Uncertainty of input parameters and sensitivity analysis in life cycle assessment: an Italian processed tomato product

Iolanda De Marco*, Stefano Riemma, Raffaele Iannone

*Corresponding author e-mail address: idemarco@unisa.it

In the last years, food industries have sought to achieve more sustainable productions to meet the consumers' needs and limit the damages to the environment. The agri-food sector is one of the most impactful on the environment, due to resources depletion, land degradation and emissions. In Italy, one of the most important sectors in the agri-food industry is the tomato processing. Indeed, Italy is one of the world leading processed tomato producers, representing approximately 13% of the global production and 48% of European production. According to the latest data released by the National Association of the Canned Vegetables Industry (Anicav), Italy's processed tomato production totalled 5.1 million metric tons (MMT) in 2016. Among them, mashed tomato ("passata") represents about 50 % of packaged tomato volumes in Italy. The aim of this work is to use a Life Cycle Assessment (LCA) approach to make a "from cradle to grave" analysis of this Italian processed product. In particular, the environmental performances of 500 g mashed tomato packaged in Tetra Pak®, produced by a Southern Italy company, are studied. The uncertainty of the input parameters is taken into account and a Monte Carlo simulation is performed. All data are analyzed using SimaPro 8.4.0 software, adopting ReCiPe 1.12 method at midpoint and endpoint level.

It is clear that both agricultural steps, processing steps and packaging materials' production generate relevant contributions to impact categories at midpoint and endpoint level. In particular, cultivation is the main contributor to the majority of midpoint categories. In order to identify, among the processing steps, the most affecting ones, an in-depth analysis is proposed. Among them, blanching, concentration and pasteurization steps are the main contributors to the emissions. A sensitivity analysis, considering the effect of the substitution of the energy sources, is conducted. Two improved scenarios are proposed to minimize the emissions at endpoint level, and it can be observed that the most promising solution, from the environmental point of view, would lead to a global reduction of 33.3 % of the emissions affecting human health, ecosystem diversity and resource bioavailability.

Keywords: Process optimization; Sustainable productions; Tomato processing; Italian *passata*; Uncertainty of data; Minimized emissions.

1. Introduction

The food industry is among the world's largest industrial sectors and food productions significantly contribute to the environmental impact, mainly because of the high energy consumption (Guinée et al., 2006; Roy et al., 2009; Smith et al., 2008). Indeed, all the steps of food productions generate high emissions: agricultural steps require fertilizers, pesticides, energy and water; equipment used during production consumes electric power, natural gas or fuel oil; eventually, packaging materials require high quantity of energy for their production. In a recent study, it was estimated that in Europe the food contribution to the final consumption of goods is about 27 % (Tukker et al., 2011). Therefore, nowadays, one of the major challenges of the food processing industries, in terms of process optimization and innovation, is the necessity of decreasing the environmental impact of food productions (Valsasina et al., 2017).

In order to address a production towards a higher sustainability, the environmental impact and the resources' utilization have to be accurately determined through the life cycle of the product. Life cycle assessment (LCA) is a helpful tool, which allows the quantitative evaluation of the environmental impacts of a product, process, or activity throughout its life cycle or lifetime, through a "from cradle to grave" analysis (Reap et al., 2008). In some cases, in order to perform detailed analyses of specific productions, the system boundaries covered only part of the process, using "from cradle to gate" (Andræ et al., 2004), "from gate to gate" (De Marco et al., 2015; Jiménez-González et al., 2000) or "from gate to grave" (Rossi et al., 2015) approaches. Different papers based on LCA analyses were published in different areas, such as, for example, food and beverages (Berlin, 2002; Berlin et al., 2007; Biswas and Naude, 2016; De Marco and Iannone, 2017; De Marco et al., 2016; De Marco et al., 2018; Prosapio et al., 2017; Roy et al., 2009), wines' production (Gazulla et al., 2010; Iannone et al., 2016) and wastewater treatments (Al-Salem et al., 2014; Lassaux et al., 2007; Tillman et al., 1998).

An important sector in the agri-food industry is the tomato processing; 41 million tons of tomatoes are processed annually at global level (WPTC, 2016). Italy is one of the world leading processed tomato producers, being the first one in the Mediterranean area and the third one worldwide (after California and China). Many papers were published on LCA of the agricultural steps of tomato production, considering greenhouse or open field cultivations (Antón et al., 2014; Cellura et al., 2012a; Cellura et al., 2012b; Dias et al., 2017; Ntinas et al., 2017; Payen et al., 2015; Roy et al., 2009; Torrellas et al., 2012; Torrellas et al., 2013). For example, Torrellas et al. assessed the environmental impacts of a tomato crop in a multi-tunnel greenhouse on the coast of Almeria (Spain) (Torrellas et al., 2012), with the aim of suggesting alternative cleaner productions in greenhouse areas. Antón et al. included new impact categories linked to water consumption, land use, and pesticides and fertilizers' use, which are important for agricultural LCA (Antón et al., 2014). Payen et al. compared from an LCA point of view local and imported tomatoes (Payen et al., 2015), Dias et al. proposed life cycle perspectives on the sustainability of Ontario (Canada) greenhouse tomato production (Dias et al., 2017).

In addition, only few papers focused their attention on the processing steps of tomato derivatives' productions. Among them, Karakaya and Özilgen calculated energy utilization and carbon dioxide emissions during the production of some tomato products, such as fresh, peeled, diced, and juiced tomatoes (Karakaya and Özilgen, 2011); from their analysis, it can be noticed that the highest energy consumer and the most important source of carbon dioxide emissions is the product transportation to the distribution centers. Del Borghi et al. performed a "from cradle to grave" LCA analysis of different tomato products, such as tomato purée, chopped and peeled tomatoes (Del Borghi et al., 2014); they identified cultivation and packaging subsystems as the most impactful steps on different categories. Manfredi and Vignali performed an in-depth analysis on glass jar packaged tomato puree produced in Northern Italy (Manfredi and Vignali, 2014); packaging, constituted by the glass jar, was the main contributor to most impacts, followed by cultivation and processing steps. Garofalo et al. studied the effect of different steps throughout peeled canned tomato production in Southern Italy on the global warming potential (Garofalo et al., 2017); the most impactful step was landfill disposal, followed by packaging, processing and cultivation steps. De Marco et al. performed a "from gate to gate" study, considering processing and packaging steps in mashed tomato production (De Marco et al., 2017); packaging was the main contributor to the majority of impact categories.

