

Article

Upscaling via a Prospective LCA: A Case Study on Tomato Homogenate Using a Near-to-Market Pasteurisation Technology

Maria Calero ^{1,*}, Gabriela Clemente ¹, Dinar Fartdinov ², Sancho Bañón ³, Israel Muñoz ²
and Neus Sanjuán ¹

¹ ASPA Group, Department of Food Technology, Universitat Politècnica de València, 46022 Valencia, Spain; gcleme@tal.upv.es (G.C.); nsanjuan@tal.upv.es (N.S.)

² Food Technology Program, Institute of Agrifood Research and Technology (IRTA), 17121 Girona, Spain; dinar.fartdinov@irta.cat (D.F.); israel.munoz@irta.cat (I.M.)

³ Department of Food Science & Technology and Human Nutrition, Faculty of Veterinary Science, University of Murcia, 30100 Murcia, Spain; sanchoba@um.es

* Correspondence: macapas@upvnet.upv.es

Abstract: Thanks to food technology, the production of cold tomato soups such as *salmorejo*, a traditional Spanish dish, has become industrialised. Thermal treatments play an important role in ready-to-eat meals, prolonging their shelf-life. Radiofrequency (RF) heating is less energy-intensive than conventional heat exchangers and has been successfully used to pasteurise food; novel applications, however, provide results at laboratory or pilot scale, so conclusions might not be translatable to industry. In this study, a prospective Life-Cycle Assessment of *salmorejo* pasteurised using RF was performed to highlight the relevance of upscaling and to compare its environmental impacts with those of conventional pasteurisation. “Gate-to-gate” results show that the pilot has greater environmental impacts due to its greater energy consumption, as thermal energy is not recovered. The packing and landfill of organic waste exhibit the highest impacts at industrial scale. RF technology does not imply significant environmental improvements versus conventional pasteurisation. Potential changes in the energy background of future scenarios have relevant consequences in the environmental impacts. “Farm-to-factory-gate” analysis highlights ingredients and tomato valorisation as the most impacting stages. The prospective LCA of scaled up scenarios constitutes a tool for environmental screening in food ecodesign, contributing to Sustainable Development Goal 12.

Keywords: emerging technology; prospective LCA; pasteurisation; radiofrequency; *salmorejo*; scale up; tomato homogenate



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1. Introduction

Food products are associated with relevant environmental impacts throughout their life cycle. Literature on food life-cycle assessment (LCA) shows that the agricultural stage is often the largest contributor to their total life-cycle impacts [1], with food processing in second place, accounting for 28% of the total energy use in the EU [2]. In a review on energy usage within the food industry, Ladha-Sabur et al. [3] highlight processes involving phase change (e.g., drying, freezing, etc.) as the most energy-demanding ones, although thermal treatments (pasteurisation, blanching, etc.), which are extensively used in the food industry, are also remarked as energy-intensive operations accounting for a large share of the energy consumption in food processing. However, such treatments play an important role in making fresh ready-to-eat meals long-lasting. The same review also remarks on the energy consumption associated to cleaning in dairy products [3], while energy consumption for cleaning in other food products has not been accounted for. Process optimisation, and technological and manufacturing behavioural changes have been proposed to decrease energy consumption in food manufacturing [4].

Traditional Spanish meals, in particular those forming part of the Mediterranean diet, are held in higher and higher regard and increasingly consumed as part of a healthy lifestyle. Therefore, industry has made some homemade recipes available in supermarkets thanks to advances in food science and technology. That is the case of cold tomato soups, such as *gazpacho* and *salmorejo*, which are in great demand in Spain, especially during the warmest months. Its production is thus seasonal: 70–80% is consumed between May and September. In the last few years, such cold soups have also become popular abroad, and these products are being exported to France, Portugal, Belgium, the United Kingdom, and Germany [5] in greater quantities every year. In 2018, 64.4 million litres of *gazpacho* were produced [6]. The economic importance of those tomato homogenates has recently been highlighted by their soaring sales [7]. Recipes of *gazpacho* (mostly tomato, other fresh vegetables, and olive oil) and *salmorejo* (mostly tomato, garlic, bread, and olive oil) are similar and even made along the same processing lines. Hereinafter, we will refer to *salmorejo*, instead of cold tomato soup or viscous tomato homogenate, to distinguish it from others, such as *gazpacho*.

These vegetable soups are often pasteurised to extend their shelf life using conventional heating treatments, which involve transferring heat to the food through conduction or convection mechanisms. The conditions used in conventional heating processes can lead to an alteration of the sensorial and nutritional properties [8]. Therefore, novel pasteurisation technologies, such as dielectric heating (e.g., radiofrequency), have been developed, allowing for the effective inactivation of the common microorganisms and enzymes at lower processing times and temperatures, and the improved preservation of food quality with respect to conventional methods [9,10]. Another factor that has driven the development of such alternative technologies is the operating expenses: these are lower as less energy is consumed [11]. In principle, dielectric technologies are less energy-intensive [12,13] and, thus, more sustainable.

Radiofrequency (RF) heating has been studied in solid food for the purposes of sterilising dried fruits [14,15], cereals [16,17], spices [18,19], and meat [20–22]. The success of its application to liquids in continuous processing is due to the high degree of penetration of RF energy, achieving a uniform heating of the product [23]. Specifically, research on the RF pasteurisation of liquids has been carried out in dairy products [24], and even in liquid viscous foods [25], such as liquid egg [26]. However, there are no studies available into acidified homogenates with added acidulants, such as citric juice or vinegar, that require mild pasteurisation temperatures. Despite all this research work, current studies on liquid foods only provide results at laboratory and/or pilot scales, so that there may often be great uncertainty as regards the results at industrial scale [27], since the scaling up has not been carried out. In fact, there has been no reported use of RF technology for the commercial pasteurisation of acidified food despite its huge potential [13].

Taking into account that Sustainable Development Goal (SDG) 12 calls for sustainable and responsible consumption and production, prospective tools are needed to detect the environmental hotspots at early stages of product design, when there are still opportunities to use environmental guidance for major changes. Along these lines, prospective LCA has been shown to be a suitable tool with which to assess the environmental impact of novel foods or conventional foods developed using new processing techniques [28–31], providing useful information at early stages of product development to be further incorporated into industrial-scale manufacturing [32,33]. However, inventory data area great challenge in prospective LCAs, as many times only lab or pilot scale data are available. Many authors agree that the scaling effects should be considered when assessing emerging technologies [34–36]. Upscaling in the food industry is usually complex and, thus, a pilot plant is useful in the testing of new processing equipment under industrial-like operating conditions [37]. Several LCA studies on alternative food-processing technologies are only at laboratory or, at least, at pilot scale [38]. In addition, cleaning of the processing line is mostly not accounted for in the LCA literature into processed food, neglecting that the food industry is one of the most water-intensive and also the need to optimise cleaning protocols [38,39]. This means that the conclusions of such research might not be translatable

to industrial scale, since economies of scale, changes in the recipe, potential energy, or material recovery, or the inclusion of additional unit processes, among other things, may not be taken into account. Upscaling permits the bridging of the gap between lab or pilot data and inventory data [40], and avoids overestimation of the impacts, as can happen when using pilot data [41–43]. In this way, a likely environmental impact of the novel product can be determined, which allows for further comparison with that of a reference product system [44]. Different upscaling alternatives can be found in the literature on prospective LCA. For instance, Piccinno et al. [45] and Zhou et al. [40] proposed frameworks to scale up chemical production processes to industrial scale from laboratory experiments and pilot plants, respectively. Tsoy et al. [46] and Thonemann et al. [47] review upscaling methods applied in prospective LCA and provide methodological guidance. It must be highlighted that the impacts of the scaled-up system are not often compared to those of the reference product or technology [46,47].

To the best of the authors' knowledge, the environmental impacts of products pasteurised with RF have not been assessed this far. Thus, in this study, a prospective LCA of *salmorejo* pasteurised with RF was carried out, with a twofold goal: to highlight the relevance of upscaling when performing prospective LCAs and also to compare their environmental impacts with those of *salmorejo* processed using conventional pasteurisation technology. To this end, current industrial data, together with information from a real pilot plant, are the basis for an industrial upscaling considering two throughputs; in addition, the environmental impacts of the product at pilot and industrial scales are assessed by using LCA.

2. Materials and Methods

To carry out this case study, the ISO 14040/44 standards [48,49] were taken into account, in addition to literature on prospective LCAs. Specifically, the study of Thonemann et al. [47] was used to support decision making for the prospective case study. These authors highlight three main challenges that arise when conducting a prospective LCA, namely, comparability, data, and uncertainty. These challenges affect different methodological aspects of the LCA that, as can be observed in the second column of Table 1, can be interconnected and not necessarily assigned to one challenge, as challenges also overlap with each other. It must be noted that only those relevant aspects from Thonemann et al. [47] followed in our research are included in Table 1.

2.1. Aim of the Study, Goal, and Scope Definition

The aim of the LCA study is as defined in Section 1. In this way, this study aims to answer the following questions: How relevant is processing in the *salmorejo* life-cycle and how can its impacts be reduced? Are there relevant differences between RF and conventional pasteurisation? Which unit processes and life-cycle stages most contribute to impacts? Can the impact of *salmorejo* processing be reduced by improving energy production processes?

The intended application is: (a) to demonstrate the relevance of upscaling in the development of food products using new processing technologies by showing the differences in the LCA results between a real pilot plant and simulated industrial processing; (b) to compare the environmental impacts of *salmorejo* processed with RF with those of the same product processed with conventional pasteurisation methods.

Table 1. Methodological recommendations to overcome the challenges of prospective LCAs (elaborated from the study of Thonemann et al. [47]).

Challenge	Methodological Aspect	Recommendation
COMPARABILITY	Aim of the study	The aim of the study should include the technology readiness level (TRL) and manufacturing readiness level (MRL) as an indicator of the maturity of the technology. In comparative prospective LCAs, the intended application of comparison should be explicitly stated. To ensure comparability, the same or consistent time frame and technological maturity levels are needed for all the modelled technologies. This means, for instance, that the background data should be adapted to the technological maturity levels.
	Functionality and System boundaries	When the new product substitutes the conventional without providing additional functions, the definition of the functional unit is straightforward. In that case, downstream life-cycle stages, such as the use and the end-of-life, can be neglected.
	Life-Cycle Impact Methodology	Impact-assessment methodologies need to be as comprehensive as possible and must include the newest developments. Midpoint methods are preferred over endpoint ones since they minimise uncertainty.
DATA	Availability	Data for the foreground and background systems must be differentiated. The foreground system is scaled-up using data obtained at lab/pilot scales and also other data sources (e.g., patents, expert interviews, unpublished results). From these data, the process can be simulated either by using specific software or performing calculations. Background data are usually taken from databases or from literature.
	Quality	In the foreground system, process-engineers' communications can support LCA-practitioners' decisions and improve data quality.
	Scaling	Upscaling can be carried out by generating predictive scenarios or by setting scenario ranges. Foreground processes are upscaled by using different methods (from existing plants, consultations with machinery suppliers or process engineers, use of mass and energy balances, power laws, etc.) to find out the mass and energy inputs and outputs for each unit process. This can imply varying the background system for the different scenarios, as it changes over time. Technicians' and engineers' knowledge is key to creating realistic flowcharts for the upscaling. In prospective LCAs, the attributional approach is mostly applied instead of the consequential one.
UNCERTAINTY	Uncertainty	Uncertainty analysis, such as Monte Carlo simulation, is recommended, especially for the scaled-up system.

