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Opening up the Black Box: A Systematic Literature Review of Life Cycle Assessment in Alternative Food Processing Technologies

Running title:

Opening the Black Box: Reviewing LCA in Food Processing Alternatives

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Abstract

The last few decades have stood out because of the improvements made in food processing under two axes: plurality (conventional technologies co-existing with new alternatives) and sustainability (jointly with efficiency, quality and safety). This article aims at discussing how these technological developments in food processing are addressed in life cycle literature, regarding case studies in which different food processing alternatives are compared. From the examined case studies some methodological aspects were underscored to improve the application of LCA in food processing: the functional unit, system boundaries, scale and data source issues, as well as the relevance of process water and wastewater composition. Furthermore, different findings have emerged with a direct impact on future developments: the (re)thinking of technological and operational conditions (with an emphasis on cleaner production techniques), the inclusion of scale decision and consumption, and the importance of incorporating nutritional, sensorial and socio-economic dimensions to assist decision making.

Highlights

- How to evolve towards a more sustainable food system is a golden question
- Technological alternatives co-existing today are not usually included in food LCAs
- Eco-friendly processing implies rethinking technologies and operational conditions
- Up-scaling should be incorporated into prospective LCAs
- Methodological proposals to harmonize LCAs of processed food have been highlighted

Keywords: Life Cycle Assessment, Food system, Food processing, Environmental load, Sustainability, Systematic literature review

1. Introduction

Processed food represents one of the icons of contemporary society. Try, for instance, to imagine the experience of one single meal without using any processed food, ready or semi-ready for consumption. In fact, more than half the volume of food sold in the world is processed (IMAP, 2010), while it is projected that the worth of the global packaged food market will be over US$ 2.2 trillion by 2021 (Euromonitor, 2016).

This context underscores the food industry among the main industrial sectors, but also places it at the forefront in terms of its social and environmental burdens. On the one hand, the health problems attributed to nutritional imbalance, such as obesity and cardiovascular diseases, are one of the major causes of death around the world (FAO et al., 2017; Lazarides, 2012; Saguy et al., 2013). On the other hand, food production and distribution consume a considerable amount of energy, contributing significantly to global greenhouse emissions, as well as to water consumption and waste generation (Defra, 2017). This implies a double nuance as regards the corporate social responsibility of the food industry (Saguy et al., 2013): to ensure consumer health and well-being in an articulated manner with both society and natural environment in which the food system is embedded.

This should be considered under the present-day consumption trends related to food products (Silva et al., 2018), in a global economy no longer restricted to developed countries (Euromonitor, 2015). As a result, the number of food companies interested in this twofold improvement is increasing worldwide (Dijekic et al., 2018).

This has encouraged both improvements in existing technologies and in the development of new alternatives, mainly non-thermal processing technologies, such as High Hydrostatic Pressure, High-Intensity Electric Field Pulses or Supercritical Fluid Extraction. These advances are described as promising in nutritional terms (Jermann et al., 2015; Toepfl, 2006), and at the same time they are claimed to be more environmentally friendly than the conventional techniques (Lazarides, 2011).

To confirm the potential environmental yield of these processing alternatives, tools with which to assess their impact are needed nevertheless. In this sense, Life Cycle Assessment (LCA) stands out as a recognized powerful method permitting the assessment of the environmental load of food products throughout their entire life cycle, as can be confirmed by the high number of studies published.

Different reviews on LCA of agri-food products have been carried out. Most of them focus on case studies about the primary production of foods such as milk (Baldini et al., 2017), pig (MacAuliffe et al., 2016), vegetables (Bessou et al., 2013; Cerruti et al., 2014; Perrin et al., 2014) or fish

(Henriksson et al., 2012; Vázquez-Rowe et al., 2012). They aim at analysing methodological choices, detecting gaps and weaknesses and providing recommendations to harmonize the studies. Notwithstanding, fewer reviews analysing case studies on processed foods can be found, such as wine (Rugani et al., 2013), edible oils (Kathri and Hain, 2017), cheese (Finnegan et al., 2018), or a food miscellany (Roy et al., 2009), and even these ones are mostly focused in the methodological aspects of the primary production stage. In turn, Hospido et al. (2010) review the role of LCA in the development of novel food products and processes.

From that picture, a gap in the literature emerges since the coexistence of technological alternatives arising from recent developments is marginalized in most of the existing LCA literature. Taking into account the importance of the food processing sector and the technological improvements developed in the last years, the main purpose of this article is to discuss how technological developments in food processing are addressed in life cycle literature, regarding case studies on LCA and carbon footprint (CFP) in which different food processing alternatives are compared. To this end, a systematic literature review was conducted, exploring the methodological challenges involved when applying LCA/CFP to processed food in order to provide recommendations to harmonize future practices. Furthermore, by analysing the main findings of these comparative studies, this review also aims at highlighting some challenges that must be faced to improve the sustainability assessment of food processing.

2. Systematic Review Strategy and Selection of LCA in Food Processing Studies

Over recent years, there has been a proliferation of new approaches with which to increase the scientific rigor of the knowledge-mining process such as systematic literature review (Denyer and Tranfield, 2009; UNEP/ SETAC, 2013), in which the high comparative power attributed to it comes from its essence. A method of reviewing existing research studies in an organized, systematic and transparent way, in order to summarize all the existing information about the phenomenon of interest, at the same time that the personal biases of the researchers are better controlled, and the scientific validity is improved (Denyer and Tranfield, 2009). For that reason, it is expected to pre-determine, to follow and to share a clear protocol, designed according to the main objectives of the research, detailing the strategy of knowledge mining pursued in the investigation.

In this study, the scope was case studies where alternative food processing technologies where compared. Web of Science, Scopus and Google Scholar databases were explored due to their credibility and scientific coverage. The entire collection of the respective databases was consulted considering records registered until September 2018.

The search strategy was planned following three main phases, as shown in Figure 1 (Clune, Crossin and Verghese, 2017, Denyer and Tranfield, 2009, and Moher et al., 2015). Identification, followed by the Screening and eligibility of the studies to ensure their alignment with the scope of the systematic review, ending up with a Final analysis, based on a quantitative and qualitative assessment of the content of the selected records.