The small number of papers concerning the industrial steps of tomato productions underlines that limited attention was devoted to these steps. Moreover, the uncertainty of the input parameters, which generates a variability in the analysis (Guo and Murphy, 2012), was considered in few papers (Bojacá et al., 2012; Ntinas et al., 2017; Romero-Gámez et al., 2017). Indeed, in LCA studies on food products, it is particularly important to take into account the uncertainty of data, because agricultural inputs are variable with climate variations (Meneses et al., 2016). In the case of tomato production (as in the other cases of agricultural products), the uncertainty of data is mainly due to the variability in local management practices and to the climate changes (Bojacá et al., 2012; Romero-Gámez et al., 2017).

It is also important to mention that in most studies, the industrial process was considered as a "black box", without exploiting the detailed operations constituting the whole process (Sanjuán et al., 2014). As a result, it is difficult to reproduce these studies on similar products because data are aggregated, and the contribution of each unit operation to the overall emissions is not known. For this reason, the aim of this paper is to make a step forward with respect to the existing literature providing an in-depth analysis of all the steps of mashed tomato (or Italian "passata") production, considering the uncertainty of the input parameters.

Moreover, a typical problem in LCA studies is the resources' allocation, which refers to criteria for quantifying the energy consumption of each step. In this paper, resource allocation was avoided and data considered in the life cycle inventory were directly calculated through mass and energy balances on the single unit operations constituting the process.

To sum up, the purpose of this study is an in-depth from cradle to grave LCA analysis of an Italian mashed tomato production (Italian "passata"), taking into account the influence of the uncertainty of the process inputs into the production.

2. System description

In Table 1, the main activities of the process under investigation are reported.

Table 1: Process details and assumptions

Main step	Process	Characteristics and details
Cultivation	Energy supply to facility	Italian energy mix low voltage
	Soil tillage	Diesel supply
	Fertilizing	Diesel and fertilizers (Nitrogen, phosphorous and potassium) supply
	Disease control	Diesel, pesticides, herbicides and insecticides supply
	Irrigation	Diesel, water and hoses supply
	Seedling production	Diesel, fertilizers, pesticides and electricity supply
	Harvesting	Diesel supply

Processing	Tomatoes supply to facility	Transport by truck, 25 t
	Energy supply to facility	Italian energy mix low voltage
	Washing and sorting	Energy and water supply
	Grinding	Energy supply
	Blanching	T=66 °C; energy, water and fuel oil supply
	Refining	Energy supply
	Concentration	Double effect; from 5 to 7 °Bx; energy, water and fuel oil supply
	Pasteurization	T=96 °C; t=4 min; Energy, water and fuel oil supply
	Cooling	T=30 °C; water supply
Packaging	Supporting materials supply	Transport by truck, 25 t
	Energy supply to facility	Italian energy mix low voltage

In the following paragraphs, a detailed description of the different steps is reported.

2.1 Cultivation

The Italian territory, due to its mild climate and terrain, presents areas particularly suited for tomato cultivation. The analyzed cultivation area is localized in Apulia region (Southern Italy). The preliminary operations are related to the soil tillage, which needs to be ploughed, disked and harrowed to prepare the transplant bedding some months before (in the previous autumn). Nutrients are provided to the soil through mineral fertilizers (nitrogen, phosphorous and potassium); nitrogen supply is divided into two doses, one before and one after transplanting, which takes place from April to May. In order to protect tomatoes, pesticides, herbicides and insecticides are supplied. Tomatoes have to be irrigated in abundance and with regularity. In spring, they are irrigated 2-3 times a week, but in the warmer months of summer, it is necessary to water them daily. Tomatoes reach the full maturity a couple of months after transplanting, and, therefore, are harvested in August and September and delivered to the processing company through 25 tons trucks after a first sorting of fruits on the field, in order to discard the unsuitable fruits.

Data regarding cultivation steps were supplied by fifty Apulia farmers and ratified by already published data (Garofalo et al., 2017).

2.2 Processing

Fresh tomatoes are unloaded from 25 tons trucks, discharged into a collecting channel and washed with a flow of water, pumped at a flow rate 5 times higher than the downloaded amount of tomato. This water stream delivers the tomatoes to the roller elevator, which carries the product to the sorting station, where it is manually sorted. Green, damaged and discolored tomatoes are discharged and transferred to a local company, which handles the organic wastes coming from all the companies of the area. Water used for washing is considered as “slightly contaminated by organic and inorganic compounds” and treated in a proper machine. Suitable fruits are chopped and, then, the pulp is pre-heated at 66 °C in a “cold-break” process, using saturated steam produced in an oil-fired boiler. The blanching treatment is necessary to inactivate enzymes and reach the right consistency of the final product. The pulp obtained through the “cold break” process shows better color and taste compared to the one obtained with the traditional higher temperature or “hot break” treatment. After the blanching, tomatoes are forced in an extractor for the refining operation, where pulp and juice are separated from skins. The concentration from 5 °Bx to 7 °Bx consists in the removal of water from the juice through evaporation. The juice is pumped to a double-effect evaporator, where water is separated from tomato pulp using saturated steam. Then, the tomato puree has to be pasteurized; it is sent to a tube-in-tube heat exchanger, where it flows in the internal tube and it is heated from 60 to 96 °C; saturated vapor is sent counter-currently in the outer tube. Once reached the temperature of 96 °C, the puree is kept at that temperature for 4 minutes and, then, it is cooled down at 30 °C using cooling water at 20 °C. The obtained “passata” is characterized by a soluble solids content equal to 7 °Bx, a pH value equal to 4.2-4.5, not too high Bostwick consistency (8 cm in 60 s) and presence of syneresis (about 25 % released serum moisture).

Data regarding processing steps were supplied by a local company and their reasonableness was verified comparing them with already published data (Del Borghi et al., 2014; Manfredi and Vignali, 2014).

2.3 Packaging

Each batch of 500 g product, then, is aseptically pumped in a Tetra Pak® brick, which constitutes the primary packaging. The container is a bonded drinks carton consisted of: (a) *paper*, which gives strength, stiffness and light protection; (b) *low density polyethylene (LDPE)* that holds the liquids and creates a barrier against the air; (c) *aluminum*, which provides a further and effective protection against air, light and bacterial microorganisms that may deteriorate the product. The packaging caps are made of *high density polyethylene (HDPE)*.