Nowadays, RF technology is used at industrial scale for the continuous pasteurisation of liquid foods, which is an advantage when tackling the scaling up in this research, although it is not yet used in viscous liquids. Moreover, the industrial production of *salmorejo* is already competitive and the introduction of the RF technology, which is at a mature stage of development, would just imply a substitution of part of the heating treatment already installed in present-day plants. Thus, although the upscaling is more straightforward as there are few degrees of freedom (most parameters will be locked), the possibility of modifying the design and ultimately environmental performance is limited [50,51].

The prospective LCA of the product pasteurised using a conventional heat exchanger (TRL 9) and the emerging technology (RF) at both pilot (TRL 7) and industrial scales is tested in the present ($t_0 = 2020$) and it is also projected in the future (t_1), namely, 2040 (Figure 1). This year was chosen because RF is a novel near-to-market technology and we assumed it could be fully implemented in 20 years.

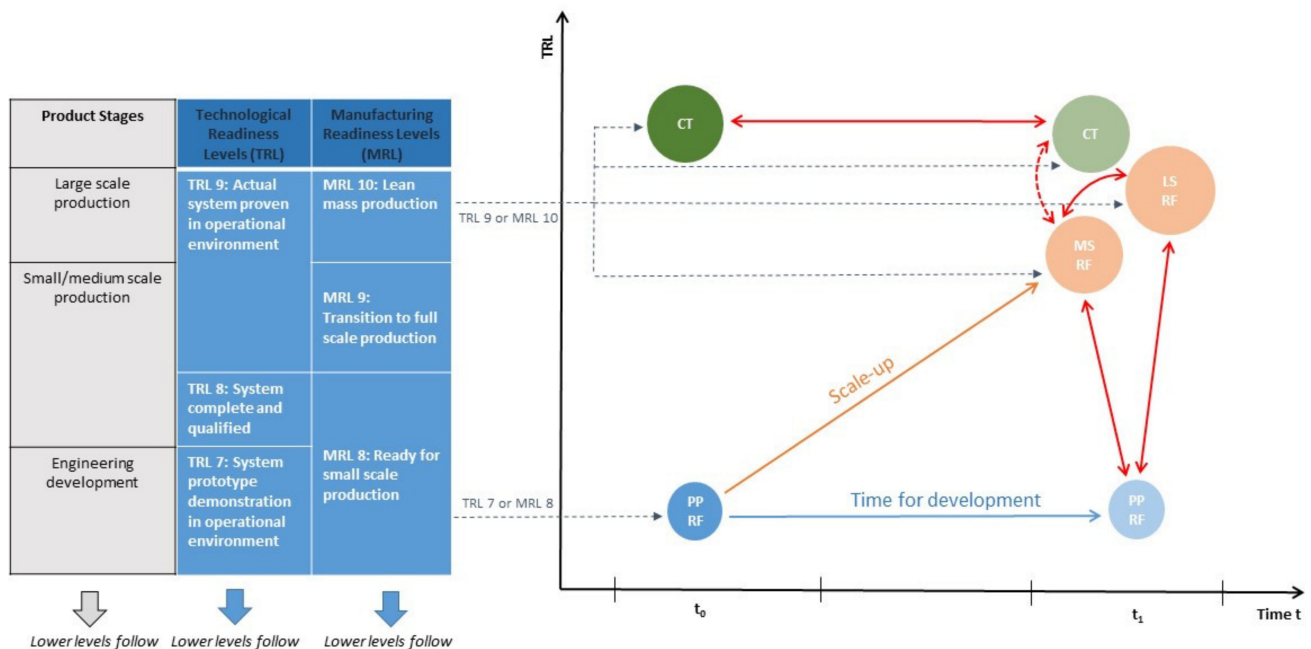


Figure 1. Temporal and technological status of each of the studied scenarios (adapted from Gavankar et al. [42], European Commission [52], and Thonemann et al. [47]). CT, conventional technology; PP, pilot plant; MS, medium-scale; LS, large-scale; RF, radiofrequency. Continuous red arrow: intra-technology comparison. Dotted red arrow: inter-technology comparison. Dark colour: technology in current time. Light colour: predicted technology.

The functional unit (FU) is defined as 1 kg of pasteurised packed *salmorejo*, without including the weight of the packaging. Previous studies carried out in the research project, and still to be published, show that product quality and shelf life are the same, regardless of the pasteurisation technology applied or the production scale; hence, the reference flows are the same. As to the system boundaries, two perspectives are applied, namely, “gate-to-gate” and “farm-to-factory-gate” (see Figure 2). The core system is the *salmorejo* processing, including the management of solid organic waste and the wastewater treatment from facility cleaning. The distribution, use (e.g., refrigeration), and the end-of-life stages (e.g., management of the packaging waste derived from product consumption) are not included in this study, as they are assumed to be the same because, as stated above, the product quality and shelf life are the same.

According to the Inventory Life Cycle Data (ILCD) handbook [53], foreground refers to the parts of the system susceptible to changes due to decision makers (in this case, *salmorejo* producers and project researchers), while background refers to those processes not directly affected by those actors, usually established as average production mixes and other market data. Foreground systems are those of the pilot plant and industry (the blue font in Figure 2), while the rest is part of the background system (the black font in Figure 2). Water, chemicals, energy, and wastewater corresponding to the cleaning-in-place (CIP) of the equipment are also included in the background system.

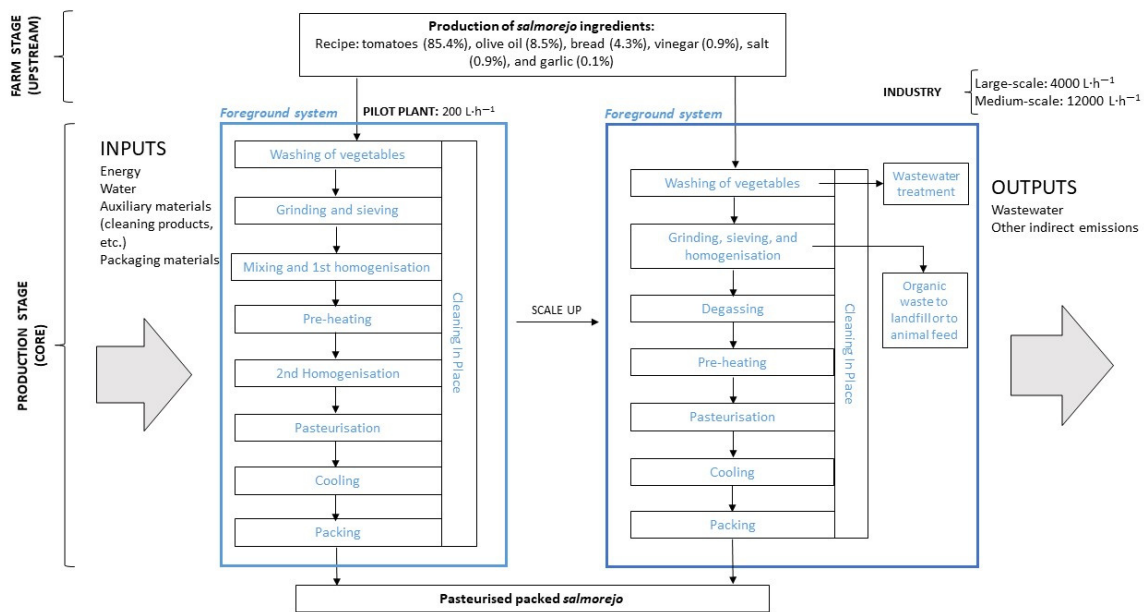


Figure 2. Processes involved in *salmorejo* production at pilot and the industrial scales. CT: conventional technology, RF: radiofrequency.

2.2. Scaling-Up Procedure and Data Collection

There is no sole method for scaling up, but an array of methods can be found [54]. Arvidsson et al. [50] differentiated two main approaches for the modelling and process upscaling of the foreground system, namely, predictive scenarios or scenario ranges. The predictive method seeks to reflect likely technological developments, also taking into account the status quo. Scenario ranges include minimum and maximum extreme scenarios or even a grading scale. In this study, the applied upscaling methodology corresponds mainly to the predictive approach, as RF technology is well-founded at commercial scale.

It must also be remarked that going from pilot to industrial scale often entails changes in the processing line, which can be summarised in three categories [36,55]. The first category takes place inside a unit process as some processes can change, e.g., yield, energy supply, energy efficiency, amount of waste, etc. The second category corresponds to synergies between processes, for instance, heat recovery or material recovery. The third category refers to changes in production capacity because it is not always fully used in pilot plants, whereas industrially the production capacity is efficiently organised, which can entail changes in the energy consumption and in the number of required unit processes. To sum up, plant configuration can be modified as a consequence of upscaling, resulting in a rearrangement of the sequence of unit processes or the addition of new ones.

As stated in the introduction, industrial *gazpacho* processing is the same as that of *salmorejo*, except for the ingredients. The same industrial line is even often used for making either *gazpacho* or *salmorejo*. Thus, except the recipe, the same processing is considered for the upscaling (e.g., unit processes, equipment used, energy consumption, etc.). In addition, *gazpacho* is more commonly produced (in terms of the number of industries) and the output is greater (in tonnes per year) than that of *salmorejo*; thus, more information is available. Then, when specific information on the industrial production of *salmorejo* was not available (e.g., unit processes involved, product capacity of factories, etc.), data from *gazpacho* processing were used instead. However, as stated in the introduction, the production of *salmorejo* is already carried out at commercial scale; hence, the procedure relies not only on the pilot plant, which is usually the starting point, but also on current information from equipment manufacturers.