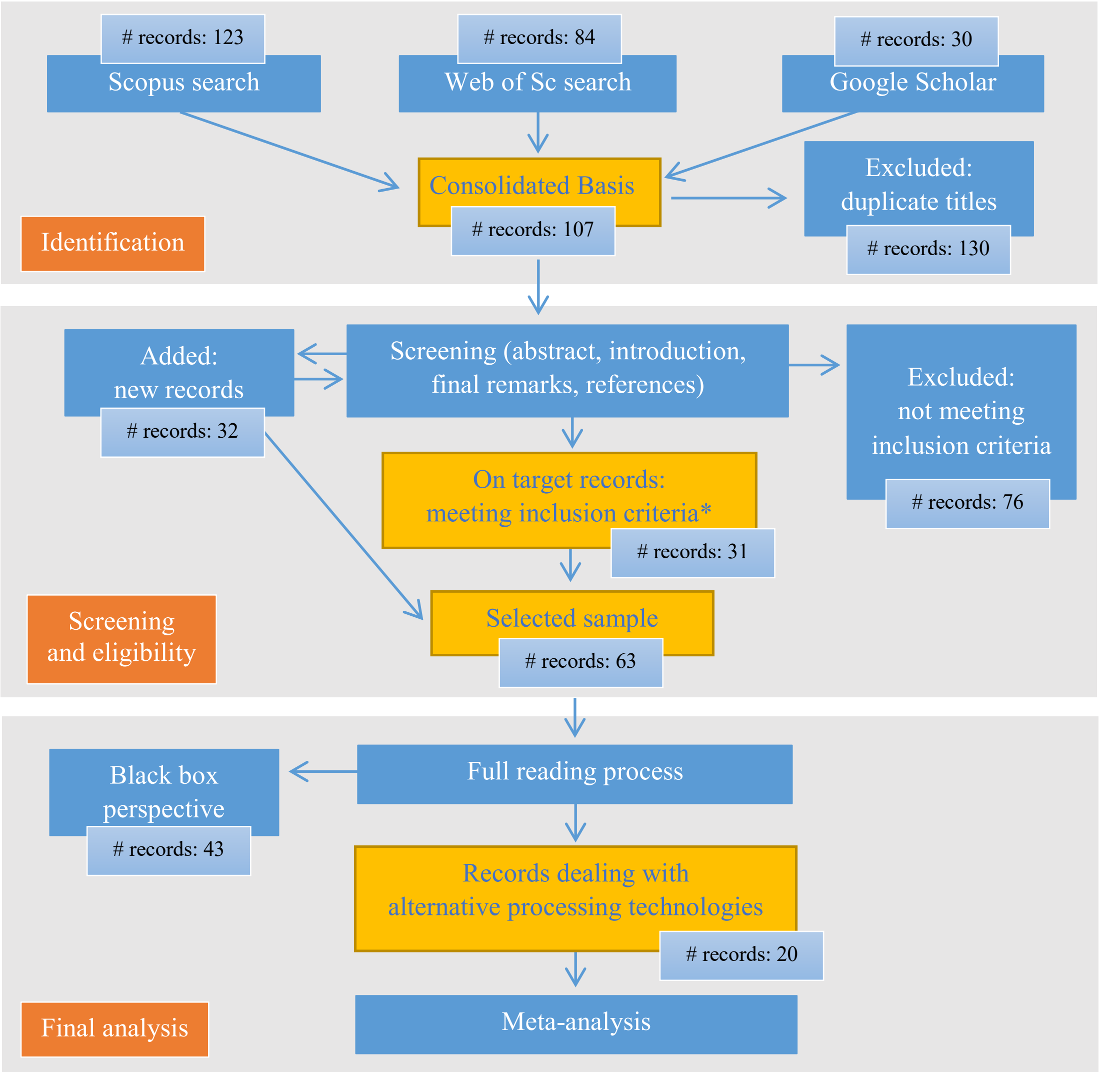

Figure 1. Systematic review strategy. Based on Clune, Crossin and Verghese (2017), Denyer and Tranfield (2009) and Moher et al. (2015). *LCA studies on food processing.

From that three databases, articles, articles-in-press, books, book chapters and conference articles were screened by a six-filter strategy, taking advantage of the tools provided by the respective databases. Initially, six terms (life cycle assessment, food, production, processing, technology, and preservation) were combined, focusing their identification either in titles, key words or in the abstracts.

As shown in Table 1, from the total results found for *life cycle assessment*, a second filter was applied, by using the terms in quotation marks to guarantee the accuracy of the search, in this way, excluding contaminations by occurrences of synonyms of the terms or other variations, translations, abbreviations, plurals, etc.

Table 1. Sequence of filters and results of the systematic review strategy.

Filters / Databases	**Life Cycle Assessment**	**"Life Cycle Assessment"**	**"Life Cycle Assessment" and food**	**"Life Cycle Assessment" W/10; Near/10 food; In the title**	**Product* or Process* or Technolog* or Preserv***	**Not waste, Not biofuel*, Not pack***	**Consolidated base**
	1st filter	**2nd filter**	**3rd filter**	**4th filter[1]**	**5th filter**	**6th filter**	
Scopus	37,018	18,489	1,479	258	238	123	**107**
Web of Sc.	25,934	16,702	1,516	192	173	84	
Google Sch.	276,00	171,000	38,100	221	38	30	

Source: Based on records from Scopus, Web of Science and Google Scholar databases, completed in September 2018. [1]The 4th filter refers to proximity operators offered by the databases. Scopus (w/10) and Web of Science (near/10) by controlling the distance between the main term of interest ("Life Cycle Assessment") and a specific complement (food processing). Google Scholar, by searching for a specific term or words combination in the title ("Life Cycle Assessment" and food).

Next, a third filter was used to ensure both the adherence and relevance to the food field, by using "life cycle assessment" AND food. The fourth filter consisted of the application of the proximity operators offered by Scopus, Web of Science and Google Scholar. This allowed to control the distance between "life cycle assessment" AND food in the records selected. The idea was to identify records in which "food" was quite closed of the title, or being part of it. The fifth filter was the Boolean operator asterisk, used as a way to broaden the search by finding words that start with the same letters, retrieving any variations of a term. Finally, a sixth filter was employed to eliminate waste, biofuel and packing (and their variations) approaches among the selected records. The selected documents were grouped and duplicate records were subsequently removed. The result of the Identification phase was a consolidated base of 107 records (Figure 1).

In the second phase, Screening and eligibility, the selected records were revised to ensure the adherence of the records to the scope of the review. It was observed that many LCA studies use the terminology "food processing" but do not properly deal with food processing technologies. This was the case of 71% of the consolidated basis, *i.e.* 76 records out of 107 in the sample (Figure 1). A possible interpretation could be that the terms "food product", "food processing" and "processed food", including their variations, are often used as a strategy to sensitize the reader (a way to increase the audience), whereas the essence of the discussion often remains attached to the farming stage. It is important to highlight as well that food production involves a complex system, from the farm level, through the industrial transformation, distribution and consumption to waste management, which may also contribute to this lack of accuracy in the terminology used in the scientific documents.

Additional records were found by screening the text and the reference list of each document; as well as by monitoring of new publications in the area. As a result, 32 new documents were identified, culminating in a sample of 63 studies into LCA applied to food processing (Figure 1).

Finally, in the last phase of the search strategy, these 63 papers were analysed in-depth following a full reading process, looking for those in which different processing techniques are compared. It was observed that when LCA studies properly deal with food processing technologies, a black box perspective prevails. This means that a detailed analysis considering the contribution of each process step to the whole process is not carried out, with the consequent lack of transparency and reproducibility (Sanjuan et al., 2014; Walker et al., 2018). 43 out of 63 LCA studies into food processing technology (i.e. 68%) were discarded because either a black box perspective prevailed or alternative processing techniques were not compared, resulting in a final sample of 20 records, that is, 32% of the selected sample (Figure 1).

3. Selected LCA studies on Alternatives in Food Processing Technologies

As regards the purpose, the 20 reviewed studies can be classified into three: those which compare alternative operational conditions, another comparing technological approaches, and a third group in which the effect of production scale is analysed. Table 2 presents a classification proposal for these 20 papers according to their typology and emphasis.

The discussion on the operational conditions is present in four studies (20% of the reviewed studies). Take for instance, Sanjuan et al. (2011) who assess different technical and cleaner production criteria in order to determine the most eco-efficient techniques for cheese production. While Zhou et al. (2017a) calculate the CFP of cooling systems for cooked rice.

The second group discusses the environmental impact of variations in the technological approach and encompasses 13 studies (65%), which, in turn, could be grouped into two. A first category, covering four studies (20%), considers the environmental impact of emerging technologies complementing conventional food processing methods. For instance, Krokida et al. (2016) compare the conventional production of skimmed milk powder with the inclusion of reverse osmosis. While Kyriakopoulou et al. (2015) compare conventional techniques for β-carotene extraction with and without microwave or ultrasounds. The second category, which comprises nine papers (45%), contrasts different technologies, such as pulsed electric fields (PEF) and high pressure processing (HPP) for juice pasteurisation (Aganovic et al., 2017; Davis et al., 2010), or deep-freezing, drying assisted by infrared radiation and ohmic aseptic treatments in the production of semi-finished apricots (De Marco and Iannone, 2017),

The remaining three studies (15%), referring to the third group, analyse the environmental burdens of different production scales, which generally affect to the processing techniques. Davis and Sonneson (2008) and Schmidt Rivera et al. (2014) compare homemade and industrially manufactured dishes. Meanwhile, Calderón et al. (2018) compare four different production scales for the same dish: canned and consumed at home, catering company, restaurant, and homemade cooking.