A Tetra Pak® brick has seven layers: (1) LPDE for the external one, (2) print ink, (3) paper, (4) adhesive LDPE layer, (5) aluminum, (6) adhesive LDPE layer and (7) LDPE in contact with the mashed tomato.

The secondary packaging is constituted by cardboard boxes containing 24 Tetra Pak® bricks; they are transported to the final storage warehouse through the usage of pallets (tertiary packaging).

3. LCA methodology

LCA analysis allows correlating a broad set of data regarding the life cycle of a product or a process in order to identify the process steps that are critical from an environmental point of view. The main phases of an LCA analysis are presented in the following sub-sections and, according to ISO 14040 and ISO 14044, the procedure is standardized and divided into four phases: 1) Goal and scope definition; 2) Data collection and life cycle inventory; 3) Impact assessment and 4) Interpretation (ISO, 2006a, b).

3.1 Goal and scope definition

The goal of this study is to evaluate the environmental impacts, through an in-depth “from cradle to grave” analysis, of the production and packaging of mashed tomato (Italian “passata”).

All the inputs and outputs are related to the chosen functional unit (FU), which is 500 g of mashed tomato produced and packaged in Tetra Pak® by a Southern Italy company. The boundaries of the system include all the steps; i.e., tomatoes’ cultivation, their transportation to the factory, processing, packaging and end of life. The transport of the packaging materials to the company and the management of wastewater are also included into the system boundaries. On the contrary, the transport of the packaged mashed tomatoes to the distribution centers, the market step and the use of the products are not included.

3.2 Data collection and life cycle inventory

The life cycle inventory (LCI) consists in the quantification of all the inputs and outputs (usage of resources and materials, consumption of electricity and fuels, and determination of transportation) for the steps included in the system boundaries. Data must be representative, consistent and accurate, and, through mass and energy balances, they are organized in tables, constituting the inventory. LCI is a crucial stage, because the validity of the LCA analysis strongly depends on the quality of data. Considering that each production is specific, only primary data regarding the cultivation and industrial steps of the process under analysis were recovered through questionnaires and personal interviews. In particular, crop inventory data were supplied from fifty Apulia (Southern Italy) farmers, whereas processing data were provided by a local company. Each equipment was designed and the process simulated through mass and energy balances, in order to verify the data supplied by the company, avoiding allocation.

Data related to the end of life of the packaging materials were obtained from specific Italian consortia (COMIECO, 2016; COREPLA, 2016; Tetrapak, 2010). Background data regarding, for example, packaging materials production and inputs and outputs associated with the production of 1 kWh of electricity were retrieved by Ecoinvent 3.1 database.

The resulting inventory for the inputs of the different main steps of mashed tomatoes production is shown in Tables 2-4. In order to consider the variability of the input data, the inventory was compiled considering a period from 2005 to 2015.

Table 2: Tomatoes' cultivation primary inventory data for inputs per FU from 2005 to 2015 (1 FU is 500 g of packaged mashed tomato)

Input	Unit	Most expected values	Min	Max	Fitting function
Diesel	kg	$3.57x10^{-3}$	$2.48x10^{-3}$	$5.18x10^{-3}$	Triangular
Water	kg	$3.86x10^{1}$	$3.08x10^{1}$	$6.36x10^{1}$	Triangular
Nitrogen fertilizer	kg	$2.14x10^{-3}$	$1.60x10^{-3}$	$2.77x10^{-3}$	Triangular
Phosphorous fertilizer (P_2O_5)	kg	$2.57x10^{-3}$	$1.92x10^{-3}$	$3.33x10^{-3}$	Triangular
Potassium fertilizer (K_2O)	kg	$1.71x10^{-3}$	$1.28x10^{-3}$	$2.22x10^{-3}$	Triangular
Herbicides	kg	$4.00x10^{-5}$	$3.12x10^{-5}$	$5.04x10^{-5}$	Triangular
Insecticides	kg	$5.71x10^{-6}$	$4.51x10^{-6}$	$7.31x10^{-6}$	Triangular
Fungicides	kg	$2.00x10^{-4}$	$1.60x10^{-4}$	$2.64x10^{-4}$	Triangular
Hoses	kg	$1.00x10^{-3}$	$9.50x10^{-4}$	$1.08x10^{-3}$	Triangular
Electricity	kWh	$6.86x10^{-3}$	$5.53x10^{-3}$	$9.89x10^{-3}$	Triangular

Table 3: Mashed tomato production primary inventory data for inputs per FU from 2005 to 2015 (1 FU is 500 g of packaged mashed tomato). SD is the standard deviation; R^2 is the coefficient of determination.

Step	Input	Unit	Most expected values	Fitting function	SD	R^2
Transportation	Transport by truck	tkm	$1.00x10^{-2}$	lognormal	$8.66x10^{-2}$	0.851
Washing and sorting	Tomatoes	kg	$1.00x10^{0}$	lognormal	$7.72x10^{-3}$	0.654
	Water	kg	$6.05x10^{-2}$	normal	$3.55x10^{-4}$	0.752

	Electricity	MJ	2.38x10^{-3}	lognormal	2.12x10^{-2}	0.973
	Transport by conveyor belt	tkm	2.94x10^{-5}	lognormal	2.79x10^{-2}	0.973
Chopping	Tomatoes	kg	9.31x10^{-1}	lognormal	7.91x10^{-4}	0.592
	Electricity	MJ	3.69x10^{-3}	lognormal	5.94x10-3	0.851
Blanching	Tomatoes	kg	9.31x10^{-1}	lognormal	1.36x10^{-3}	0.753
	Fuel oil	kg	4.65x10^{-3}	normal	6.15x10^{-5}	0.766
	Water	kg	3.21x10^{-3}	lognormal	1.73x10^{-2}	0.851
Refining	Tomatoes	kg	9.31x10^{-1}	lognormal	2.01x10^{-3}	0.654
	Electricity	MJ	3.69x10^{-3}	lognormal	1.07x10^{-2}	0.921
Concentration	Tomatoes	kg	7.22x10^{-1}	lognormal	2.35x10^{-3}	0.768
	Electricity	MJ	3.12x10^{-4}	lognormal	5.21x10^{-3}	0.851
	Fuel oil	kg	5.98x10^{-3}	lognormal	1.83x10^{-2}	0.654
	Water	kg	5.17x10^{-3}	lognormal	3.32x10^{-3}	0.654
Pasteurization	Tomatoes	kg	5.15x10^{-1}	lognormal	2.82x10^{-3}	0.851
	Fuel oil	kg	2.26x10^{-3}	normal	1.71x10^{-4}	0.936
	Water	kg	1.56x10^{-3}	normal	3.89x10^{-5}	0.682
	Electricity	MJ	2.58x10^{-4}	normal	4.18x10^{-6}	0.954
Holding step	Tomatoes	kg	5.05x10^{-1}	normal	6.20x10^{-4}	0.752
	Fuel oil	kg	1.09x10^{-7}	lognormal	2.08x10^{-2}	0.973
	Water	kg	7.55x10^{-8}	lognormal	1.20x10^{-2}	0.654
Cooling	Tomatoes	kg	5.05x10^{-1}	normal	3.82x10^{-3}	0.802
	Water	kg	1.09x10^{-1}	lognormal	9.83x10^{-4}	0.848