Taking all this into account, as well as available literature [45,46,56], the upscaling procedure followed for the foreground system is summarised in Table 2. The procedure consists of three steps, and for each step the associated calculations or the treatment of the

information is presented, together with its corresponding outcome and the data sources required. Firstly, in step 1, representative production lines in the Spanish *gazpacho* and *salmorejo* market are studied to set up the most realistic scenarios for the upscaling for both thermal processing technologies: conventional tubular heat exchangers and RF. As a consequence, scenarios are designed that take into account two production capacities at industrial scale and available information on waste management at industrial processing plants. In step 2, the ingredients of commercial *salmorejo* are examined, and real plants are investigated in detail, analysing the production lines and the unit processes involved, process parameters, and packed products. Once the unit processes are defined for the industrial scales, step 2 also includes research on the equipment available in the market for the corresponding scales. Step 3 consists of designing a processing line for each industrial scale, which will give outcome data concerning mass and energy inputs and outputs and reference flows of the unit processes. The methods used to estimate these data include mass and energy balances, but also extrapolations using linear regressions (e.g., to relate the power of equipment with process capacity) and optimisation factors based on economies of scale. Optimisation factors are applied to specific unit processes, assuming that their efficiency increases (e.g., reduction in energy requirements) with the scale [44]. Caduff et al. [57] found that, if the cost scaling factor for equipment is based mainly on material input and utility supply, it can be used as a scaling factor in the LCA. In Section 3.1, the specific calculation methods and data sources used to estimate the energy consumption at each scale are detailed.

Table 2. Overview of the procedure used in the predictive scaling up, outcomes, and data sources.

Procedure Step	Information Treatment and Calculations	Outcome	Data Sources
1. Scenario definition. Representative throughputs/production capacities of production plants are set. Other criteria can be used (e.g., organic waste management).	Investigate current most common <i>salmorejo</i> / <i>gazpacho</i> plant production capacities. Existing alternatives for waste management are also investigated.	Two productive scales: medium- and large-scale productions.	On-line press releases on <i>salmorejo</i> production.
2. To have an overview of common industrial plants and different production lines. Investigation of the equipment used for the pilot and industrial scales in each unit process.	Unit processes involved, flowchart, ingredients and recipe, production parameters, sales format. Process parameters of the unit processes (temperature, pressure, product flow, nominal power, etc.).	Scaled-up production flow of the productive scales.	Industrial producers' data: videos of productive lines, interviews, and researchers' know-how. Pilot plant equipment brands, equipment manufacturers' on-line data and consultation, engineers' know-how. Personal communications with equipment manufacturers. Literature review.
3. To forecast designs and working conditions of the productive lines at industrial scales from information gathered in previous steps.	Selection/calculation of processing conditions of the scenarios (industry data, equipment, etc.). Mass and energy balances needed for the LCA.	Scaled-up values of material and energy inputs and outputs and elementary flows for each unit process.	Mass and energy balances, potential laws and regression, literature on food engineering, interviews with producers, pilot plant parameters, and expert judgement.

Modelling can also affect the background processes. When background systems are not expected to change very much, status quo scenarios are justified. However, in this study, they were expected to change, and future scenarios are applied to avoid a temporal mismatch with the foreground system. Specifically, the literature was referred to in order to predict the electricity production mix and the natural gas (see Section 3.1.3).

2.3. Impact Assessment Methods and Impact Categories

The method Recipe 2016 v1.1 Midpoint (H) [58] was used to assess the following impact categories: climate change, no biogenic (CCnB) and climate change, biogenic (CCB), as CO₂ eq.; fine particulate matter (FPM), as kg PM_{2.5} eq.; fossil depletion (FD), as kg oil eq.; freshwater eutrophication (kg P eq.) (FWEU); ionising radiation (IR), as kBq Co-60 eq. to air; land use (LU), as annual crop eq.·y; marine eutrophication (MEU), as kg N eq.; metal depletion (MD), as kg Cu eq.; photochemical ozone, ecosystems (PHE) and photochemical ozone, human health (PHH), as kg NO_x eq.; ozone depletion (ODE), as kg CFC-11 eq.; terrestrial acidification (TA), as kg SO₂ eq.; terrestrial ecotoxicity (TEC), as kg 1,4-DB eq. In addition, freshwater ecotoxicity (ET), as CTUe (Comparative Toxic Units, ecotoxicity), and both cancer (HTC) and non-cancer (HTnC) human toxicity are characterised through UseTox 2.12 [59], as CTUh (Comparative Toxic Units, human), and water scarcity (WSC) with AWARE 1.2C [60], as m³ world eq.

3. Results and Discussion

3.1. Implementation of the Scaling-Up Procedure

3.1.1. Throughput of *Salmorejo* at Industrial Scale and Scenarios

The processing of pasteurised *gazpacho* and *salmorejo* is mainly performed at medium or large scales, although there are also small processors manufacturing fresh *gazpacho* and *salmorejo* that are supplied to nearby stores. This study focuses on packed pasteurised *salmorejo* and the chosen industrial throughputs are 4000 L·h⁻¹ and 12,000 L·h⁻¹, corresponding to medium- and large-scale industrial production, respectively. The two industrial scales chosen were estimated according to data on *salmorejo* marketed by different firms gathered from Spanish press releases and consultation with experts in the sector revealing throughputs of the most representative brands of *gazpacho* and *salmorejo* from 2015 to 2019.

Different scenarios are developed according to the production capacity (pilot, medium scale, and large scale), the pasteurisation technology (conventional and novel RF technology) and the end-of-life of the organic waste from the process (landfill and valorisation to animal feed). Specifically, the “gate-to-gate” studied scenarios are:

- (1). Pilot, medium, or large scale, using the novel technology (RF) in the future.
- (2). Conventional pasteurisation using heat exchangers or RF technology at medium scale in the future.
- (3). Conventional heating with heat exchangers in the present or in the future, at medium scale.

The analysed “farm-to-factory-gate” scenario corresponds to:

- (4). Large scale RF technology in the future in which the organic processing waste is landfilled or valorised to animal feed.

3.1.2. Industrial Processing of Pasteurised *Salmorejo*

Recipe and Product Characterisation

The traditional homemade recipe for 1 L of *salmorejo* typical from Córdoba (Andalusia) is 1 kg of tomatoes (76.00%), 200 g of bread (15.20%), 100 g of olive oil (7.60%), 5 g of garlic (0.38%), and (0.78%) 10 g of salt. However, the commercialised packed *salmorejo* differs from these quantities and may even contain additional ingredients.

The recipe was formulated so that the mixture could be processed in the pilot plant of the Institute of Agrifood Research and Technology (IRTA Monells, Catalonia), originally designed for milk and juices, with a 200 L·h⁻¹ processing capacity. The viscosity and density of the formulation, mainly determined by the bread content, are factors limiting the transportation of the product through the tubular heat exchangers, the RF equipment, and the entire pumping capacity of the equipment. Thus, the *salmorejo* elaborated at the pilot plant contains 87.6% tomatoes (*Solanum lycopersicum*, vine variety), 5.0% olive oil, 5.0% breadcrumbs of white wheat bread, 1.5% vinegar, 0.7% salt, and 0.2% freeze-dried garlic. The measured dynamic viscosity (rheometer Haake 550 with MV1 probe) and density

(250 mL pycnometer) of the formulation are $14 \text{ mPa}\cdot\text{s}^{-1}$ ($20 \text{ }^\circ\text{C}$) and $1034 \text{ kg}\cdot\text{m}^{-3}$, respectively. Each trial produced 150 L of *salmorejo* in continuous flow.

It can be foreseen that, at industrial scale, the installed equipment also somehow determines the recipe. The fresh vegetable content, water content, and viscosity of *salmorejo* hinders microbial and enzymatic inactivation without losing sensorial and nutritional value at industrial scale. Thus, in commercial *salmorejo* and *gazpacho* it is common practice to add water in order to decrease the viscosity of the mixture and favour continuous-flow processing. Nevertheless, in this research the industrial scale *salmorejo* recipe is assumed to be the same as the pilot.

Processing Line

Since the industrial production of *salmorejo* is both well-known and well-established, as stated in Section 2.1, the upscaling was not based on the pilot plant unless data were unknown or unavailable. Indeed, the processes involved in the pilot or industrial plants observed through the abovementioned (Table 2) information sources were different (Figure 2). Then, although pilot plant unit processes differ from those at industrial level, the relevant process in the pilot was RF pasteurisation, which would support the prediction of the overall processing conditions at industrial scale. The unit processes at industrial scale include:

- Reception and washing of tomatoes, performed by aspersion or by sinking the tomatoes into water. Tomatoes can also be brushed to better clean the product surface and remove the remaining water before the subsequent process.
- Grinding, sieving, and homogenisation by using a turbo-extractor.
- Deaeration or degassing, to remove the air bubbles trapped in the product so as to avoid its oxidation.
- Pre-heating, carried out through tubular heat exchangers.
- Pasteurisation using either conventional heating with heat exchangers or RF, the innovative technology.
- Product cooling, performed through heat exchangers.
- Primary aseptic packing in multilayer packaging (bricks), secondary, and tertiary packaging.
- Cleaning-in-place every time the plant stops and/or starts.

Two additional buffer tanks are assumed at industrial scale. The first is for the fresh product, just before the thermal treatment, which feeds the heating/cooling equipment; the second is for the pasteurised product, and from it the packing machine is fed. Instead, at pilot scale, tomato reception and washing, as well as the packing of the final product, are performed manually, while grinding, sieving, and homogenisation occur in different pieces of equipment: cutter, 3 mm steel automatic sieve, and colloid mill, respectively. In addition, the product is not degassed and a second high-pressure homogenisation is carried out, just prior to the pasteurisation. At both pilot and industrial scales, the thermal treatment consists of a preheating step with a tubular heat exchanger, followed by pasteurisation in conventional heat exchangers or RF pasteuriser and a subsequent cooling step, also using tubular heat exchangers.

3.1.3. Forecast Design and Processing Conditions. Building up the Life-Cycle Inventory (LCI)

Table 3 summarises the decision making as regards the upscaling for each scenario, while the following subsections explain how these decisions were adopted and the specific data sources used.

Table 3. Aspects accounted for in the modelling of the foreground and background systems for the pilot scale and the two studied industrial scales. R: primary data from the pilot plant. PS: predictive scenario or extrapolated from real data (e.g., equipment specifications). SR: scenario ranges (maximum and minimum).