The following section addresses these 20 LCA studies as regards methodological terms (LCA typology, goal and scope, functional unit, system boundaries and impact categories targeted by the analysis).

4. Key Methodological Issues on LCA of Alternatives in Food Processing Technologies

4.1. Type of LCA

LCA studies are typically classified as attributional or consequential. Most LCA studies apply an attributional perspective (A-LCA), referring to a steady state of the internal flows of a specific production system. On the other hand, the consequential LCA (C-LCA) aims to evaluate the environmental consequences of a decision, normally a change in the demand of the product to be investigated, trying to overcome the limitations of the attributional approach when quantifying the indirect effects of that decision. Other classifications can be found in the literature. Specifically, Sandén et al. (2005) classify LCA based on three dimensions, namely responsibility, time and technical generality. According to the time dimension, a prospective LCA is looking forward at future environmental impact. Following this classification, Hospido et al. (2010) recommend a prospective A-LCA as the most suitable approach with which to evaluate novel systems (product or technology) at a future steady time. Recently, Arvidsson et al. (2017) define prospective LCA as those studies of emerging technologies in early development stages, when there are still opportunities to use environmental guidance for major alterations. It must be noted that in a recent paper Guinée et al. (2018) discuss the emergence of other modes of LCA, among them prospective LCA. Those authors state that A-LCA focuses on modelling a situation as it is, either in the past, present or future, but without any changes, and recommend to include the remaining types of LCA in a group called explorative LCA.

Table 2. Processing variants considered in LCA and CFP studies into alternative food processing technologies.

Typology		**Processes compared**	**References**	**Sector / Product**
Operational Conditions (OC)		Alternative parboiling processes	Roy *et al.* (2007)	Rice
		Degree of milling	Roy *et al.* (2009)	Rice
		Cleaning and degree of automation	Sanjuán *et al.* (2011)	Dairy (cheese)
		Different cooling methods for cooked rice	Zhou *et al.* (2017a)	Rice
Technological Approach	*Emerging technologies assisting conventional ones*	Conventional production of skimmed milk powder vs. including a RO[1] pretreatment	Krokida *et al.* (2016)	Dairy (milk powder)
		Extraction with solvents vs., ultrasound or ,microwave assisted	Kyriakopoulou *et al.* (2015)	β-carotene (apple a algae)
		Freeze drying: conventional vs. assisted with osmotic dehydration pretreatment	Prosapio *et al.* (2017)	Fruit (strawberries)
		Freezing (conventional vs. ultrasound assisted)	Xu *et al.* (2016)	Water
	Contrasting different technologies	Conventional (thermal) vs. alternative technologies: PEF[2], and HPP[3]	Aganovic *et al.* (2017)	Juice (tomato and watermelon)
		Mild thermal pasteurization vs. PEF[2] and HPP[3]	Davis *et al.* (2010)	Juice (carrot)
		Milk powders vs. Milk concentrates	Depping *et al.* (2017)	Dairy (milk)
		Drying: drum vs. multistage drying	De Marco *et al.* (2015)	Fruits (apple)
		Deep-freezing, drying assisted by infrared radiation, and ohmic aseptic treatment	De Marco and Iannone (2017)	Fruits (apricot)
		Chilling vs. superchilling	Hoang *et al.* (2016)	Fish (salmon)
		Preservation methods: autoclave pasteurization, microwaves, HPP[3] and modified atmosphere packaging	Pardo and Zufía (2012)	Meals
		Oil extraction: hexane vs. supercritical CO2	Li *et al.* (2006)	Oil (soybean)
		Ultra-High Pressure Homogenisation vs. conventional UHT[4] processing	Valsasina *et al.* (2016)	Dairy (milk)
Production scale		Domestic vs. industrial	Calderón *et al.* (2018)	Meals
			Schmidt Rivera *et al.* (2014)	
			Sonesson *et al.* (2005)	

RO[1]: reverse osmosis; PEF[2]: Pulsed Electric Fields; HPP[3]: High Pressure Processing; UHT[4]: Ultra High Temperature.

From the sample of studies reviewed, only Valsasina et al. (2017) conducted both attributional and consequential analyses. As to the consequential one, the aim was to assess the possibility of using UHPH sterilised milk for fresh cheese production, since its shelf life is longer than that of conventional UHT milk. Therefore, a system expansion accounting for the avoided production of fresh cheese was investigated. Additionally, Schmidt Rivera et al. (2014) designed a scenario which considered the displacement of animal feed as a consequence of upgrading processing waste as fodder through system expansion, which can thus be considered a C-LCA. The remaining 19 studies can be classified as A-LCA, that is, they intend to make a snapshot of the methodologies in order to detect hot spots of the technological innovations, without taking into account further consequences of its implementation, such as rebound effects.

On the other hand, only Aganovic et al. (2017) and Pardo and Zufía (2012) classify their respective studies as prospective LCA, whereas Sonesson et al. (2005) recommend to make prospective studies to find processing systems that are better than today's. Taking into account Arvidsson et al.'s (2017) definition of a prospective LCA, many of the analysed studies can be included in that category, since they analyse technologies in an early phase of development, such as Davis et al. (2010), and even on laboratory scale (Zhou et al., 2017a, Xu et al., 2016).

4.2. System boundaries

Mapping the process and setting the boundaries are important steps to clarify parts of the food system analysed (Djekic et al., 2017). Assessing the whole product life cycle (*from cradle- to-grave, or cradle-to-consumer*) allows the magnitude of the environmental impact to be quantified, as does the contribution of the processing stage to the total impact. Nevertheless, an analysis restricted to processing (*from farm gate-to-factory gate*) may be an interesting approach if the LCA is intended for technological comparisons, provided that the technologies to be compared ensure the same ratio of agricultural raw material input to food product output (Arcand et al., 2012). Along these lines, Hospido et al. (2010) suggest, for comparative studies, including only the parts of the system that are affected (and, therefore, show differences) by the change.

This perspective helps us to understand that ten of the analysed studies (50% of the revised studies) conduct a *farm gate-to-factory gate* analysis (Table 3). Of those, Aganovic et al. (2017) and de Marco et al. (2015) additionally considered *farm-to-factory gate* and *gate-to-grave* system boundaries, respectively. A full *cradle-to-grave* analysis is performed in six of the reviewed studies (30%) as can be seen in Table 3. The remaining studies adopt cut-off variations justified by their respective main goal and scope. For instance, *cradle-to-factory gate* is employed by De

Marco et al. (2015) and Kyriakopoulou et al. (2015), while the consumer is considered by Calderón et al. (2018) (*factory gate-to-consumer*), and Roy et al. (2009) (*cradle-to-consumer*).

The *farm gate-to-factory gate* boundaries allow eliciting environmental information related to the sphere of influence of the food processor. However, in that case, the displacement of environmental loads to other life cycle stages, such as waste generation and management, cannot be quantified.

In turn, the inclusion of capital goods in the system boundaries is a controversial issue. Considered as an explicit part of the product system in ISO standards (Finkbeiner et al., 2006, ISO14040:2006a,b), a common problem seems to be the lack of information about the environmental burden of producing and maintaining processing infrastructure (Davis et al., 2010, Xu et al., 2016).