Table 4: Packaging and end of life primary inventory data for inputs per FU (1 FU is 500 g of packaged mashed tomato). SD is the standard deviation; R^2 is the coefficient of determination.

Step	Input	Unit	Most expected values	Fitting function	SD	R^2
Packaging	Tomatoes	kg	5.00x10^{-1}	normal	1.13x10^{-2}	0.865
	Tetra Pak®	kg	1.70x10^{-2}			
	Cardboard	kg	1.00x10^{-3}	lognormal	2.85x10^{-3}	0.999
	HDPE	kg	4.30x10^{-3}	lognormal	1.57x10^{-2}	0.891
	Electricity	MJ	1.73x10^{-1}	lognormal	6.46x10^{-3}	0.761
	Transport by truck	tkm	1.16x10^{-2}	lognormal	3.75x10^{-3}	0.877
Recycle	Paper	%	79.7			
	HDPE	%	40.7			
	Tetra Pak®	%	19.0			
Energy recovery	Paper	%	9.0			
	HDPE	%	43.7			
	Tetra Pak®	%	22.0			
Landfill	Paper	%	11.3			

HDPE	%	15.6
Tetra Pak®	%	59.0

3.3 Impact assessment

The elaboration of the inventory data was performed through the LCA software SimaPro 8.4.0 (PRé Consultants, 2014) in agreement with the reference standard for LCA (i.e. ISO 14040-14044). ReCiPe 1.12 method (Goedkoop et al., 2009) was used to aggregate the inventory results first in terms of 18 midpoint categories and, then, in terms of damages to human health, ecosystem diversity and resource availability (endpoint categories). The list of the impact categories at midpoint and endpoint level assessed in the present study is shown in Table 5. The hierarchist (H) time perspective was chosen among the three proposed by the ReCiPe method; this time perspective is based on the most common policy principles concerning time-frame and is the most balanced one.

Table 5: Environmental impact categories with their respective acronyms and units

Impact category	Acronym	Unit
Midpoint level		
Climate change	CC	kg CO_2 eq
Ozone depletion	OD	kg CFC-11 eq^1
Terrestrial acidification	TA	kg SO_2 eq
Freshwater eutrophication	FE	kg P eq
Marine eutrophication	ME	kg N eq
Human toxicity	HT	kg 1,4DCB eq^1
Photochemical oxidant formation	POF	kg NMVOC^1
Particulate matter formation	PMF	kg PM_{10} eq
Terrestrial ecotoxicity	TET	kg 1,4DCB eq^1
Freshwater ecotoxicity	FET	kg 1,4DCB eq^1
Marine ecotoxicity	MET	kg 1,4DCB eq^1
Ionizing radiation	IR	kBq U235 eq^1
Agricultural land occupation	ALO	m^2 x yr
Urban land occupation	ULO	m^2 x yr
Natural land transformation	NLT	m^2
Water depletion	WD	m^3
Water stress index	WSI	m^3
Mineral resource depletion	MRD	kg Fe eq
Fossil fuel depletion	FD	kg oil eq
Endpoint level		

Human health	HH	DALY[1]
Ecosystem diversity	ED	species.yr
Resource availability	RA	\$

[1] CFC-11: Chlorofluorocarbon; 1,4DCB: 1,4 dichlorobenzene; NMVOC: Non Methane Volatile Organic Carbon compound; U235: Uranium 235; DALY: disability-adjusted life years; species.yr: loss of species during a year; \$: increased cost.

In addition, the water consumption was estimated by using the water stress index (WSI), which takes into account blue water consumption; indeed, blue water denotes consumption of any surface and groundwater, and in the specific case of agricultural production, irrigation water (Pfister et al., 2009). The WSI indicates the portion of consumptive water use that deprives other users of freshwater. A WSI below 0.09 indicates low stress, a WSI from 0.09 to 0.5 indicates medium stress, a WSI from 0.5 to 0.91 indicates high stress and a WSI from 0.91 to 1 indicates very high stress (Núñez et al., 2015).

3.4 Interpretation and uncertainty analysis

In the life cycle interpretation phase, the variability of input data was considered, because it can have a noticeable influence on the results. In order to take into account the input parameters' variability, a probability density function was assigned to each parameter. In the case of cultivation, the available data were scarce for each parameter, and, therefore, triangular distributions were adjusted, which modes, minimum and maximum values are reported in Table 2. In the case of industrial and packaging steps, statistical distributions were adjusted for each parameter, performing goodness of fit tests to choose the best option. Data were well fitted by normal or log-normal distributions, which mean and standard deviation values are reported in Tables 3 and 4. The obtained probability distributions were compared with hypothesized distributions through a Chi-square test. This statistic test is given as:

$$\chi^2 = RSS/E_i \tag{1}$$

with $$RSS = \sum_{i=1}^{n}(O_i - E_i)^2 \tag{2}$$

where RSS is the residual sum of squares, n is the number of bins, O_i is the observed frequency in bin i, E_i is the expected frequency of the hypothesized distribution in bin i. Based on the degrees of freedom df, defined as n-1, and the χ^2 value, it is possible to estimate the differences between observed and expected frequencies.

If $\chi^2 = 0$, the observed and expected frequencies are exactly coincident; the higher is the χ^2 value, the higher is the discrepancy among the values.

Once assigned the proper distributions to all the input parameters, the well-known Monte Carlo simulation approach was followed and the impact results were obtained in form of ranges of values instead of single values. The function implemented in the SimaPro 8.4.0 software (triangular, normal or log-normal) was used, considering a sample size of 5000 trials. The obtained distribution functions gave the results in terms of expected values and lower and upper bounds of the 95 % confidence interval (i.e., 2.5th and 97.5th percentiles) for each of the 18 midpoint indicators. The obtained probability distributions were compared with hypothesized distributions through a Chi-square test.