	Scaled Up Item	Pilot Scale		Medium Scale		Large Scale	
FOREGROUND	Production capacity (L·h ⁻¹)	150	R	4000	PS	12,000	PS
	Energy supply for heating	Electricity	R	Natural gas	PS	Natural gas	PS
	Boiler efficiency	80%	PS	85%	PS	95%	PS
	Nominal power of RF equipment (kW)	45	R	135 (linear regression)	PS, R	320 (linear regression)	PS
	Pasteurisation time (s)	2	PS	1.5	PS	1	PS
	Thermal energy recovery (from the pasteurised product)	Not done		85%	PS, SR	90%	PS, SR
	Organic waste generated (tomato pomace)	12%	R	8%	PS	5%	PS
	Efficiency of RF equipment	65%	R	80%	PS	80%	PS
BACKGROUND	Electricity	Forecast Spanish production mix in 2040 PS					
	Natural gas	Methane emissions: 40% reduction in 2040 PS					

Foreground System

(a) Tomato washing

Tomato washing in the pilot plant is performed manually. In the case of large industrial-scale processing, data from De Marco et al. [61] for tomato-paste production were used; specifically, in that study tomatoes are cleaned in a simple collecting channel with a water flow rate of 0.0605 kg water per kg tomato and an energy consumption of 0.00857 kWh per kg tomato. To estimate the energy and water consumption at medium scale, and according to Caduff et al. [62], the classical power law (Equation (1)) for economies of scale was used based on the throughput [63]:

$$C_{large\ scale} = C_{medium\ scale} \left(\frac{PC_{large\ scale}}{PC_{medium\ scale}} \right)^{exp} \quad (1)$$

where C stands for the water (L) or energy (kWh) consumption of the corresponding scale; PC is the processing capacity (L·h⁻¹) at the corresponding scale; and exp is the exponent, 0.6 in this case study, as it is the average value according to Wooley et al. [63].

(b) Mashing, sieving, and homogenisation

In the pilot plant, the nominal powers of the equipment (grinding, sieving, mixing, and homogenisation machines) as well as real processing times were used to calculate the energy consumption. Process conditions can be consulted in Table S1 (see Supplementary). The energy consumption of electric devices is closely related to its nominal power, and Equation (2) was used when processing time was available (from pilot plant, industrial conditions, or scientific literature):

$$E = P \cdot t \cdot \Psi \quad (2)$$

where E is the energy consumption (kWh); P is the nominal power of the equipment (kW); t the processing time (h); and Ψ is the fraction of nominal power consumed by the equipment. Empirical values for Ψ are 52% for vacuum pumps and 28% for stirrers [64]. RF equipment has an energy efficiency of 65% [65] and an improvement of up to 80% is assumed in the future scenarios.

No data on the power of turbo extractors were found in the technical sheets of machinery suppliers. Thus, at large scale, the electricity consumption of this process is calculated as the sum of the pulper, finisher, and pump unit processes used for tomato juice from *Fenco Food machinery* [66]; from the value at large scale, the consumption at medium scale is calculated using Equation (1).

The organic waste (tomato pomace) measured in the pilot plant accounts for 12% of the tomato input. Based on the Italian *National Agency for New Technologies, Energy and Sustainable Economic Development* (ENEA) [67], 5% tomato pomace is considered in the juice-extraction process at large industrial scale, whereas at medium scale, 8% is assumed. In principle, organic waste is landfilled. When recovered, according to ENEA [67], tomato pomace is mostly dried and sold for animal feed, substituting conventional fibre and protein sources [68]. Marcos et al. [69] added up 180 g of tomato pomace, which substitutes both 100 g of barley straw and 48.1 g of wheat bran (as fibre sources), and 50 g of soybean meal (as protein source). This information was used in the present study to calculate the avoided loads associated with the use of dried tomato pomace instead of barley straw, wheat bran, and soybean meal in a common ruminant's diet formulation. Table S2 (see Supplementary) shows the inventory data for organic-waste management (landfill and valorisation).

(c) Degassing

Vacuum deaeration removes the excess air trapped in the liquid food, resulting from grinding and filtering. In this way, there is less risk of fruit oxidation and potential changes in colour and flavour and, at the same time, the efficiency of the pasteurisation process grows. At large scale, the electricity consumption from ENEA [67] for fruit-juice deaeration was taken, whereas at medium scale it was calculated by using the power law (Equation (1)). In addition, *salmorejo* was pumped to the next unit process (thermal treatment) with a 26.10 kW pump and a 55.93 kW one, corresponding to medium and large scale, respectively.

(d) Thermal treatment: preheating, pasteurisation, precooling, and cooling

Pasteurisation is a mild thermal process applied to liquid foods to extend their shelf life and to ensure the safety concerns associated with both vegetative pathogens and enzymes. This thermal process affects product quality and extends the product shelf life. Pasteurised *salmorejo* kept under refrigeration has a shelf life of up to 6 months, regardless of the pasteurisation method used. Industrial *salmorejo* has a pH of around 3.8, due to the natural acidity of tomato and the addition of wine vinegar. Hence, the microbiological deterioration of *salmorejo* is unlikely, since the proliferation of moulds, yeasts, lactic acid bacteria, and other microbes is difficult under refrigeration and in acidic conditions. This type of vegetable homogenate undergoes sensorial changes mainly for non-microbiological reasons [70]. Vegetable enzymes responsible for colour and flavour alterations, such as peroxidase and polyphenol oxidase, are quite resistant to pasteurisation. Moreover, preheating treatments and the presence of residual oxygen may enhance the activities of both enzymes. The pectin methylesterase enzyme degrades pectin, producing a gradual clarification. The polygalacturonase enzyme, in turn, degrades the polygalacturonic acid from the previous reaction, also enhancing clarification. According to Dufort et al. [71], reference pasteurisation data to ensure the inactivation of a cocktail of microorganisms (*Escherichia coli*, *Salmonella enterica*, and *Listeria monocytogenes*) in acidified tomato-based foods are 71.1 °C for 30.6 s. However, this treatment may not inactivate the aforementioned enzymes; therefore, heating the *salmorejo* by RF at 80 °C for 3 s ensures an efficient inactivation of pectin methylesterase (and indirectly of polygalacturonase) and peroxidase enzymes, and an acceptable inactivation of polyphenol oxidase enzyme. Using higher temperatures and/or longer holding times scarcely improves these results and involves certain sensorial

risk, since cooked-like flavours may appear. For this reason, according to previous research on tomato processing [72,73], the pasteurisation temperature in the pilot plant was set at 80 °C (Table 4).

Table 4. Process conditions of the pasteurisation at the three scales. RF: radiofrequency. CT: conventional.

	RF and CT	RF-Technology Pasteurisation		Heat-Recovery Rates	
	Pasteurisation Temperature (°C)	ΔT RF Heating (°C)	RF Treatment Time (s)	RF Heating ² (%)	Heat Exchangers (%)
Pilot plant ¹	80	40	2	0	80
Medium scale ²	80	20	1.5	85	85
Large scale ²	80	20	1	90	85

¹ Tested conditions. ² Data provided by RF equipment manufacturer [74].

Once the pasteurisation temperature is set, the operating conditions of the equipment used at each scale must be defined. Pre-heating and precooling are carried out through tubular heat exchangers using hot and cold water as heating and cooling media, respectively. In the pilot plant, the hot water was generated with an electric boiler, whereas at industrial scale it was assumed to be a condensing boiler with natural gas. As explained in Section 3.1.2, the second homogenisation, which is conducted in specific equipment with a power of 2.2 kW in the pilot plant, is performed in the tubular exchanger used for pre-heating at industrial scale.

At both industrial scales, the heat from the pasteurised product leaving the RF equipment was recovered by the heat exchanger used for preheating, whereas in the pilot plant there is no heat recovery (Table 4). Pasteurisation using RF technology works with electricity and the RF triode equipment is cooled down either through air (pilot RF equipment scale) or by using a water loop (industrial equipment scales), in which water is chilled to below 16 °C [65]. To estimate the energy needed in the heat exchangers used for preheating the product, the mass and energy balances in the heat exchangers were carried out from measurements in the pilot plant (Table 4), such as the inlet and outlet temperatures of water (w) and product (p) (Equation (3)):

$$E = m_w c_{p_w} \Delta T_w = m_p c_{p_p} \Delta T_p \quad (3)$$

where m is the mass flow ($\text{kg}\cdot\text{h}^{-1}$); c_p is the specific heat ($\text{kJ}\cdot\text{kg}^{-1}\cdot\text{°C}^{-1}$); and ΔT is the temperature change (°C, and subindexes w and p stand for water and product, respectively).

In the case of the scaled-up processes, the same pasteurisation temperature as in the pilot plant was assumed. However, the temperature change (ΔT) and treatment times of each treatment step (preheating, pasteurisation, precooling, and cooling) were readjusted according to large RF industrial equipment requirements [65].

By considering heat recovery at the two industrial scales, the synergies between different equipment within the productive line are included. At both industrial scales, heat recovery is achieved with the hot output product, which is used to pre-heat the input product. As regards the heat-recovery rates provided by the equipment supplier [74], the best scenario (90% recovery) was used for the large scale, whereas at medium scale the worst scenario (85%) was assumed. The energy requirement was calculated according to equations for thermal energy recovery from Sanjuán et al. [66].

To scale up the RF equipment, a regression analysis was applied using empirical data from the technical specifications of different machines [65]. The resulting linear relationship was used to calculate the scaled-up nominal powers for medium ($4000\text{ L}\cdot\text{h}^{-1}$) and large industrial scales ($12,000\text{ L}\cdot\text{h}^{-1}$) (see Supplementary Table S3; see Supplementary Figure S1). The energy consumption of RF equipment was calculated by multiplying the nominal power of the equipment by the processing time taken from the pilot trials (Equation (2)).

The energy for cooling the *salmorejo* down to 4 °C was calculated as one third of the total energy needed to cause the temperature change, as calculated by Aganovic et al. [75]. The coolant mixture consists of water (65%) and propylene glycol (35%) in a close loop circuit.

In the pilot plant, pumping from thermal treatments to packing was performed with three pumps of 2.2 kW each. For medium and large scales, a 26.10 kW and 55.93 kW pump were included, respectively.

(e) Packing

The primary packaging chosen was liquid multilayer cardboard brick with a plastic lid and 1 L capacity, the most widely used in commercialised *salmorejo*. The amount of packaging was adapted from Del Borghi et al. [76] assuming that, from the primary packaging, 0.006 g per kg of product corresponds to a high density polyethylene (HDPE) lid, 96% of the secondary packaging is cardboard, and the rest is low density polyethylene (LDPE) film (see values of each packaging component in Table 5). In addition, EUR-pallets were assumed to be reused 7.5 times on average. The filling was performed with a Joytech 35 kW filler [67].

(f) Cleaning-in-place

Cleaning operations can represent a significant share of the total energy and water consumption in food processing [77]. However, few LCA studies into food production include the cleaning of the whole processing line.