Of the reviewed papers, only Davis et al. (2010), Deeping et al. (2017), Kyriakopoulou et al. (2015), Sanjuan et al. (2011), Xu et al. (2016), and Zhou et al. (2017a) evaluated the possibility of including capital goods. Input-output LCA was used to estimate the overall environmental impacts of capital goods in Sanjuan et al. (2011), Xu et al. (2016) and Zhou et al. (2017a). Deeping et al. (2017) took the production and transport of raw materials as a proxy for the inventory of these goods and depreciated their environmental impacts linearly over their lifetime. On the other hand, Kyriakopoulou et al. (2015) took site levelling works and land occupation of capital infrastructure into consideration. Davis et al. (2010) excluded the production of capital goods due to lack of data, since if the life span and capacities of the equipment are taken into account, the burden split per manufactured unit (e.g., per litre of juice) is expected to be very small.

4.3. Functional unit

The definition of the functional unit (FU) is a critical issue for all LCAs, and especially in food, where different proposals can be found in the literature (Martínez-Blanco et al., 2010; Tyszler et al., 2016; Rice et al., 2018). Hospido (2010) and Weidema (2003) recommend the classification of properties as the starting point for the correct definition of the products under comparison. Nevertheless, food quality is a complex issue ranging from the organoleptic properties (e.g. texture or colour) to the nutrient content (*i.e.*, macronutrients, such as lipids or carbohydrates; micronutrients, such as vitamins or minerals and specific compounds, such as antioxidants) and safety aspects (e.g. the presence of pathogens). Furthermore, these properties can be substantially affected by the processing technologies. Hence, given that this review focuses on process comparison, the FU must then ensure that the compared processes yield products of the same quality.

Table 3. LCA type, function unit and system boundaries choices of the LCA and CFP selected studies.

Typology	Authors	Type of LCA	Functional unit	System boundaries
Operational Conditions	Roy *et al.* (2007)	ALCA	1 ton rice	Gate-to-gate
	Roy *et al.* (2009)	ALCA	1 kg final product or 1 MJ energy supplied by the final product	Cradle-to-grave
	Sanjuan *et al.* (2011)	ALCA	1 kg cheese ripened over 105 days	Gate-to-gate
	Zhou *et al.* (2017)	ALCA	0.02 kg cooked rice in a plastic meal box	Gate-to-gate
Technological Approach *Emerging technologies assisting conventional ones*	Krokida *et al.* (2016)	ALCA	1 kg of skimmed milk powder unpacked	Gate-to-gate
	Kyriakopoulou *et al.* (2015)	ALCA	1 kg β-carotene extract	Cradle-to-grave
	Prosapio *et al.* (2017)	ALCA	450 g strawberries	Cradle-to-grave
	Xu *et al.* (2016)	ALCA	1 mL deionized water frozen from 4 to −10 °C	Gate-to-gate
Technological Approach *Contrasting different technologies*	Aganovic *et al.* (2017)	ALCA.	1 kg pasteurized juice, PET bottled, and ready for sale	Gate-to-gate and farm to factory gate
	Davis *et al.* (2010)	ALCA	1 L carrot juice at the point of sale	Cradle-to retailer
	Depping *et al.* (2017)	ALCA	1 kg skim-milk concentrate ready to be further processed at the customer stage with a DMC of 12.5%, reconstituted/diluted in skim milk (FU1), 30%, reconstituted/diluted in skim milk (FU2) or water (FU4), 35%, reconstituted/diluted in skim milk (FU3) or water (FU5).	Cradle-to-grave
	De Marco *et al.* (2015)	ALCA	3 kg weight apple powder (95 ºBrix) package	Gate-to gate and gate-to-grave
	De Marco and Iannone (2017)	ALCA	1 kg on dry basis of semi-finished apricots produced and packaged	Gate-to-gate
	Hoang *et al.* (2016)	ALCA	1 kg salmon at the end of the cold chain (at domestic fridge)	Cradle-to-consumer
	Pardo and Zufía (2012)	ALCA	1 kg pre-cooked dish of fish and vegetables processed to achieve a threshold 30 days shelf life period	Cradle-to-grave
	Li *et al.* (2006)	ALCA	1 ton of soybean oil production per hour	Gate-to-gate
	Valsasina *et al.* (2017)	ALCA CLCA	1000 L of raw milk to reach commercial sterility	Gate-to-gate
Production scale	Calderón *et al.* (2018)	ALCA	1 kg finished hot product ready to be consumed	Gate-to-consumer
	Schmidt Rivera *et al.* (2014)	ALCA	0.360 kg meal for one person	Cradle-to-grave
	Sonesson et al (2005)	ALCA	1 meal for one person ready for eating	Cradle-to-grave

In Table 3, the FUs of all the reviewed studies are summarised. Obviously, all the reviewed papers consider that the function of food processing is producing food. Hence, the FU is expressed as mass (kg) or volume (L) of the raw material or final product, that is, the processed product. It can also be observed that, for many of the examined papers, the FU covers a quality aspect of the final product related with the processes being evaluated. This is especially true for the studies in which different technological approaches are compared. For instance, Aganovic et al. (2017) compare pasteurisation methods for fruit juices and the level of microbial inactivation to be attained is, thus, included in the FU definition. In turn, De Marco et al. (2015) compare dehydration systems for apple powder and the FU considers the sugar content of the dehydrated products (95 ºBrix). While Depping et al. (2017) define five FUs. Those authors aim at comparing the substitution of skim milk powder by skim milk concentrates as ingredients for processed foods, since milk powder is more energy intensive. Consequently, they define five FUs as 1 kg skim milk concentrate ready to be further processed with specific dry matter contents according to the concentrations needed for the subsequent applications (yogurt, ice cream, etc.). Only Valsasina et al. (2017) use the mass of raw material to denote the technology's function of providing safe drinkable milk (defined as the processing of 1000 litres of raw milk to reach commercial sterility). As can be observed in Table 3, the FUs of the studies comparing changes in the operational conditions or the use of emerging technologies assisting conventional ones do not consider the quality aspect. This can be related to the fact that those shifts in the analysed processes are mostly aiming at improving their environmental performance (e.g. by reducing dehydration time, changing solvent or cleaning agents) and substantial changes in the characteristics of the final product are not expected.

As to the studies assessing the production of a dish on different production scales, it must be borne in mind that the function of the dish can be different in each case, both concerning to the organoleptic properties and the shelf life, especially on the factory level, when the product exhibits a longer shelf life. However, as pointed by Sonesson et al. (2005), many consumers consider a ready-to-eat meal to be equivalent with a corresponding home prepared meal. Therefore, the chosen FU (1 kg of ready-to-eat product) allows the objective of the study to be reached without considering any other quality attribute.

4.4. Inventory analysis: sources and data quality

As a rule, data describing the foreground system are collected from the specific process; they can be directly measured, estimated, or elicited from interviews with stakeholders. This is the case of most of the conventional processes analysed.

For instance, as presented in Table 4, Depping (2017) gathered the data for the conventional process from technical visits to processing plants. In the same way, Pardo and Zufía (2012) conducted technical visits using questionnaires, interviews and internal reports, which represent average data from a typical working day. On the other hand, Roy et al. (2007) and Hoang et al. (2016) based their LCAs of already existing technologies on literature data.