4. Results and discussion

4.1 Emissions at midpoint level and input data uncertainty analysis

The environmental analysis of the mashed tomatoes production was performed in terms of midpoint categories. The results of the impact assessment as well as the contribution of cultivation, processing and packaging steps (materials + their end of life) to each midpoint impact category are reported in Table 6. The relative contributions of these main steps to the impact categories are graphically represented in Figure 1; the impact due to the packaging materials is decoupled from the gain due to materials' end of life.

Table 6: Impact assessment at midpoint level (1 FU is 500 g of packaged mashed tomato)

Impact category	Total	Cultivation	Processing	Packaging
CC	$7.74\text{x}10^{-1}$	$6.81\text{x}10^{-1}$ (88.0%)	$4.30\text{x}10^{-2}$ (5.6%)	$5.03\text{x}10^{-2}$ (6.4%)
OD	$5.12\text{x}10^{-8}$	$3.07\text{x}10^{-8}$ (60.0%)	$1.67\text{x}10^{-8}$ (32.6%)	$4.20\text{x}10^{-9}$ (7.4%)
TA	$1.03\text{x}10^{-3}$	$6.29\text{x}10^{-4}$ (61.3%)	$2.11\text{x}10^{-4}$ (20.6%)	$2.43\text{x}10^{-4}$ (18.1%)
FE	$3.16\text{x}10^{-5}$	$1.00\text{x}10^{-5}$ (31.6%)	6.76x10-6 (21.4%)	$1.61\text{x}10^{-5}$ (47.0%)
ME	$4.33\text{x}10^{-4}$	$6.87\text{x}10^{-5}$ (15.9%)	$2.14\text{x}10^{-4}$ (49.4%)	$1.61\text{x}10^{-4}$ (34.7%)
HT	$3.93\text{x}10^{-2}$	$1.87\text{x}10^{-2}$ (47.4%)	$8.09\text{x}10^{-3}$ (20.6%)	$1.45\text{x}10^{-2}$ (32.0%)
POF	$1.12\text{x}10^{-3}$	$8.29\text{x}10^{-4}$ (73.9%)	$1.56\text{x}10^{-4}$ (13.9%)	$1.85\text{x}10^{-4}$ (12.2%)
PMF	$1.19\text{x}10^{-3}$	$1.06\text{x}10^{-3}$ (89.1%)	$6.89\text{x}10^{-5}$ (5.8%)	$8.64\text{x}10^{-5}$ (5.1%)
TET	$2.10\text{x}10^{-3}$	$2.09\text{x}10^{-3}$ (99.5%)	$6.07\text{x}10^{-6}$ (0.3%)	$5.51\text{x}10^{-6}$ (0.2%)
FET	$4.06\text{x}10^{-3}$	$2.47\text{x}10^{-3}$ (60.9%)	$1.06\text{x}10^{-3}$ (26.1%)	$6.11\text{x}10^{-4}$ (13.0%)
MET	$3.43\text{x}10^{-3}$	$2.01\text{x}10^{-3}$ (58.7%)	$9.23\text{x}10^{-4}$ (26.9%)	$5.72\text{x}10^{-4}$ (14.4%)

IR	2.34x10^{-2}	5.61x10^{-3} (24.0%)	9.35x10^{-3} (40.0%)	8.81x10^{-3} (36.0%)
ALO	3.81x10^{-2}	1.15x10^{-2} (30.1%)	1.44x10^{-3} (3.8%)	4.72x10^{-2} (66.1%)
ULO	1.35x10^{-3}	7.11x10^{-4} (52.7%)	2.94x10^{-4} (21.8%)	5.06x10^{-4} (25.6%)
NLT	3.01x10^{-3}	2.97x10^{-3} (98.7%)	2.58x10^{-5} (0.9%)	1.40x10^{-5} (0.4%)
WD	3.99x10^{-2}	3.87x10^{-2} (96.9%)	5.44x10^{-4} (1.4%)	8.61x10^{-4} (1.7%)
WSI	2.39x10^{-2}	2.34x10^{-2} (97.9%)	3.08x10^{-4} (1.3%)	2.80x10^{-4} (1.2%)
MRD	6.16x10^{-3}	3.00x10^{-3} (48.6%)	1.69x10^{-3} (27.4%)	1.68x10^{-3} (24.0%)
FD	6.41x10^{-2}	1.86x10^{-2} (29.0%)	2.76x10^{-2} (43.0%)	2.29x10^{-2} (28.0%)

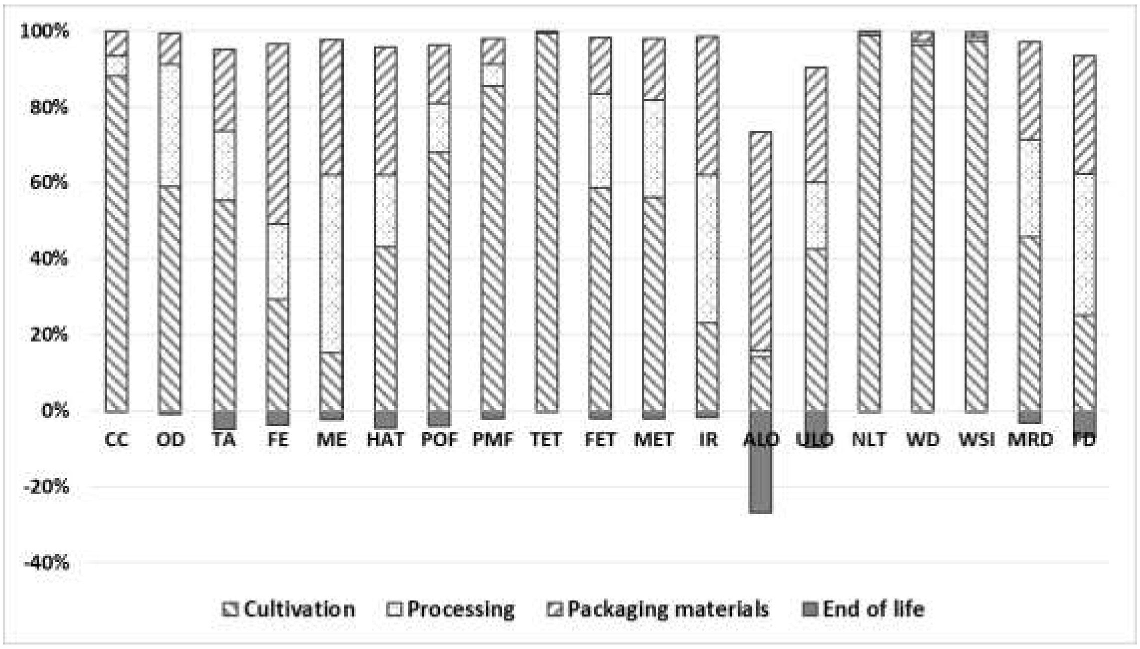


Figure 1: Impact assessment at midpoint level of the mashed tomato production.