According to data collected at the pilot plant, an open CIP circuit cleans the whole processing line in which basic (1% NaOH) and acid (2% HNO₃) solutions are used, and which consumes 920 L of water, takes 45 min in total, and neither water nor cleaning solutions are reused in the next CIP. The thermal energy for heating the cleaning solutions is recovered from the boiler's condensing gases.

It is not recommendable to use a pilot plant to predict the cleaning variables (time, volume of cleaning solutions, water temperature, etc.) of a CIP cleaning line at industrial scale, since the equipment used is not representative and the scaling factors and rules are unclear [78]. Therefore, a company specialising in industrial CIP [79] was consulted and the CIP was designed according to the dimensions of the equipment used in the two industrial *salmorejo* scales.

At industrial scale, four CIP lines are considered. Specifically, two CIP lines working simultaneously: one line for the turboextractor and degassing equipment and a second for the two buffer tanks. In addition, two autonomous CIP lines are used for specific equipment, namely, the pasteuriser, which comprises the tubular heat exchangers and the RF, and the packing line. The CIP protocol used in all the lines is summarised as follows: (1) rinsing with water at room temperature to remove the remaining product attached to the surface of the tubes (2–5 min); (2) cleaning with alkaline solution at 80 °C (10–30 min); (3) rinsing (1–2 min); (4) cleaning with acid solution at 70 °C (10–20 min); (5) last rinsing (3–5 min). Note that the shortest cleaning time corresponds to those CIP lines for equipment working at room temperature and the longest corresponds to the cleaning of the heat exchangers where high temperatures are reached. The first rinsing can be carried out with water from the previous rinsing, which is still quite clean. Cleaning solutions are recirculated at 2 m·s⁻¹ at least to ensure an effective dragging. Cleaning solutions are heated with the plant boiler using natural gas. Two pumps were assumed for each CIP line and another for the autonomous systems, each pump with a power of 33.56 kW for medium scale, and 55.93 kW for large scale. It must be noted that the equipment for tomato washing is not cleaned using CIP, but with foam applied with pressure guns. Wastewater generated in the CIP together with that from tomato washing is treated in a municipal wastewater treatment plant (Table 5).

Table 5. Life-cycle inventory data for 1 kg *salmorejo* at the three production scales (processing stage). CT: conventional pasteurisation; RF: radiofrequency.

Unit Process	Pilot Plant	Medium Scale	Large Scale	Type of Data, Data Sources, and Additional Comments
Tomato washing				
<i>Input</i>				
- Electricity (kWh)	-	0.0133	0.0086	Ecoinvent 3.6 modified according to data from Table S4 (see Supplementary)
- Water (kg)	NA ¹	0.0939	0.0605	Water production, deionised (Ecoinvent 3.6)
<i>Output</i>				
- Wastewater (kg)	NA ¹	0.0939	0.0605	Municipal wastewater treatment mix (GaBi DB v.9)
Mashing, sieving, and homogenisation				
<i>Input</i>				
- Electricity (kWh)	0.02201	0.0170	0.0110	Ecoinvent 3.6 modified according to data from Table S4 (see Supplementary)
<i>Outputs</i>				
- Organic waste (kg)	0.12	0.08	0.05	
Degassing	NA ¹			
<i>Input</i>				
- Electricity for deaeration (kWh)	-	0.1188	0.1080	Ecoinvent 3.6 modified according to data from Table S4 (see Supplementary)
- Electricity for pumping (kWh)	-	0.00065	0.00047	Ecoinvent 3.6 modified according to data from Table S4 (see Supplementary)
Pre-heating				
<i>Inputs</i>				
- Electricity (kWh)	0.1348	-	-	Ecoinvent 3.6 modified according to data from Table S4 (see Supplementary)
- Natural gas—RF (kWh)	-	0.0445	0.0445	Heat production, natural gas, at boiler condensing modulating < 100 kW (Ecoinvent 3.6)
- Natural gas—CT (kWh)	-	0.0795	-	Heat production, natural gas, at boiler condensing modulating < 100 kW (Ecoinvent 3.6)
- Water (kg)	1.60	0	0	Water production, deionised (Ecoinvent 3.6)
Pasteurisation				
<i>Inputs</i>				
- Natural gas—CT (kWh)		0.0215	-	Heat production, natural gas, at boiler condensing modulating < 100 kW (Ecoinvent 3.6)
- Electricity—RF (kWh)	0.000248	0.0000209	0.000011	Ecoinvent 3.6 modified according to data from Table S4 (see Supplementary)
Pre-cooling				
<i>Inputs</i>				
- Water (kg)	4.11	0	0	Water production, deionised (Ecoinvent 3.6)
<i>Outputs</i>				
- Wastewater	4.11	0	0	Municipal wastewater treatment mix (GaBi DB v9)

Table 5. Cont.

Unit Process	Pilot Plant	Medium Scale	Large Scale	Type of Data, Data Sources, and Additional Comments
Cooling				
- Electricity for cooling (kWh)	0.00594	0.01930	0.01930	Ecoinvent 3.6 modified according to data from Table S4 (see Supplementary)
- Electricity for pumping	0.0746	0.00065	0.00047	Ecoinvent 3.6 modified according to data from Table S4 (see Supplementary)
Filling and packing				
<i>Inputs</i>				
- Multilayer cardboard brick container (kg)	0.03	0.03	0.03	Liquid packaging board container production (Ecoinvent 3.6)
- Lid of container (HDPE) (kg)	0.006	0.006	0.006	Polyethylene production, high density (Ecoinvent 3.6)
- Corrugated board (kg)	0.0249	0.0249	0.0249	Corrugated board box production (Ecoinvent 3.6)
- Film (LDPE) (kg)	0.0025	0.0025	0.0025	Packaging-film production, low-density polyethylene (Ecoinvent 3.6)
- EUR-Pallet (kg)	0.0002	0.0002	0.0002	EUR-flat pallet production (Ecoinvent 3.6)
- Electricity filler (kWh)	0.018095	0.018095	0.018095	Ecoinvent 3.6 modified according to data from Table S4 (see Supplementary)
- Compressed air (m ³ /L)	0.031	0.031	0.031	Compressed air, 600 kPa gauge (Ecoinvent 3.6)
CIP cleaning				
<i>Inputs</i>				
- Electricity (kWh)	0.0108	0.0009	0.0006	Ecoinvent 3.6 modified according to data from Table S4 (see Supplementary)
- Natural gas	0	0.0087	0.003	Heat production, natural gas, at boiler condensing modulating <100 kW (Ecoinvent 3.6)
- Water	0.5907	0.1932	0.0740	Water production, deionised (Ecoinvent 3.6)
- Acid agent (nitric acid)	0.0043	0.0002	0.00006	Nitric acid production, product in 50% solution state (Ecoinvent)
- Basic agent (caustic soda)	0.022	0.004	0.0001	Sodium hydroxide, without water, in 50% solution state (Ecoinvent 3.6)
<i>Outputs</i>				
- Wastewater	0.76667	0.50119	0.24970	Municipal wastewater treatment mix (GaBi DB v.9)

¹ NA: not available.

Background Modelling

Raw-materials production

All the ingredients needed for *salmorejo* are supposed to be produced in Spain. As to the farming stage, the Ecoinvent 3.6 database was used for the production of tomato (processing grade at open fields), breadcrumbs, salt (sodium chloride), grape (for making vinegar), and onion. Onion was used as a substitute for garlic because no process for garlic is available in the database and the potential error is negligible as the mass contribution of this ingredient is only 0.2% of the total product mass. The olive-oil inventory was developed using olive-farming data from Romero-Gómez et al. [80], corresponding to the traditional, non-mechanised, rainfed, conventional production, and olive-oil processing data from Navarro et al. [81]. As to vinegar production, wine production (grape pressing and wine making) was modelled according to Borsato et al. [82], whereas data for must boiling and acetification processes were taken from Bartocci et al. [83].

Only transport to the industrial plant of those ingredients with a mass contribution of over 5% was considered. *Salmorejo* industries are mainly located in the south (Andalucía) and east (Murcia and *Comunitat Valenciana*) of Spain, and taking into account that Almeria and Jaen are the greatest producers of tomatoes and olive oil, respectively, the corresponding average transport distances to the three manufacturing locations were assumed, specifically 386 and 340 km. The tomatoes are transported in refrigerated lorries and after arriving at the processing plant they are kept in cool storage. Cull tomatoes (waste left in the fields) are assumed to be 10% of the yield [84].

Energy production

As explained in Section 2.1, as regards prospective LCAs, background processes can change in the future. Specifically, changes forecast to both the Spanish electricity mix and natural-gas production in 2020 and 2040 are accounted for. Data on the evolution of the different technologies of the Spanish electricity mix in 2020 (t_0) and 2040 (t_1) were retrieved from Navas-Anguita et al. [85]. Table S4 (see supplementary) shows the precise technological share for each of these two-time frames. Note that there are great differences between 2020 and 2040. In 2040, it is predicted that 94% of the electricity will be produced by renewable energy sources, contrasting with just 54% in 2020. This will affect the environmental results and lower impacts are expected in the electricity mix of 2040. As to potential changes in natural-gas production, the main environmental concern is not related to its combustion, but to the methane leaked at extraction from wells and transportation through pipelines. Besides being a far more potent greenhouse gas than carbon dioxide, methane can account for up to 9% of the total greenhouse gas emissions associated with the whole life-cycle of natural gas [86]. The International Energy Agency estimates that up to 40–50% of these methane emissions could be avoided without any cost [87]; thus, a 40% reduction in methane emissions was considered when predicting the natural gas used in 2040.

Using the information explained in the whole Section 3.1.3, the life-cycle inventory for *salmorejo* production was estimated; this is summarised in Table 5 together with the data sources of the inventory processes used.

3.2. Prospective LCA Results

3.2.1. Comparing Production Scales

The environmental impacts of the “gate-to-gate” prospective LCA of the RF technology at pilot, medium, and large scales were assessed and compared. The results (Table 6) show that the impacts at pilot scale, despite including fewer unit processes, are between 1% and 39% greater, depending on the impact category, than at medium and large scales, mainly due to the greater energy consumption and the change from an electric boiler in the pilot plant to natural gas at industrial scale. In this way, Pereira da Silva et al. [43] observed reductions of up to 97% of environmental impacts with the industrial upscaling with respect to the laboratory scale, in the extraction of starch from mango.

Table 6. Environmental impacts of 1 kg *salmorejo* pasteurised using novel RF technology at pilot, medium, and large scales in 2040.