However, applying LCA at early product development stages is challenging due to the lack of foreground inventory data, mainly those concerning emerging food technologies. A compound strategy is usually employed, mixing data obtained directly (from laboratory or pilot experiments) and indirectly (e.g. interviews with stakeholders, patents or literature data). Pilot plant data were used in three studies (15% of the reviewed sample). Pardo and Zufía (2012) collected data on alternative preservation methods from personal communication with technology suppliers together with the equipment specifications and experiments at a pilot plant. Aganovic et al. (2017) collected primary data for the thermal and PEF processes from respective continuous pilot scale units, whereas a small industrial scale unit was used for the HP treatment. Due to its batch nature, the HP process was taken as a starting point for the definition of the production capacity.

Laboratory scale experiments were the basis for the data in two of the reviewed studies (10%), namely Kyriakopoulou et al. (2015), and Xu et al. (2016). Interesting to highlight Kyriakopoulou et al. (2015) considered a potential upscale regarding the solvents' recycling and reuse, although they do not provide data on other scaling aspects (e.g. energy consumption of industrial equipment). It must be noted that the magnitude of the impacts on lab scale may be far from that of the real processes. Nevertheless, as Sampaio et al. (2017) state, results from lab scale experiments may be useful for choosing alternative materials and techniques in the early stages of product development and provide the basis for process design in the pilot stage.

Data used by Li et al. (2006) for the conventional solvent and alternative supercritical CO_2 extraction of soybean oil were based on mass and energy balance calculation. Simulation was used as data source for the three scales compared by Sonesson et al. (2005).

As can be observed in Table 4, for both already existing and emerging technologies, background data are mostly obtained from LCA databases, mainly Ecoinvent, and published studies.

Table 4. Data sources (*Fd*: foreground data, *Bd*: background data) and life cycle impact assessment (LCIA) method of the LCA and CFP selected studies.

Typology	**Authors**	**Data sources_**	**LCIA method**
Operational conditions	Roy *et al.* (2007)	*Fd*: literature *Bd*: n.s.[1]	Energy consumption (literature) and CFP (emissions factors from literature)
	Roy *et al.* (2009)	*Fd*: manufacturer (milling process), laboratory (cooking process) *Bd*: literature	Only inventory analysis
	Sanjuan *et al.* (2011)	*Fd*: manufacturer *Bd*: GaBi 4	EDIP
	Zhou *et al.* (2017)	*Fd*: Experimental data using industrial equipments *Bd*: literature	IPCC
Technological approach *Emerging technologies assisting conventional ones*	Krokida *et al.* (2016)	*Fd*: manufacturer and literature data *Bd*: Ecoinvent and GaBi 6	CML
	Kyriakopoulou *et al.* (2015)	*Bd*: Ecoinvent v2.0	CML
	Prosapio *et al.* (2017)	*Fd*: manufacturer (conventional processing) and experimental data (osmotic pretreatment). *Bd*: literature	ReCiPe
	Xu *et al.* (2016)	*Fd*: Laboratory scale *Bd*: literature and stakeholders	IPCC
Technological approach *Contrasting different technologies*	Aganovic *et al.* (2017)	*Fd*: Pilot scale. *Bd*: literature and Ecoinvent v3.2	IMPACT 2002+
	Davis *et al.* (2010)	*Fd*: manufacturer (conventional processing), literature and communications with experts (alternative technologies). *Bd*: Ecoinvent v2.0.	CML
	Depping *et al.* (2017)	*Fd*: manufacturer *Bd*: Ecoinvent v3.1	CML
	De Marco *et al.* (2015)	*Fd*: manufacturer *Bd*: Ecoinvent v3.1	IMPACT 2002+
	De Marco and Iannone (2017)	*Fd*: processing company *Bd*: Ecoinvent v3.1	ReCiPe
	Hoang *et al.* (2016)	Fd: literature Bd: Ecoinvent v3	CML
	Pardo and Zufía (2012)	*Fd*: manufacturers (data for conventional processes). Trials at pilot scale (alternative processes) *Bd*: Ecoinvent v2.0	ReCiPe
	Li *et al.* (2006)	*Fd*: based on mass and energy balance calculations. *Bd*: n.s.[1]	n.s.[1]
	Valsasina *et al.* (2017)	*Fd*: Pilot scale. *Bd*: Ecoinvent v3	ReCiPe
Production scale	Calderón *et al.* (2018)	*Fd*: manufacturers and house cook. *Bd*: Ecoinvent v2, LCA Food DK, BUWAL250, IDEMAT 2001, ETH-ESU 96.	CML Eco-indicator 99
	Schmidt Rivera *et al.* (2014)	*Fd*: industrial processing. *Bd*: Ecoinvent v2	CML
	Sonesson et al (2005)	Foreground data:Simulation software Background data: n.s[1]	n.s.[1]

[1] n.s: not specified.

4.5. Impact categories targeted by the analysis

Table 4 shows the impact assessment methods used in the examined studies. The predominant methods are CML baseline 2000 (Frischknet et al., 2007) (35% of the selected studies), followed by the two ReCiPe versions (Goedkoop et al., 2008; Huijbregts et al., 2017) (20% of the examined studies).

Regarding the impact categories (Table 5), the most widely assessed in the reviewed articles are global warming potential (95% of the studies), followed by eutrophication and acidification potential (75%), ozone layer depletion (55%), resource depletion fossil and mineral (50%) and photochemical ozone formation (50%).

Despite considering water use in the inventories of most of the reviewed papers, the impact caused by the consumption of this resource has only been tackled by De Marco and Iannone (2017), Pardo and Zufía (2012), Prosapio et al. (2017), Sanjuan et al. (2011), and Valsasina et al. (2017), that is, 25% of the reviewed papers. It is also remarkable that, although eutrophication is assessed in many studies, wastewater composition (eg, COD, BOD or N and P concentration), which is what mainly contributes to eutrophication in the processing stage, has only been taken into account by Sanjuan et al. (2011) and Depping et al. (2017).

As to the robustness of the results, none of the reviewed studies performed an uncertainty analysis, although many carried out a sensitivity or scenario analysis. Nevertheless, those analyses mostly focus on the parameters affecting upstream or downstream stages, such as the composition of the electricity mix, transport distance or packaging material (e.g. Aganovic et al., 2017; Depping et al., 2017; Marco and Ianonne, 2017). Of those who analysed the effect of changes on processing parameters, it is worth mentioning Valsasina et al. (2017), who assessed the effect of process upscaling, Xu et al. (2016), who took into account the effect of changing the emission factors of the equipment, and Zhou et al. (2017a), who studied the effect of changing the cooling load quantity. Schmidt Rivera et al. (2014) also carried out a thorough sensitivity analysis on process parameters and other variables affecting different life cycle stages.

Table 5. Impact categories employed in LCA and CFP selected studies.