It is evident that the agricultural steps (cultivation) have a considerable impact on the majority of the midpoint categories, because of the diesel consumption for planting/harvesting and of the energy and water consumption for irrigation. In particular, cultivation is the main contributor to all the midpoint categories, with the exclusion of FE, ME, IR, ALO and FD.

Processing steps' contribution is relevant (higher than 10 %) on all the midpoint categories, except for CC, PMF, TET, ALO, NLT, WD and WSI; in particular, the impacts in terms of ME, IR and FD are higher for processing steps than for cultivation and packaging steps, because all the steam consumed during the process is produced from oil-fired boilers.

Packaging steps' contribution is higher than 10 % on all the midpoint categories, except for CC, OD, PMF, TET, NLT, WD and WSI; packaging materials' production is the main contributor in terms of FE and ALO, mainly because of the production of the paper contained in Tetra Pak® and in the cardboard boxes. The actual Italian end-of-life scenario contributes to reduce the emissions due to the packaging step for almost all the midpoint categories; the maximum decrease is in the case of ALO (27%), because this category is the one most affected by packaging. These reductions are due to the avoided impacts of primary materials' production. The emissions could be further reduced, increasing the percentage of Tetra Pak® recycled and decreasing the percentage of Tetra Pak® landfilled.

The previous results were obtained considering the most expected values reported in Tables 2-4 for the different input parameters. In order to identify the impact categories most affected by the uncertainty of input data, a Monte Carlo simulation was performed. Table 7 shows the obtained results for each midpoint indicator, with the indication of the mean; the standard deviation (SD); the coefficient of variation (CV), defined as the ratio between the SD and the mean; the standard error of the mean (SEM), defined as the standard deviation of the sampling distribution of the mean.

It is possible to observe that the variations of the values are low for almost all the midpoint indicators and thus the data have good reliability (Beccali et al., 2010). The impact categories most affected by uncertainty (with higher CV values) are water depletion (WD) and water stress index (WSI).

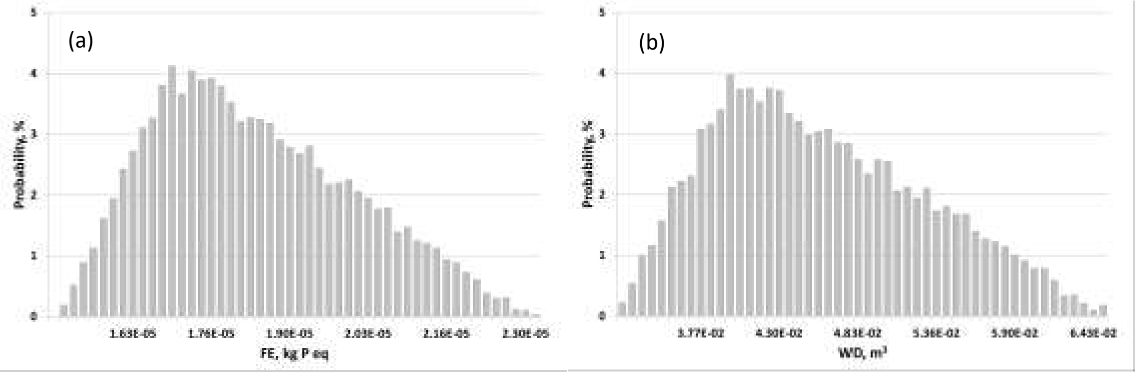
Table 7: Results of the uncertainty analysis using Monte Carlo simulation at midpoint level

Impact category	Mean	SD[1]	CV[1] (%)	SEM[1]
CC	7.41×10^{-1}	1.04×10^{-2}	1.41	1.04×10^{-4}
OD	5.06×10^{-8}	3.57×10^{-9}	7.06	3.57×10^{-11}
TA	8.80×10^{-4}	3.46×10^{-5}	3.93	3.46×10^{-7}
FE	1.83×10^{-5}	1.67×10^{-6}	9.13	1.67×10^{-8}
ME	2.89×10^{-4}	7.29×10^{-6}	2.52	7.29×10^{-8}
HT	2.90×10^{-2}	2.37×10^{-3}	8.16	2.37×10^{-5}
POF	1.02×10^{-3}	2.34×10^{-5}	2.30	2.34×10^{-7}
PMF	1.16×10^{-3}	1.92×10^{-5}	1.65	1.92×10^{-7}
TET	2.13×10^{-3}	1.69×10^{-4}	7.94	1.69×10^{-6}
FET	3.85×10^{-3}	3.25×10^{-4}	8.46	3.25×10^{-6}
MET	3.21×10^{-3}	2.84×10^{-4}	8.86	2.84×10^{-6}

IR	$1.58\text{x}10^{-2}$	$8.05\text{x}10^{-4}$	5.11	$8.05\text{x}10^{-6}$
ALO	$1.33\text{x}10^{-2}$	$2.40\text{x}10^{-4}$	1.81	$2.40\text{x}10^{-6}$
ULO	$1.06\text{x}10^{-3}$	$5.38\text{x}10^{-5}$	5.08	$5.38\text{x}10^{-7}$
NLT	$3.05\text{x}10^{-3}$	$3.78\text{x}10^{-5}$	1.24	$3.78\text{x}10^{-7}$
WD	$4.56\text{x}10^{-2}$	$7.13\text{x}10^{-3}$	15.62	$7.13\text{x}10^{-5}$
WSI	$2.76\text{x}10^{-2}$	$4.27\text{x}10^{-3}$	15.4	$4.27\text{x}10^{-5}$
MRD	$5.14\text{x}10^{-3}$	$4.88\text{x}10^{-4}$	9.48	$4.88\text{x}10^{-6}$
FD	$4.78\text{x}10^{-2}$	$1.54\text{x}10^{-3}$	3.22	$1.54\text{x}10^{-5}$

[1] SD: standard deviation; CV: coefficient of variation; SEM: standard error of the mean

As an example, the probability distributions for the 5000 iterations of the uncertainty analysis in the case of the four categories with higher CV values are reported in Figure 2. Similar probability diagrams were obtained for the other ReCiPe midpoint categories. Therefore, a Chi-square test was applied, because the input data have different distributions (triangular, normal or log-normal); their combination would result in a non-predictable distribution. According to the "central limit theorem" of the probability theory, the normalized sum of the different input data would tend toward a normal distribution, if the number of data is sufficient. It was possible to observe that all the histograms reported in Figure 2 are well-fitted by asymmetric peak functions, such as lognormal and ECS (Edgeworth-Cramer Series) curves, as it is possible to observe in Table 8, where the Chi-square test parameters are reported.