		"Gate-to-Gate"				"Farm-to-Factory-Gate"	
		Pilot	Medium Scale		Large Scale	Large Scale	
		RF—Landfill	RF—Landfill	CT—Landfill	RF—Landfill	RF—Landfill	RF—Valorisation
Climate change, default, excl. biogenic carbon (kg CO ₂ eq.)	CCnB	2.55·10 ⁻¹	1.78·10 ⁻¹	1.86·10 ⁻¹	1.49·10 ⁻¹	3.96·10 ⁻¹	4.87·10 ⁻¹
Climate change, incl. biogenic carbon (kg CO ₂ eq.)	CCB	1.72·10 ⁻¹	9.40·10 ⁻²	1.01·10 ⁻¹	6.31·10 ⁻²	1.61·10 ⁻¹	2.55·10 ⁻¹
Fine particulate matter formation (kg PM _{2.5} eq.)	FPM	2.32·10 ⁻⁴	1.92·10 ⁻⁴	1.92·10 ⁻⁴	1.85·10 ⁻⁴	6.55·10 ⁻⁴	6.78·10 ⁻⁴
Fossil depletion (kg oil eq.)	FD	6.95·10 ⁻²	5.73·10 ⁻²	6.03·10 ⁻²	5.57·10 ⁻²	1.25·10 ⁻¹	1.72·10 ⁻¹
Freshwater eutrophication (kg P eq.)	FWEU	4.50·10 ⁻⁵	3.60·10 ⁻⁵	3.60·10 ⁻⁵	3.60·10 ⁻⁵	1.44·10 ⁻⁴	1.46·10 ⁻⁴
Ionising radiation (kBq Co-60 eq. to air)	IR	1.09·10 ⁻²	1.00·10 ⁻²	1.00·10 ⁻²	9.70·10 ⁻³	2.05·10 ⁻²	2.18·10 ⁻²
Land use (Annual crop eq.·y)	LU	8.90·10 ⁻²	8.80·10 ⁻²	8.80·10 ⁻²	8.80·10 ⁻²	4.08·10 ⁻¹	3.95·10 ⁻¹
Marine eutrophication (kg N eq.)	MEU	2.80·10 ⁻⁵	2.20·10 ⁻⁵	2.10·10 ⁻⁵	2.10·10 ⁻⁵	4.17·10 ⁻⁴	4.05·10 ⁻⁴
Metal depletion (kg Cu eq.)	MD	1.50·10 ⁻³	1.00·10 ⁻³	9.90·10 ⁻⁴	7.60·10 ⁻⁴	2.38·10 ⁻³	2.12·10 ⁻³
Photochemical ozone formation, ecosystems (kg NO _x eq.)	PHE	4.30·10 ⁻⁴	3.60·10 ⁻⁴	3.60·10 ⁻⁴	3.50·10 ⁻⁴	1.39·10 ⁻³	1.44·10 ⁻³
Photochemical ozone formation, human health (kg NO _x eq.)	PHH	4.10·10 ⁻⁴	3.40·10 ⁻⁴	3.40·10 ⁻⁴	3.30·10 ⁻⁴	1.36·10 ⁻³	1.41·10 ⁻³
Stratospheric ozone depletion (kg CFC-11 eq.)	ODE	7.20·10 ⁻⁷	3.00·10 ⁻⁷	3.00·10 ⁻⁷	2.90·10 ⁻⁷	1.85·10 ⁻⁶	1.83·10 ⁻⁶
Terrestrial acidification (kg SO ₂ eq.)	TA	5.40·10 ⁻⁴	4.30·10 ⁻⁴	4.30·10 ⁻⁴	4.00·10 ⁻⁴	1.98·10 ⁻³	2.05·10 ⁻³
Terrestrial ecotoxicity (kg 1,4-DB eq.)	TEC	3.90·10 ⁻¹	3.20·10 ⁻¹	3.10·10 ⁻¹	2.90·10 ⁻¹	2.05·10 ⁰	2.08·10 ⁰
Ecotoxicity (CTUe)	ET	6.30·10 ²	4.50·10 ²	4.50·10 ²	4.20·10 ²	1.92·10 ³	2.00·10 ³
Human toxicity, cancer (CTUh)	HTC	1.04·10 ⁻⁸	8.80·10 ⁻⁹	8.70·10 ⁻⁹	8.50·10 ⁻⁹	2.48·10 ⁻⁸	2.57·10 ⁻⁸
Human toxicity, non-canc. (CTUh)	HTnC	5.24·10 ⁻⁸	2.90·10 ⁻⁸	2.90·10 ⁻⁸	2.70·10 ⁻⁸	1.86·10 ⁻⁷	1.89·10 ⁻⁷
Water scarcity (m ³ world eq.)	WSC	3.97·10 ⁻¹	1.10·10 ⁻¹	1.30·10 ⁻¹	9.00·10 ⁻²	2.28·10 ⁰	2.26·10 ⁰

The greatest differences between the pilot and the medium scale correspond to CCnB (16% greater at pilot scale), CCB (29%), MD (17%), and ODE (19%). The differences between medium and large scales are evident only for CCnB (8%), CCB (17%), and MD (10%). In this regard, Aganovic et al. [75] studied the novel dielectric heating of tomato juice at pilot scale and concluded that the energy balance and environmental outputs might slightly change by increasing product capacity.

Figures 3 and 4 show the relative contribution of each unit process to the total environmental impacts of *salmorejo* production per category at pilot and medium scales. The results of the relative contribution of the unit processes to the total environmental impacts at large scale are quite similar to those at medium scale and, thus, such data are not shown.

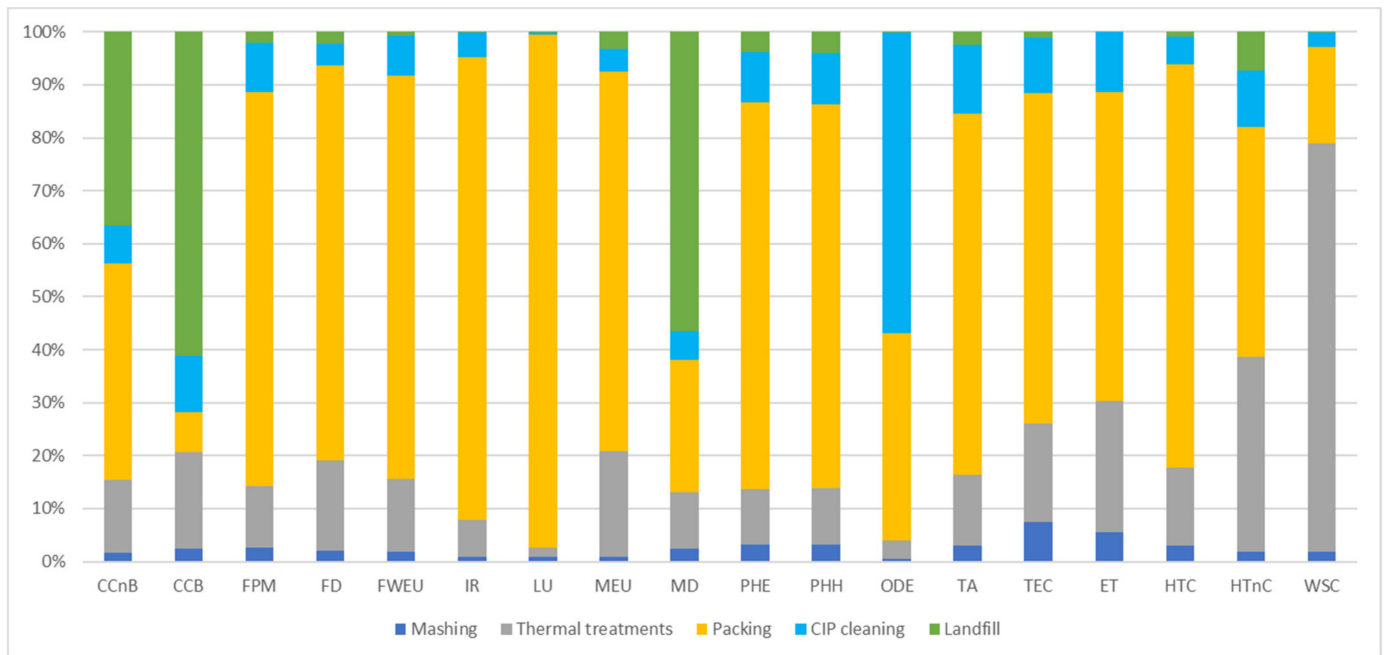


Figure 3. Contribution of the unit processes to the environmental impacts of 1 kg *salmorejo* at pilot scale using RF pasteurisation, “gate-to-gate” system boundaries, for the year 2040.

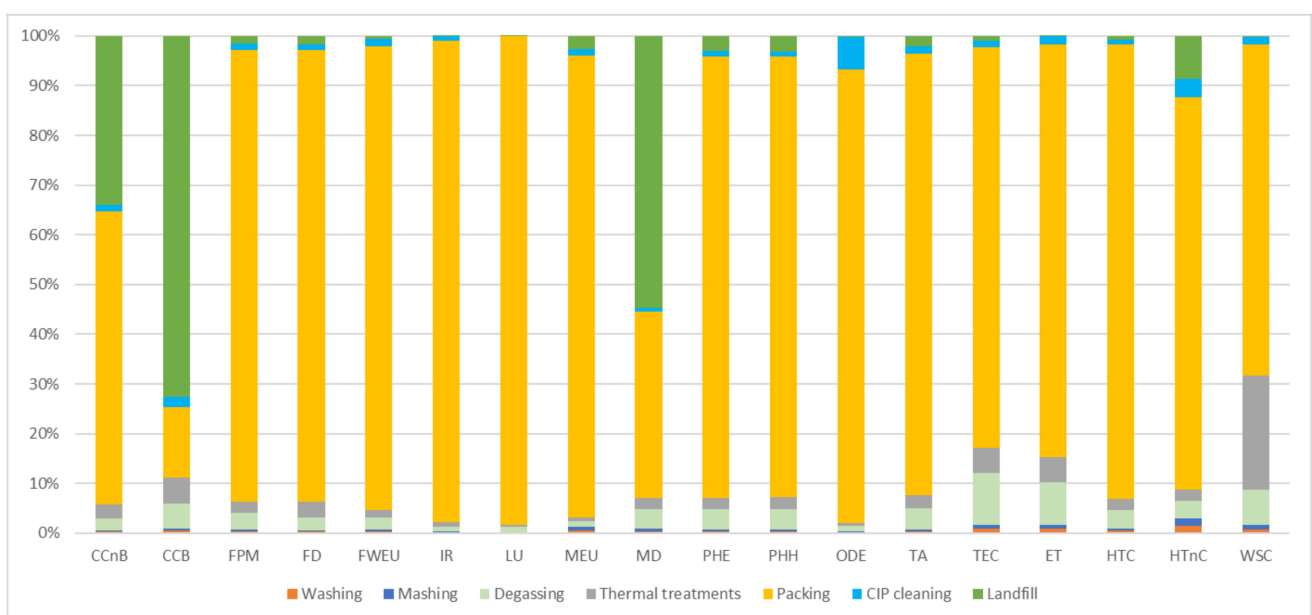


Figure 4. Contribution of the unit processes to the environmental impacts of 1 kg *salmorejo* at medium scale using RF pasteurisation, “gate-to-gate” system boundaries, for the year 2040.