Typology	Authors	GWP	EPa	EPt	WDP	ODP	PMF	APa	APt	PE/CED	POFP	HTPc	HTPnc	RO	RnO	TETP	FETP	METP	IR	ALO	ULO	NLT	MRD/ADe	FFD	HM
Operational Conditions	Roy et al. (2007)	X																							
	Roy et al. (2009)																								
	Sanjuan et al (2014)	X	eutrophication		WA[b]																				
	Zhou et al. (2017)	X																							
Emerging tec assisting conventional ones	Krokida et al. (2016)	X	eutrophication		X	X	X	acidification		X	X	X	X										X	X	
	Kyriakopoulou *et al.* (2015)	X	eutrophication			X		acidification			X	human toxicity				X	X	X					X		
	Prosapio et al. (2017)	X	M/F[a]		X	X	X		X		X	human toxicity				X	X	X	X	X	X	X	X	X	
	Xu et al. 2016	X																							
Contrasting different technologies	Aganovic et al. (2017)	X				X			X			X	X	X	X	X	aquatic toxicity		X	land occupation			X	X	
	Davis et al. (2010)	X	eutrophication					acidification		X															
	Deeping et al. (2017)	X	eutrophication					acidification		X															
	De Marco et al. (2015)	X	X			X		X	X			X	X	X	X	X	aquatic toxicity		X	land occupation			X	X	
	De Marco and Iannone (2017)	X	M/F[a]		X	X	X	acidification			X	human toxicity				X	X	X	X	X	X	X	X	X	
	Hoang et al. (2016)	X	eutrophication			X		acidification			X	human toxicity				X	X	X					X		
	Pardo and Zufía (2012)	X	eutrophication		X			acidification		X	X														
	Li et al. (2006)	X	nitrification			X		acidification			WS/SS[c]														X
	Valsasina et al. (2017)	X	M/F[a]		X	X	X		X		X	human toxicity				X	X	X	X	X	X	X	X	X	
Production scale	Calderón et al. (2018)	X	eutrophication			X		acidification				X		X	X	ecotoxicity			X	land use			X	X	
	Schmidt Rivera et al. (2014)	X	X			X		X			X				X	X	X	X					X	X	
	Sonesson et al. (2005)	X	eutrophication					acidification			X														

GWP: Global Warming Potential; EPa: Aquatic Eutrophication Potential; EPt: Terrestrial Eutrophication Potential; WDP: Water Depletion Potential; ODP: Ozone Depletion Potential; PMF: Particulate Matter Formation; APa: Aquatic Acidification Potential; Apt: Terrestrial Acidification Potential; PED/CED: Primary Energy Demand/Cumulative Energy Demand; POFP: Photochemical Ozone Formation Potential; HTPc: Human Toxicity Potential Carcinogenic; HTPnc: Human Toxicity Potential Non Carcinogenic; RO: Respiratory Organics; RnO: Respiratory Non Organics; TETP: Terrestrial Ecotoxicity Potential; FETP: Freshwater Ecotoxicity Potential; METP: Marine Ecotoxicity Potential; IR: Ionising Radiation; ALO: Agricultural Land Occupation; ULO: Urban Land Occupation; NLT: Natural Land Transformation; MRD/ADe: Mineral Resource Depletion/Abiotic Depletion Elements; FFD: Fossil Fuel Depletion; HM: Heavy Metals. [a]M/F Marine and Freshwater Eutrophication; [b]WA water abstraction; [c]WS/SS: winter smog/summer smog.

5. Main findings

This section summarizes the main lessons learnt from the results of the reviewed studies, in a bid to underscore the potential environmental benefits of technological changes or production scale.

The group of studies *contrasting different technologies* (see Table 2) remarks that *the technological approach plays an important role in the challenge of seeking the environmental sustainability of food processing*.

New technologies tend to represent better alternatives than conventional methods, improving both quality attributes (nutritional and sensorial) and shelf life (Jermann et al., 2015; Knorr et al., 2011). In addition, many of them contribute to resource savings, as well as to decreasing energy consumption (Depping et al., 2017; De Marco et al., 2015; De Marco and Iannone, 2017; Hoang et al., 2016; Kyriakopoulou, et al., 2015; Pardo and Zufía, 2012; Valsasina et al., 2016), GHG emissions (Pardo and Zufía, 2012), and water consumption (Pardo and Zufía, 2012).

However, new technologies do not always imply an environmental improvement. In fact, when comparing alternative pasteurisation methods for juices, both Davis et al. (2010) and Aganovic et al. (2017) showed that the energy consumption of conventional pasteurisation was lower than for HPP and PEF. Despite these differences in terms of energy consumption, slight differences in the impact results were observed in the processing stage. This is mainly due to the significant contribution of other life cycle stages to the overall impacts, mainly farming and packaging production. However, Davis et al. (2010) state that, for products where more energy-intensive processing is undertaken, novel technologies might prove to be more beneficial in terms of overall energy savings. Take for instance the case study of Hong et al. (2016), it shows that despite the higher energy consumption of superchilling vs. conventional chilling, the new alternative eliminates the ice during storage and transport and decreases the packaging weight, hence the total environmental impact of the cold chain decreases.

Indeed, it must be noted that in some of the reviewed studies, the outsourced elements of the supply chains have the highest impacts regardless of the processing technique: waste management (Aganovic et al., 2017; Calderón, et al., 2018; Davis et al., 2010; Krokida et al., 2016) and packing production (Aganovic et al., 2017; De Marco and Iannone, 2017) represent two critical points in that discussion. The results from Depping et al (2017) show the environmental advantage of milk concentrates relative to that of the benchmark, milk powder, although this advantage decreases with greater transport distances. These results emphasize the importance of both considering cradle to grave system boundaries and improving the environmental performance of other life cycle stages (e.g. packaging, transport, waste management).

When analysing the results of the studies on *emerging technologies assisting conventional ones*, the impact of food processing was observed to decrease with respect to that caused by the purely conventional in terms such as energy demand (Krokida, et al., 2016; Xu et al., 2016; Prosapio et al., 2017); global warming (Xu et al., 2016; Prosapio et al., 2017), or water consumption (Krokida, et al., 2016).

From the above comments, therefore, no general conclusions about which technologies are the best can be drawn, because there are still few studies carrying out a comparative assessment of the environmental performance of technological shifts. Furthermore, as discussed in subsection 4.4, some of these studies are based on laboratory experiments, and further analyses on an industrial scale are needed. It must also be noted that the environmental impact of a technology can vary depending on the raw material processed (see, for instance, Aganovic et al., 2017) or the process design (e.g. the possibility of recovering energy or not, or the values of set points).

Moving forward in the lessons, the group of studies related to changes in *operational conditions* highlights the relevance of *(re)thinking operational conditions seeking the environmental sustainability of food consumption.*

Indeed, it is quite evident that reducing the environmental impact does not necessarily imply changing the technological base (which implicitly entails the need for large capital investments). Important environmental gains also stem from the implementation of cleaner production practices such as good housekeeping or process optimization (UNEP, 2002). As discussed by Sanjuan et al. (2011) and Zhou et al. (2017a), the challenge of increasing the environmental sustainability requires an optimisation of the industrial facilities in terms of unit operations, determining the optimal processing parameters (e.g. time, temperature), automating the process or reducing water use in cleaning processes.

In addition, the reviewed studies on *production scale*s show that *scale matters in terms of environmental performance***.** This is a polemic discussion in the field of LCA in food processing. First introduced by Andersson and Ohlsson (1999), it was later rescued by Schlich and Fleissner (2005), who coined the term ecology of scale, *i.e.* the environmental performance could depend on the volume of produced items. Contrary to what it might seem, the concept of ecology of scale suggests that large scale does not necessarily mean a greater environmental load when compared to small manufacturers, or even homemade food. Among the reviewed studies, Calderón et al. (2018) and Davis and Sonneson (2008) confirm this effect. The impact of large-scale production can be further reduced by applying other measures, such as energy efficiency, heat recovery, reverse logistics, etc., which contribute to increasing the environmental performance of food processing.

Of course, this positive effect of scale cannot be generalized, particularly when comparing industrial processing with homemade cooking. Schmidt Rivera et al. (2014) found that the impacts of preparing the meal at home from scratch were lower than those for the equivalent ready-made meal. As the authors point out, an avoidance of manufacturing, a reduction in refrigerated storage and a lower amount of waste in the life cycle of the homemade meal are the main reasons. On the other hand, Calderon et al. (2018) show that large-scale systems (ready meals industry and catering companies) incorporate measures aimed at energy saving and waste reduction and, thus, can offer a better environmental performance than small-scale systems, such as eating in restaurants or even cooking at home.