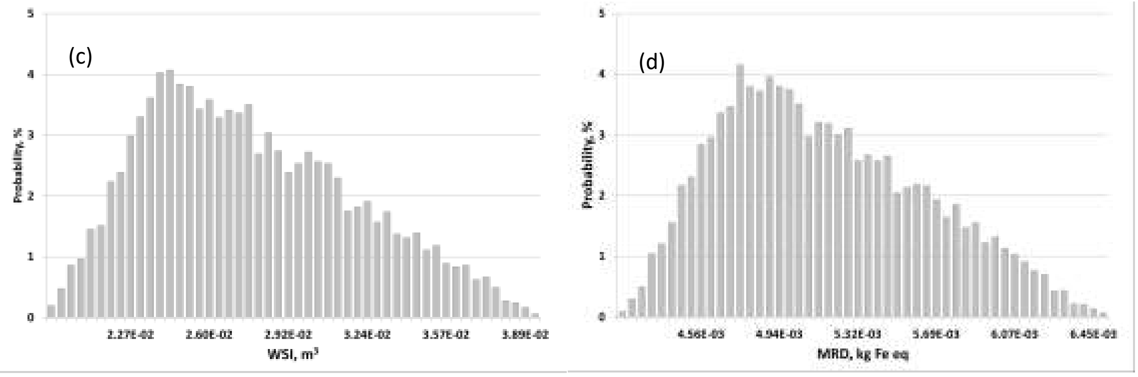


Figure 2: Uncertainty analysis of mashed tomato production. Probability distributions of: (a) freshwater eutrophication, FE; (b) water depletion, WD; (c) water stress index, WSI; (d) mineral resource depletion, MRD.

Table 8: Results of Chi-square test. RSS is the residual sum of squares and R^2 is the coefficient of determination.

Distribution	FE		WD		WSI		MRD	
	RSS	R^2	RSS	R^2	RSS	R^2	RSS	R^2
Normal	$7.63x10^{-3}$	0	$5.75x10^{-3}$	0	$6.79x10^{-3}$	0	$6.97x10^{-3}$	0
Lognormal	$6.00x10^{-4}$	0.916	$3.95x10^{-4}$	0.931	$5.26x10^{-4}$	0.917	$5.78x10^{-4}$	0.912
Lorentz	$7.21x10^{-3}$	0	$2.32x10^{-3}$	0.595	$6.39x10^{-3}$	0	$7.49x10^{-4}$	0.885
ECS	$6.45x10^{-5}$	0.991	$8.58x10^{-5}$	0.984	$1.64x10^{-4}$	0.973	$9.77x10^{-5}$	0.984

4.2 Contribution analysis at midpoint level

In order to individuate the processing steps generating the higher impacts, an in-depth contribution analysis was performed. In Table 9, the detailed results for each step of the process are reported.

Table 9: Detailed impact assessment at midpoint level of the processing steps (1 FU is 500 g of packaged mashed tomato)

	transport	W&S[1]	chopping	blanching	refining	concentr	pasteuriz	cooling
CC	$2.23x10^{-3}$	$2.69x10^{-3}$	$6.48x10^{-4}$	$2.45x10^{-3}$	$6.48x10^{-4}$	$3.21x10^{-3}$	$1.24x10^{-3}$	$7.61x10^{-5}$
OD	$3.07x10^{-9}$	$9.34x10^{-11}$	$9.28x10^{-11}$	$3.16x10^{-9}$	$9.28x10^{-11}$	$4.07x10^{-9}$	$1.54x10^{-9}$	$3.15x10^{-11}$
TA	$1.63x10^{-5}$	$6.57x10^{-6}$	$2.57x10^{-6}$	$2.28x10^{-5}$	$2.57x10^{-6}$	$2.96x10^{-5}$	$1.13x10^{-5}$	$4.62x10^{-7}$
FE	$6.16x10^{-9}$	$9.38x10^{-8}$	$1.19\ 10^{-7}$	$2.65x10^{-7}$	$1.19x10^{-7}$	$3.51x10^{-7}$	$1.37x10^{-7}$	$2.54x10^{-8}$
ME	$9.45x10^{-7}$	$3.42x10^{-6}$	$4.21x10^{-6}$	$1.19x10^{-6}$	$4.21x10^{-6}$	$1.88x10^{-6}$	$8.71x10^{-7}$	$6.25x10^{-8}$
HT	$2.87x10^{-4}$	$1.17x10^{-4}$	$1.27x10^{-4}$	$3.95x10^{-4}$	$1.27x10^{-4}$	$5.19x10^{-4}$	$2.01x10^{-4}$	$3.60x10^{-5}$
POF	$3.01x10^{-5}$	$5.89x10^{-6}$	$1.51x10^{-6}$	$1.66x10^{-5}$	$1.51x10^{-6}$	$2.15x10^{-5}$	$8.20x10^{-6}$	$2.67x10^{-7}$
PMF	$6.75x10^{-6}$	$2.11x10^{-6}$	$8.14x10^{-7}$	$6.72x10^{-6}$	$8.14x10^{-7}$	$8.71x10^{-6}$	$3.32x10^{-6}$	$1.95x10^{-7}$
TET	$2.86x10^{-7}$	$4.97x10^{-8}$	$4.51x10^{-8}$	$2.73x10^{-7}$	$4.51x10^{-8}$	$3.55x10^{-7}$	$1.36x10^{-7}$	$6.52x10^{-9}$
FET	$1.18x10^{-6}$	$1.60x10^{-5}$	$1.99x10^{-5}$	$1.72x10^{-5}$	$1.99x10^{-5}$	$2.39x10^{-5}$	$9.76x10^{-6}$	$4.92x10^{-6}$
MET	$2.88x10^{-6}$	$1.41x10^{-5}$	$1.73x10^{-5}$	$1.41x10^{-5}$	$1.73x10^{-5}$	$1.96x10^{-5}$	$8.04x10^{-6}$	$4.30x10^{-6}$