At pilot scale (Figure 3), packing, thermal treatments, waste to landfill, and CIP are the processes with the greatest environmental impact. Specifically, packing contributes more than 24% to all the impact categories and up to 97% in the case of LU. Thermal treatments are relevant in almost every category, with a contribution that ranges from 3% (ODE, LU) to 39% (HTnC), except for WSC, which accounts for 78% of the total impact, because in the pilot plant the rinsing water used for the CIP is not recirculated. Organic waste landfill is critical in CCnB (39%), CCB (66%), and MD (54%). CIP contributes up to 12% to all the categories in the pilot plant except ODE, with a 56% contribution to the total impact value.

At industrial scale (Figure 4), packing and organic waste landfill are the processes with the greatest impacts. Packing predominates, with a contribution of more than 60% to almost every impact category, except CCB (8% of the total impact), WSC (18%), and MD (25%). Tomato-pomace landfill is quite relevant in CCnB (34% at medium and 24% at large scale), CCB (71% at medium and 65% at large scale), and MD (54% at medium and 43% at large scale). The contribution of thermal treatments is small (up to 5%) to every category, except WSC, which accounts for 23% and 20% of the total impact at medium and large scales, respectively. Degassing does not make a relevant contribution to any of the impact categories (up to 7%).

For every scale, the impacts of packaging are mainly a consequence of the production of the liquid multilayer cardboard brick. Tomato-pomace landfill is critical in CCnB, and CCB due to methane release, and in MD because of the landfill infrastructure. CIP is relevant in ODE mainly because of the production of nitric acid, which generates N_2O emissions. CIP is optimised at industrial scale, which explains the smaller contribution of this stage to every impact category. As thermal treatments are also improved at industrial scales, the relative importance of the rest of the unit processes increases (e.g., packing or landfill) with respect to the pilot scale.

When comparing thermal treatments (preheating, pasteurisation, and cooling) at the three scales, it can be observed that it is more than 70% greater in the pilot plant than at medium and large scales in every impact category. In the pilot plant, the energy is mainly consumed during preheating and cooling, since the energy from the pasteurised product is not recovered. However, no significant differences as regards the RF pasteurisation were found between the pilot and the industrial scales, because the RF heating parameters were similar.

De Marco et al. [61], in a “gate-to-gate” study into mashed tomato packed in liquid multilayer cardboard brick, highlight that packaging is the main contributor to most of the environmental impacts, with shares greater than 50%. In that research [61], preliminary phases, including transportation to the processing plant, washing, sorting, grinding, blanching, and refining, contribute to more than 20% of the total impact for every category assessed, whereas pasteurisation was only relevant in ODP. Del Borghi et al. [76] find that the larger the format for tomato products, the more favourable the use of liquid multilayer cardboard brick with a plastic cap as compared with tin-plated steel or glass packages. However, the latter authors do not assess plastic bottles as an alternative packaging. *Salmorejo* is usually packed either in liquid multilayer cardboard brick or in plastic bottles. In this regard, Aganovic et al. [75] proposed HDPE bottles as a better environmental alternative than polyethylene terephthalate (PET) for tomato juice.

3.2.2. Comparing RF with Conventional Pasteurisation

When comparing RF with conventional heat exchangers at medium scale in the future (year 2040), the results reveal small differences between both pasteurisation technologies (Table 6). While some impact categories are slightly lower with RF, such as FPM (1% lower), CCnB, CCB, and FD (around 5% lower), and even 15% lower in the case of WSC, others remain the same or are even worse: this is the case for MD and HTC, which are 1% greater when using RF, TEC (3% greater), and up to 5% for MEU. The small decrease in the environmental impacts can be explained, firstly, by the fact that *salmorejo* requires mild pasteurisation temperatures; therefore, thermal treatments, already improved at industrial scale (e.g., through heat recovery), are not relevant in comparison with the remaining unit

processes (e.g., packaging) and other life-cycle stages (landfill). In addition, RF technology substitutes only one part of the thermal treatment and not the previous preheating, which is mostly made by recovering the heat of the pasteurised product. Indeed, the smallest amount of energy is consumed when using RF pasteurisation, and therefore, decreasing the preheating temperature could allow preheating only using the recovered heat, decreasing the consumption of both electricity and natural gas.

Arnal et al. [88] analysed the environmental impacts of applying pulsed electric field (PEF) technology to facilitate the steam peeling of tomato and they also found that the environmental benefits were limited from an overall processing perspective; however, when assessing only the impacts of the thermo-physical peeling stage, every environmental indicator showed a decrease of between 17% and 20% when the PEF technology was used. Aganovic et al. [75] compared the environmental impacts of three pasteurisation technologies (thermal, PEF, and high-pressure) of tomato and watermelon juices, and slight differences between them were observed. In particular, slightly higher impact was observed for HPP, followed by PEF and thermal.

3.2.3. Effect of Background Energy Processes on the Results

To detect how changes in background energy processes can affect the results, “gate-to-gate” environmental impacts of conventional present-day technology (Table 7) and that of the future (Table 6) were compared for the medium industrial scale. The most significant improvement occurs in IR (37% lower in 2040), due to the greater share of renewable electricity sources predicted in 2040 versus the oil and nuclear electricity production in the present, whereas in most of the remaining impact categories, there is either no improvement or it is unremarkable (below 5%). These results highlight the significance of the share of the energy sources; impacts could shift from one category to another. Other studies [89,90] reveal similar results in which the use of renewable energy sources in the electricity background of future scenarios significantly lessens the environmental impacts.

Processes that consume a significant amount of thermal energy produced from natural gas still have great impact in related categories, such as CCB and FD, despite the 40% reduction in methane leakages accounted for in the future scenario. Indeed, García-Gusano et al. [91] state that the relative growth in the use of natural gas in the future will be a troubling source of impacts.

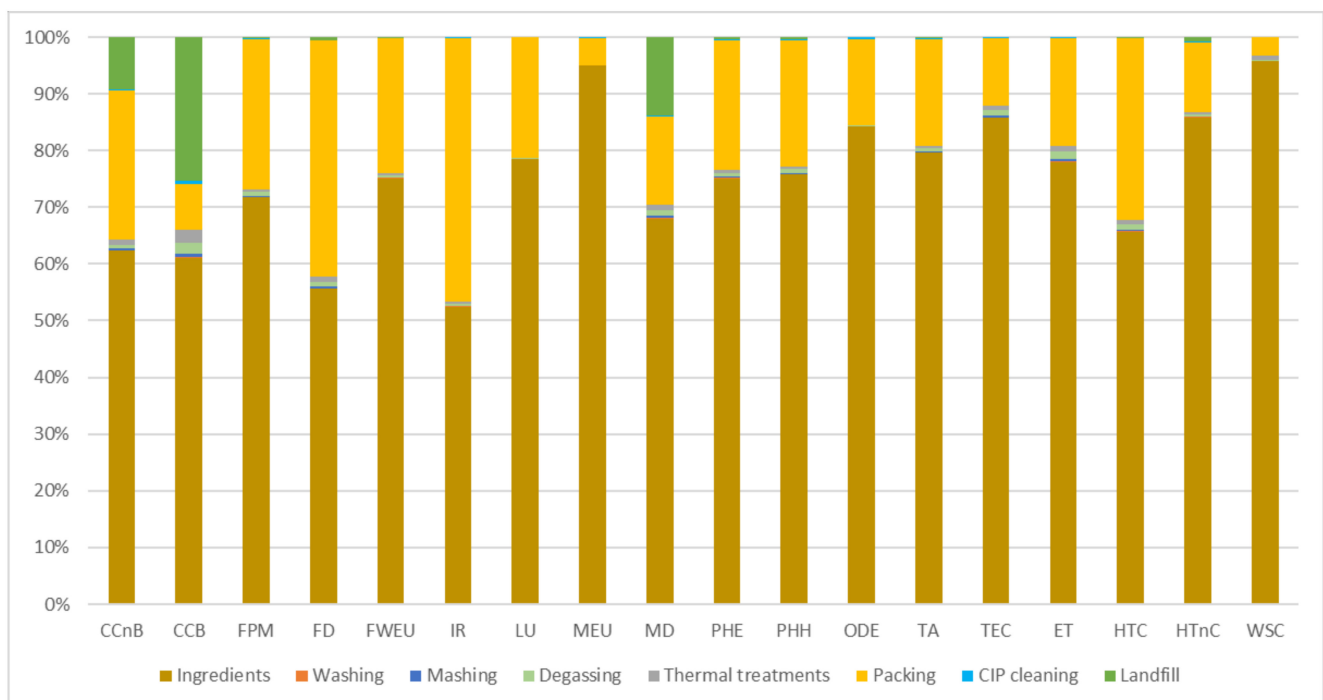
3.2.4. Expanding the Boundaries “From Farm-to-Factory-Gate” and Assessing the Valorisation of Tomato Pomace

When the system boundaries are expanded, the impact assessment results for the two waste management alternatives from large-scale production show that landfilling is preferable to valorisation in almost every category (Table 6). The only slight improvements observed are those in the valorisation scenario for LU, MEU, ODE, and WSC, which show values of under 3%, with the greatest decreases being for MD, 11% lower than in the landfilling scenario. On the other hand, the results for CCnB, CCB, and FD are, respectively, 23%, 58%, and 38% higher, due to the intensive use of the natural gas needed to dehydrate the tomato pomace. The increase in the remaining impact categories is less than 6%.

The ingredients, in particular tomato (which is the main one) growing and its refrigerated transport, make the greatest contribution to the total impact in every category, ahead of packaging and landfill (Figure 5). Similar results are obtained when organic waste is valorised, except for CCnB, CCB, and FD (Figure 6). Del Borghi et al. [76] reported similar results as regards the contribution of raw-material production and packaging for different tomato products, mainly due to the elevated energy consumption of those life-cycle stages. The importance of raw-material production (vegetables, meat, or fish) and packaging is also highlighted in the LCAs of other food products [1,61,81,88].

Table 7. Environmental impacts of the production of 1 kg *salmorejo* pasteurised using conventional technology at medium scale in 2020 (“gate-to-gate” assessment).