Finally, it should also be considered that moving technological standards is not trivial. Resistance, inertia and costs tend to slow down technological development, a context that could compromise the achievement of food sustainability if it were entirely dependent on the need to rethink technological standards.

Indeed, the processes of evaluating novel technologies can be slow (Bock et al., 2014), revealing the presence of other factors that limit emerging technologies: for example, non-technical issues, such as regulations and additional costs (Shibasaki et al., 2006 and Valsasina et al., 2017). Moreover, the willingness of manufacturers to shift the bases of production and adopt a new technology is induced by the return in investment as well as cost-efficiency, which is also a function of the production scale.

6. Recommendations for Future LCA Practices on processed food

LCA is a powerful tool of analysis that can aid to increase the sustainability of food system. Nevertheless, some issues need to be improved to harmonize and enhance its application to food processing. These issues and the recommendations are summarized in Table 6.

6.1. Methodological recommendations

In this section, methodological recommendations for the purposes of harmonizing and increasing the reliability of LCA application to processed foods are described. Although some recommendations concern LCA practice in general (e.g. those referred to result reliability), other issues are specific to food processing (e.g. the relationship between shelf life and food waste, or the importance of processing water). Available Product Category Rules (PCRs) for processed foods (e.g. preserved meat, fruit juices, etc.) have been taken into account for some of these recommendations.

6.1.1. Functional unit, other proposals

As commented on in section 4.3, when defining the FU, a quality aspect (e.g. water content or microbial reductions) of the product related with the evaluated processes is mostly considered in the studies under review. However, the issue of which FU is better when carrying on food LCAs remains unresolved. As discussed in Notarnicola et al. (2017), different points of view start to appear in this regard, such as the nutritional value of the food and also the economic and social dimensions. Ponsioen and van der Werf (2017) propose economic value, in currency units, as a FU, reflecting the way in which a consumer values the different functionalities of food. In fact, as already recommended by other authors, using several FU in the same study would allow the multifunctionality of food products (eg. cultural, hedonistic value, etc.) to be captured (Martinez-Blanco et al., 2011; Notarnicola et al., 2017). Since this review is focused on product comparisons, the use of different FU can also be useful to decrease the uncertainty due to the choice of the FU.

6.1.2. System boundaries

When comparing products, leaving out common life cycle stages allows the LCA process be simplified. Nevertheless, we cannot forget the interest of assessing the whole product life cycle, since many decisions made at the factory level, such as those referring to the selection of raw materials, packaging or product distribution, will affect upstream and downstream life cycle stages and, thus, the whole product impact. In fact, the procedure adopted in the PCRs for processed foods considers three different life cycle stages, namely upstream processes (*from cradle-to-gate*), core processes (*from gate-to-gate*), and downstream processes (*from gate-to-grave*), which shall be reported separately. Even though the focus of attention can be directed at the study of the technological performance, conducting studies that look at the entire chain seems essential. In this way, one can have a better view of the problem, better evaluating the weight of the processing and, further, identifying those parts of the life cycle where the greatest improvements can be made (Pardo and Zufía, 2012).

The inclusion of food waste generation and its treatment can also be crucial when defining the system boundaries in comparisons between alternative technologies. This is because some alternatives can extend the shelf life of foods, which, in turn, influences the amount of food waste. To better assess this, and also in relation to the improvement of inventory data for food LCAs, models linking shelf life with waste production such as the one developed WRAP (2013) are needed.

By-product upgrading is another issue related to system boundaries. By-products are generated during the processing stage of many products (e.g. whey from cheese production, peels and trims from vegetable processing, etc.). Although PCRs state that the by-products must be excluded from the system boundaries, designing scenarios including the loads avoided as a consequence of by-product upgrading through system expansion could give a better picture of the environmental impact of the product system.

6.1.3. Capital goods, yes or no?

Frischknecht et al. (2007) propose that capital goods manufacturing be included by default in LCAs. In that very paper, the authors point out that in a workshop held in 1991 in the Netherlands, it was already agreed to include capital goods in the comparative LCAs of processes in which the amount of investments would be clearly and significantly different (Huisingh 1992). Available PCRs for processed food, though, state that capital goods with an expected lifetime over three years shall not be included.

When assessing the impact of capital goods, a common problem seems to be a lack of information, although rough assumptions or educated guesses can be enough, as shown in some of the reviewed studies. In fact, both Xu et al. (2016) and Zhou et al. (2017a) could not find significant differences in the CFP results when using emission factors for equipment based on mass data instead of using economic input-output data. Frischknecht et al. (2007) suggest considering the costs of maintenance and depreciation as initial indicators of the relative importance of capital goods and, in the event of these costs being a substantial part of the product price, the environmental impacts of capital goods should not be excluded a priori.

6.1.4. The scale and data source issues

In some of the studies, real processes are compared with pilot scale or even lab scale or simulated processes, without taking into account scaling considerations. Other studies gather data from processing on lab scale, such as Xu et al. (2016), who highlight a limitation of their study as being the use of a laboratory-scale ultrasound system and a sample of 1 mL of deionized water.

As seen in section 4.4, different sources are used to obtain foreground data for new processes and, considering the inherent data scarcity in those LCAs, the authors agree with Arvidsson et al. (2017) that using several of these types of sources in the same study can be a useful means of verifying the quality of the data. As to the background data, Arvidsson et al. (2017) also underline the importance of avoiding a temporal mismatch between the foreground and background systems in order to ensure the relevance of the results.

The authors also agree with Valsasina et al. (2017) on the need to include scaling considerations in the LCA of new technologies and also on the importance of developing and validating scaling methodologies for food processing. Studies have been developed along these lines, such as the one by Caduff et al. (2014), which provided quantitative scaling factors for an accurate quantification of the environmental impacts in relation to equipment functioning. Zhou et al. (2017b), who developed a systematic methodology aimed at the chemical and pharmaceutical sectors to bridge the gaps between pilot plant operation and LCI and, also, to predict LCI on an industrial scale.

Piccino et al. (2016) elaborated a framework that helps to scale up chemical production processes for LCA studies when only data from laboratory experiments are available.

6.1.5. On the importance of process water

The food processing industry is one of the most water intensive, which is mostly discharged as effluent with a high concentration of organic pollutants (Ölmez, 2014). This points to the need to account for water consumption in the inventories of processing technologies, as does the subsequent wastewater with its corresponding quality parameters. Walker et al. (2018) developed a toolbox to determine water demand per unit process, which can also be used to estimate the wastewater discharge. As to wastewater characterisation, an analysis of the wastewater of the processing plant can be used, although this is not possible when assessing new technologies. The development of models to quantify wastewater quality could be an interesting option. Similarly to the one by Muñoz et al. (2008) for food excretion, the model should take into account the quantity of both the wastewater released and the raw materials emitted to wastewater.

6.1.6. Improving the reliability of the results

As commented on in Section 4.5, none of the reviewed studies carried out an uncertainty analysis. Using only average values to perform an LCA may be misleading due to the inherent variability associated with both model and process parameters (Escobar et al., 2015). Among others, Groen et al. (2017), Heijungs and Huijbregts (2004) and Steinmann et al. (2014) provide guidelines with which to address uncertainty and variability, thus improving the reliability of the results. Non-parametric statistics (e.g. Monte Carlo or bootstrap) stand out as the most commonly-used methods, allowing the confidence intervals to be computed in order to check whether differences between the impact results are significantly different (Ribal et al., 2017). A sensitivity analysis can be used in conjunction with an uncertainty analysis to study the robustness of the results and their uncertainty (Wei et al., 2015). A scenario analysis has been proposed to tackle the uncertainty caused by choices (Heijungs and Guinée, 2007), and is also helpful to examine the influence of different parameters on the environmental impacts (Schmidt Rivera et al., 2017).

