, different scenarios have been considered in the analysis, attempting to depict what the intervention fronts are to make the transition environmentally successful.

The results have pointed out that in Italy and Australia, for a standard company connected to the national grid, the environmental impact of the ohmic process is higher than that of the conventional heating process for both the products. The electric energy is the most impactful input, so, in order to see how the system could be improved, a sensitivity analysis has been carried out on it. A first consideration can be made on the origin of the electric energy: since the mix of primary sources depends on the country where the electric energy is produced, a sensitivity analysis was carried out to show how the environmental impact of that input changes according to the location of the industrial plant. Eight different countries were selected for this analysis: Italy, Australia, France, Germany, United States, China, Norway and India. The lowest environmental impact of the ohmic technology for most of the ReCiPe impact categories was found in Norway and in France. Assuming that the ohmic heating process is conducted in France instead of in Italy or in Australia, the results show an improvement of the environmental performances of the ohmic process. Since the change in the energy mix is not in the power of the single food industries, another solution that is worth evaluating is the electricity production on site by photovoltaic panels. The results related to this scenario highlight that, if the percentage of the photovoltaic energy is limited to the 50%, no relevant improvements are observed, while, if the percentage reaches 100%, the advantage of using the ohmic technology becomes more significant, especially on global warming potential. However, the fact that a photovoltaic plant, which provides for 100% of the electricity needed by the ohmic process, is not always feasible, leads to consider another scenario, in which the decontamination process is carried out with both the technologies: the indirect heat exchanger is used in the first part of the process until the product is not exposed to the risk of burns and quality degradation. The thermal treatment is completed in the ohmic heater to preserve the quality of the product. From an environmental point of view the combined use of the two technologies represents an intermediate solution between those that imply the total use of a single technology.

This analysis shows that in the present situation the choice of an ohmic heater does not bring the environmental benefits expected from an electric-based technology. However, it must be considered that the current context is in constant evolution. Therefore, future results could be different as an effect of the change in the mix of primary sources, imposed by the European and global decarbonization plans, and of the technological development in terms of energy efficiency. What may be useful at present is finding the most appropriate solution to accompany the transition towards electric-based technologies adopting intermediate assets, as the one which implies the combined use of the indirect heat exchanger and the ohmic heater. Such solution must make the best use of the technologies available, enhancing the positive aspects and mitigating the negative ones, without losing sight of what regards the quality of the product.

Moreover, based on the aspects discussed, future research will be oriented to discover new solutions for cleaner energy production on site, beyond the one represented by the installation of photovoltaic panels. When the use of renewable sources is not feasible, the goals of technological development should be the optimization of energy efficiency and minimization of the energy inputs. An important role in this direction can be played by cogeneration systems, that guarantee high energy efficiencies and the reduction of both energy costs and CO_2 equivalent greenhouse gas emissions.

Credit author statements

Arianna Paini carried out the Life Cycle Assessment analysis (LCA), Stefano Romei collected the primary data used in the LCA and gave technical description of the equipment, Roberta Stefanini contributed to the experimental part of the study and revised the paper, Giuseppe Vignali has coordinated the project and supported each phase of the paper conceptualization.

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

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