2020—Medium Scale		
CT—Landfill		
Climate change, default, excl. biogenic carbon (kg CO ₂ eq.)	CCnB	$1.92 \cdot 10^{-1}$
Climate change, incl. biogenic carbon (kg CO ₂ eq.)	CCB	$1.07 \cdot 10^{-1}$
Fine particulate matter formation (kg PM _{2.5} eq.)	FPM	$1.97 \cdot 10^{-4}$
Fossil depletion (kg oil eq.)	FD	$6.73 \cdot 10^{-2}$
Freshwater eutrophication (kg P eq.)	FWEU	$3.60 \cdot 10^{-5}$
Ionising radiation (kBq Co-60 eq. to air)	IR	$2.22 \cdot 10^{-2}$
Land use (Annual crop eq.·y)	LU	$8.80 \cdot 10^{-2}$
Marine eutrophication (kg N eq.)	MEU	$2.20 \cdot 10^5$
Metal depletion (kg Cu eq.)	MD	$9.70 \cdot 10^{-4}$
Photochemical ozone formation, ecosystems (kg NO _x eq.)	PHE	$3.70 \cdot 10^{-4}$
Photochemical ozone formation, human health (kg NO _x eq.)	PHH	$3.60 \cdot 10^{-4}$
Stratospheric ozone depletion (kg CFC-11 eq.)	ODE	$3.10 \cdot 10^{-7}$
Terrestrial acidification (kg SO ₂ eq.)	TA	$4.40 \cdot 10^{-4}$
Terrestrial ecotoxicity (kg 1,4-DB eq.)	TEC	$3.00 \cdot 10^{-1}$
Ecotoxicity (CTUe)	ET	$4.50 \cdot 10^2$
Human toxicity, cancer (CTUh)	HTC	$8.80 \cdot 10^{-9}$
Human toxicity, non-canc. (CTUh)	HTnC	$2.90 \cdot 10^{-8}$
Water scarcity (m ³ world equiv.)	WSC	$1.30 \cdot 10^{-1}$

**Figure 5.** Contribution of the unit processes to the environmental impacts caused by the large-scale production of 1 kg *salmorejo* using RF pasteurisation and organic waste landfill, “farm-to-factory-gate” system boundaries, for the year 2040.

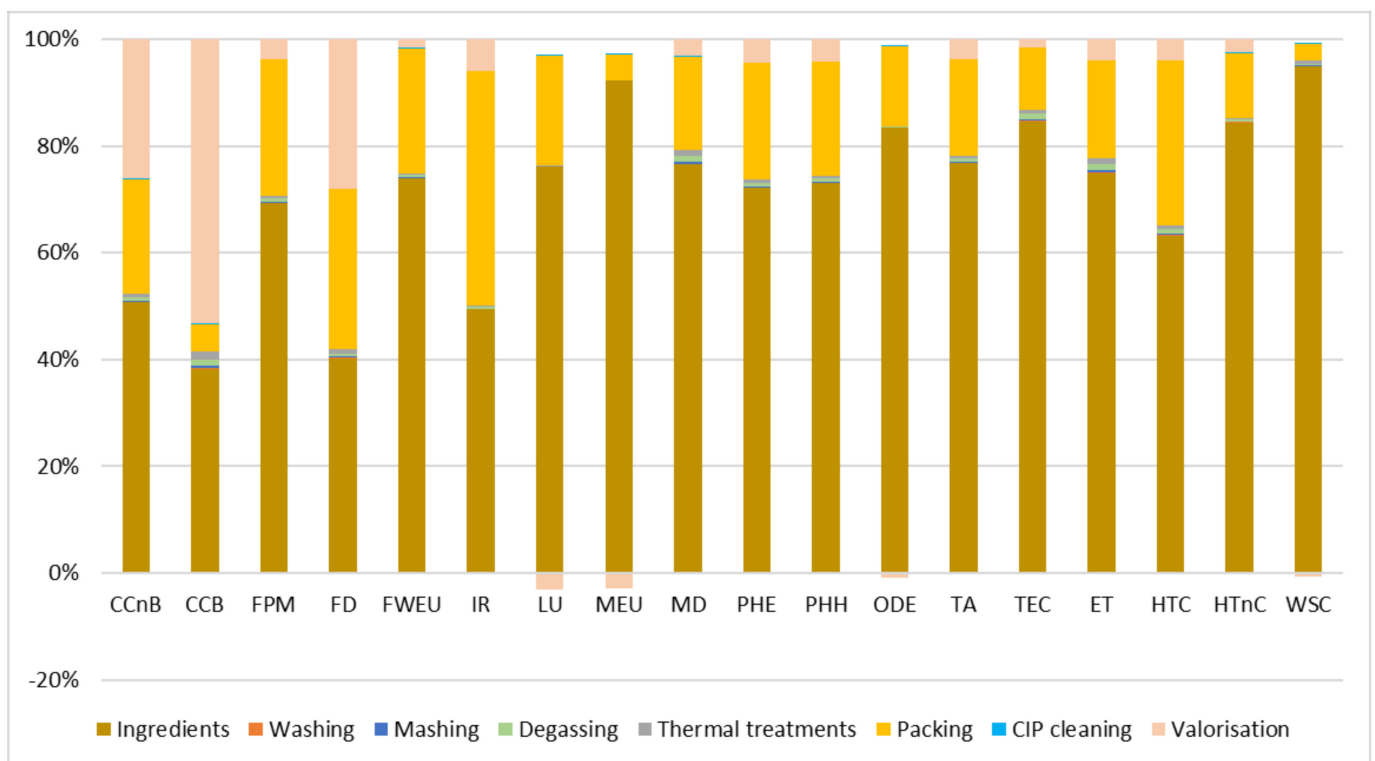


Figure 6. Contribution of the unit processes to the environmental impacts caused by the large-scale production of 1 kg *salmorejo* using RF pasteurisation, valorised organic waste, “farm-to-factory-gate” system boundaries, for the year 2040.

The valorisation of tomato pomace is critical in CCnB (26%), CCB (53%), and FD (28%), as shown in Figure 5. On the other hand, tomato-waste valorisation reveals negative impacts in LU, MEU, ODE, and WSC, due to the avoided impacts associated with growing barley straw, wheat bran, and soybean for animal feed, although these negative impacts do not offset the high values arising from the drying of the tomato pomace.

As for the landfilling scenario (Figure 5), landfill makes an important contribution to CCnB, CCB, and MD with 9%, 25%, and 14% of the total impact values, respectively. In this regard, Garofalo et al. [92] performed an LCA of whole-peeled-tomato production and highlighted waste disposal as the life-cycle stage with the highest impact. These authors [92] propose composting tomato waste as the best management option for the purposes of improving the environmental performance of the product. Other studies point to the selection of waste-treatment alternatives as crucial for reducing the environmental impact of food products [93,94]. This highlights the influence of the end-of-life stage in the environmental assessment of food products and the need to improve and develop sustainable food-waste treatment strategies.

4. Conclusions and Prospects

The environmental impact of *salmorejo* manufacturing using a novel pasteurisation technology (RF heating) was assessed through a prospective LCA. The process was scaled-up to perform a comparison between the pilot plant and two industrial scales (medium and large). In addition, the conventional medium-scale technology was compared with RF.

From the prospective “gate-to-gate” comparison between the three production scales, it can be concluded that moving from the pilot to the industrial scales reduces the environmental impact (with reductions between 1% in LU and 39% in CCB), mainly due to the energy recovery but also to a more efficient use of ingredients, water, and energy. These results are in line with previous prospective LCA studies and confirm the importance of the upscaling.

When comparing *salmorejo* manufactured using conventional and RF pasteurisation, small differences (up to 5% in every category, except 15% in WSC) are observed, because, although RF reduces the impact of the thermal treatment, this improvement is not enough to overcome the impacts of the rest of the unit processes (packing) and life-cycle stages (landfill of tomato waste). RF technology represents a part (the pasteurisation) of the total thermal treatment and preheating is still carried out using heat exchangers (needed to allow the heat recovery). In addition, CIP arises as a relevant source of impacts (up to 56% in ODE) and such results emphasise the need to include cleaning in LCAs of food processing.

Future changes in the background system, namely, by achieving a greater share of renewable sources in the electricity mix and decreasing leakage in the natural-gas distribution, can also improve the environmental profile of *salmorejo* produced using conventional methods, especially in IR (37%). Therefore, it can be concluded that both switching to novel technologies and improving energy background can have positive consequences on the environmental impacts of food products.

The “farm-to-factory-gate” assessment has shown that the agricultural production of ingredients has the greatest environmental impacts, followed by the packaging, whereas the thermal treatment makes a small contribution to the total impact (up to 2.5% in CCB and even less in the remaining categories). These results are in line with those of other LCAs of processed food. The thermal treatments of tomato products require mild pasteurisation temperatures, and thus, their contribution to the total impacts is not relevant, especially when a less energy intensive technology, such as RF heating, is used. However, although the effect of RF technology per mass unit is not relevant, if we take into account the high energy consumption of food processing globally, even small decreases can contribute to more sustainable production of food.

The valorisation of tomato pomace is not preferable to landfill, as the drying of the waste requires an intensive use of energy. Thus, other alternative tomato-pomace treatments should be further explored. For instance, the sun drying of tomato pomace, especially during the warmest months when there is greater demand for *salmorejo*, or composting, both contribute to the circular economy. Further research should also contemplate alternative packaging materials, such as HDPE or PET bottles. In addition, an uncertainty analysis can permit an assessment of how the variability of some process parameters influences the impact results, although varying the parameters of the RF can be irrelevant, as explained above.

One limitation of this study is that the data on mass and energy inputs and outputs were mostly estimated or taken from scientific literature. Data on energy and water consumption measured at existing industrial facilities could be used to validate the upscaling results. Another limitation is related to landfill, as the process used was a proxy of municipal waste and not specific for tomato pomace; therefore, the results of some impact categories could change. In addition, the inclusion of the use and end-of-life stages could change LCA results.

The prospective LCA of different scaled-up scenarios can be contemplated as a tool for environmental screening applied to food ecodesign to promote the sustainability of production, in line with SDG 12. This requires a multidisciplinary team including LCA specialists, food engineers, food technicians, and other experts involved in the development of the product, testing the pilot plants, and the design of the industrial processes.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su14031716/s1>. Table S1: Characteristics of the equipment and processing time of the pilot plant; Table S2: Inventory data for organic waste management at large scale scenario; Table S3: Processing capacity (throughput) and power of RF machines [65]; Figure S1: Linear relationship between power (P, kW) and processing capacity (PC, L·h⁻¹); Table S4: Spanish electric mix in 2020 and 2040 and inventory processes used in the prospective LCA. Data of the shares of the electricity mix have been taken from Navas-Anguita [85].

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Data Availability Statement: The data used in this study are available in the article.

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