Table 6. Overview of the main issues and recommendations to enhance the application of LCA to food processing.

Functional Unit (FU)	There is no consensus on which is the most meaningful FU for food products. Proposals based on mass of final product, price, nutritional value have been made. When comparing processing methods, the FU often takes some quality characteristic of the processed food into account so as to ensure that the compared processes yield products of the same quality. Using several FUs in the same study is recommendable, in this way the multifunctionality of food products (eg. cultural, hedonistic value, etc) is captured.
System boundaries	Different system boundaries are used in LCAs of processed food. However, assessing the whole product life cycle (from cradle to grave), as recommended by PCRs of processed food, seems essential since many decisions made at the factory level affect upstream and downstream life cycle stages. Furthermore, it allows the magnitude of the environmental impact to be quantified, as does the contribution of the processing stage to the total impact.
	When different possibilities for upgrading by-products are available, system expansion can give a better picture of the environmental impact of the product system and the avoided loads as consequence of the up-grading.
	Available PCRs for processed food state that capital goods with an expected lifetime over three years shall not be included. However, capital goods can be crucial in comparative LCAs when the amount of investments are significantly different (Huisingh, 1992). As recommended by Frischknecht et al. (2007), considering the costs of maintenance and depreciation can be initial indicators of their relative importance and, in the event of these costs being a substantial part of the product price, the environmental impacts of capital goods should not be excluded a priori. Then, the impact of capital goods can be assessed based on rough assumptions or educated guesses (mass data or economic input-output data).
Inventory data	As concerns foreground data for the processing stage, scaling considerations must be contemplated, avoiding mixing lab data with pilot or industrial scale data. Scaling methodologies specific for food processing need to be developed.
	As to background data, temporal mismatch between the foreground and background systems must be avoided to ensure the relevance of the results (Arvidsson et al., 2017).
	The food industry is water intensive, causing effluents with a high concentration of organic pollutants. Water consumption and wastewater discharge with its corresponding quality parameters should be accounted for. Toolboxes (e.g. Walker et al., 2018) can be used to estimate the amount of water consumed and discharged. Wastewater analysis can be used to characterize wastewater of existing processes. When assessing emerging technologies, the development of models could be an option to characterize wastewater.
	Processing technologies can extend the shelf life of foods, which, in turn, influences the amount of food waste generated. To assess this, models linking shelf life with amount of waste generated, such as the one developed WRAP (2013), are needed.
Results reliability	Using only average values in the life cycle inventory may be misleading due to the inherent variability associated with each parameter. Non-parametric statistics (e.g. Monte Carlo or bootstrap) together with sensitivity analysis are recommended for uncertainty and variability assessment.
	Scenario analysis allows the uncertainty due to choices to be assessed (Heijungs and Guinée, 2007). It is also helpful to examine the influence of different parameters on the results (Schmidt Rivera et al., 2017) and a support to decision making that may identify improvement opportunities (Yang and Campbell, 2017).
Reinforcing LCA with other complementary approaches	LCA can be combined with other approaches in order to obtain a better picture of the sustainability of technological changes. Examples of these approaches are food process engineering, cleaner production, life cycle costing, eco-efficiency, multicriteria methods such as DEA or AHP, consumer perception.

6.2. Further recommendations

Although the state of the art shows that there is a lack of LCA studies comparing processing technologies, the findings suggest the importance of reconsidering the role of LCA towards sustainable food processing.

Alternative technologies must be introduced into the LCA studies, by means of a comparison among the variants in food processing (contrasting different technologies, or the role of emerging alternatives in assisting conventional processing techniques). However, as stated in section 5, it must be bore in mind that both the improvement and new design of environmentally-friendly processes imply a proper selection and combination of unit operations.

Depping et al (2017) underscore how process engineering combined with environmental assessment can support processing technology selection and product design. Therefore, the optimisation of unit operations (scale, production capacity, hygienisation and cleaning lines, etc.) should contribute to the achievement of a more sustainable food system. It is expected that new aspects be tackled in future LCA practices seeking to achieve process optimisation from an environmental point of view.

Of these new aspects, emphasis should be placed on cleaner production (CP) associated with the LCA approach. CP has been defined as, "the continuous application of an integrated, preventive, environmental strategy applied to processes, products and services to increase overall efficiency and reduce risk to humans and the environment" (UNEP, 2002). What means to say CP aims at reducing water and energy consumption and also waste generation (among other aspects by increasing by-products recovery). Scenario analysis can help to select those CP strategies for food processing that promote more efficient and sustainable food products throughout their entire life cycle. Yang and Campbell (2017) underscore the use of scenario analysis as a support to decision making, opening the door to innovative thinking that may identify more improvement opportunities.

Important to remark that the consumption stage should also be properly incorporated in this scenario analysis, since consumer choices are relevant, as discussed in Aganovic et al. (2017). LCA research is required to help consumers and partners to make informed choices about different food systems and food consumption patterns, with the aim of improving sustainability in the food sector (Calderón et al., 2018). Consumer education seems to be a key element in terms of its role in the challenge of the sustainability of the food system. Therefore, there is an increased awareness that the environmentally conscious consumer of the future will consider ecological and ethical criteria in selecting food products (Pardo and Zufía, 2012), in terms such as the reduction of food waste, or the choice of appropriate packaging or waste management strategies.

The implementation of CP can also mean a reduction of process costs, which is linked to the concept of eco-efficiency. In this regard, Sanjuan et al. (2011) introduce economics into the study by assessing the eco-efficiency of technological choices that cause a lower environmental impact by using data envelopment analysis (DEA). Hence, if new technologies imply a change in the quality aspects of products and could also motivate a higher price, all of these aspects could be assessed together with the environmental profile.

Additionally, combining LCA results with multicriteria methods, such as DEA or goal programming (Ribal et al., 2016) would allow other decisive issues, such as nutritional, sensorial or economic ones, to be included in decision making. In this way, the selection of technologies will be based not only on economic and environmental criteria but also on other decisive aspects related to the quality of the final product.

From the analysis of costs and economic feasibility, and considering the added value of the product, there seems to be one last aspect to be considered: consumer perception. Is the consumer prepared to receive food submitted to alternative processes? It seems that instructional and training work should be part of both the industrial sector's and the government's positive agenda.

7. Conclusions

How to advance toward a sustainable food system is an, as yet, unanswered question. The reviewed studies show the usefulness of LCA to assess the hot spots and the positive effects of processing technologies. This matches with the efficiency perspective to attain food system sustainability, as described by Garnett et al. (2014). Under this approach, technological innovations and managerial improvements should enable supply food products with less environmental impact. Nevertheless, food system is very complex, and its sustainability involves considering other issues such as which is the recommendable level of production (and consumption) of certain foods (e.g. organic *versus* conventional, local supply *vs.* globally-sourced food, or reductions in meat and dairy), or the rebound effects that can arise as a consequence of changing technologies, etc. Furthermore, it is not merely a matter of consumer preferences but also an issue of cultural values.

Some suggestive insights have emerged from the studies highlighting the relevance of opening the black box within which food processing is usually understood. On the one hand, the revision of the state of the art shows that some methodological aspects should be incorporated into LCA to harmonize its application and increase the results' reliability. Additionally, the combination of LCA with other disciplines such as process engineering, cleaner production, cost assessment or multicriteria methods can provide a valuable contribution towards the sustainability of food production systems.

The act of delving further into the achievement of a more sustainable food system implies opening up the black box, analysing alternative processing methods, defining and assessing other innovative scenarios, and integrating also the food quality dimension, in which LCA should be understood as an approach to assessing how different shifts can be coupled with the improved sustainability of food systems.

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