IR	$3.49x10^{-4}$	$8.84x10^{-5}$	$1.12x10^{-4}$	$1.19x10^{-3}$	$1.12x10^{-4}$	$1.54x10^{-3}$	$5.88x10^{-4}$	$1.20x10^{-5}$
ALO	$0.00x10^{0}$	$1.88x10^{-5}$	$2.64x10^{-5}$	$3.48x10^{-5}$	$2.64x10^{-5}$	$4.71x10^{-5}$	$1.88x10^{-5}$	$2.82x10^{-6}$
ULO	$0.00x10^{0}$	$2.44x10^{-6}$	$2.28x10^{-6}$	$2.66x10^{-5}$	$2.28x10^{-6}$	$3.44x10^{-5}$	$1.31x10^{-5}$	$8.08x10^{-7}$
NLT	$0.00x10^{0}$	$7.84x10^{-8}$	$1.05x10^{-7}$	$6.15x10^{-6}$	$1.05x10^{-7}$	$7.92x10^{-6}$	$3.00x10^{-6}$	$9.92x10^{-9}$
WD	$1.55x10^{-5}$	$1.12x10^{-5}$	$4.50x10^{-6}$	$3.23x10^{-5}$	$4.50x10^{-6}$	$4.30x10^{-5}$	$1.60x10^{-5}$	$1.09x10^{-4}$
WSI	$9.40x10^{-6}$	$3.77x10^{-5}$	$1.64x10^{-6}$	$1.82x10^{-5}$	$1.64x10^{-6}$	$2.42x10^{-5}$	$8.97x10^{-6}$	$6.60x10^{-5}$
MRD	$9.56x10^{-5}$	$2.25x10^{-5}$	$2.66x10^{-5}$	$7.99x10^{-5}$	$2.66x10^{-5}$	$1.05x10^{-4}$	$4.07x10^{-5}$	$7.42x10^{-6}$
FD	$7.69x10^{-4}$	$2.80x10^{-4}$	$2.00x10^{-4}$	$5.94x10^{-3}$	$2.00x10^{-4}$	$7.65x10^{-3}$	$2.90x10^{-3}$	$1.94x10^{-5}$

[1] W&S is washing and sorting

The different contributions were graphically reported in Figure 3.

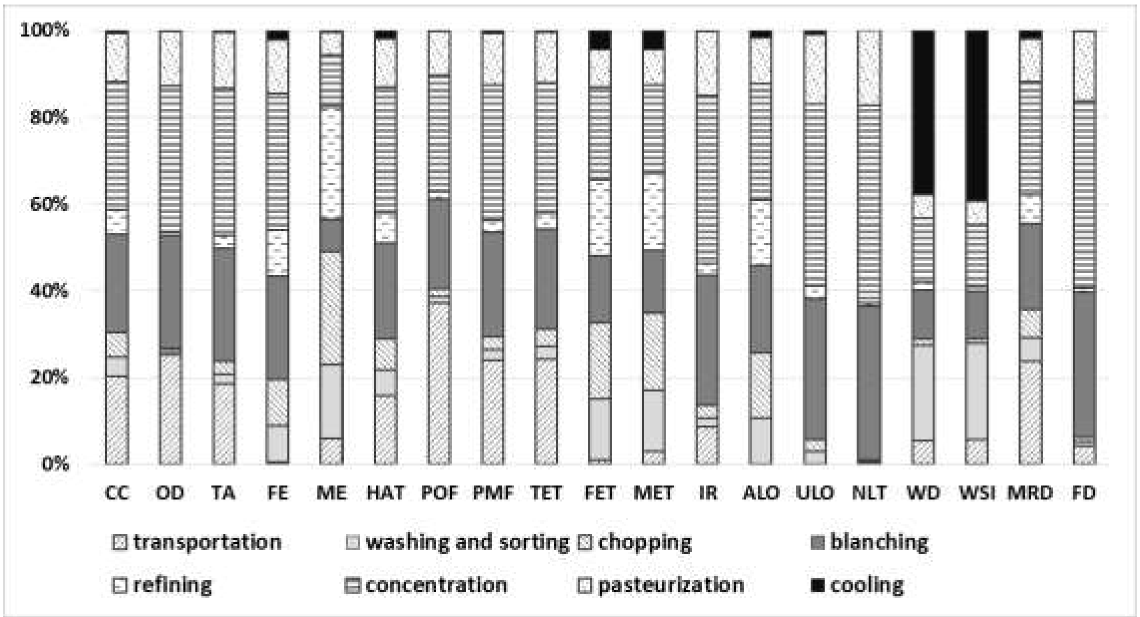


Figure 3: Relative contributions of the processing steps at midpoint level

It is evident that:

- the cooling step has a considerable impact only in terms of WD and WSI;
- the transportation step has an impact higher than 10 % in terms of CC, OD, TA, HAT, POF, PMF, TET and MRD;
- the washing and sorting step has an impact higher than 10 % in terms of ME, FET, MET, ALO, WD and WSI;
- both chopping and refining steps have considerable impacts in terms of FE, ME, FET, MET and ALO;

- blanching, concentration and pasteurization steps are the major contributors to the majority of the midpoint categories.

The latter result can be ascribable to the high quantities of energy necessary for these three steps (in terms of electricity and fuel).

4.3 Improvement opportunities and sensitivity analysis

In order to estimate the possible reduction of the emissions due to the modification of some input variables, a sensitivity analysis is proposed. The performed analysis considers the possibility of substituting the fuel used in the heat exchangers and modify the electricity source. Indeed, fuel oil and electricity at grid referred to the Italian energy mix are used in the base case. Therefore, the performed sensitivity analysis considers:

- for the fuel used in the exchangers, the use of biogas obtained from agricultural waste or liquefied petroleum gas (LPG) instead of fuel oil;
- for the electricity source, the installation and usage of photovoltaic panels and the substitution of a portion (20 or 40%) of the electricity grid with electricity produced by the installed photovoltaic panels.

The results of the sensitivity analysis are shown in the radar charts in Figure 4.

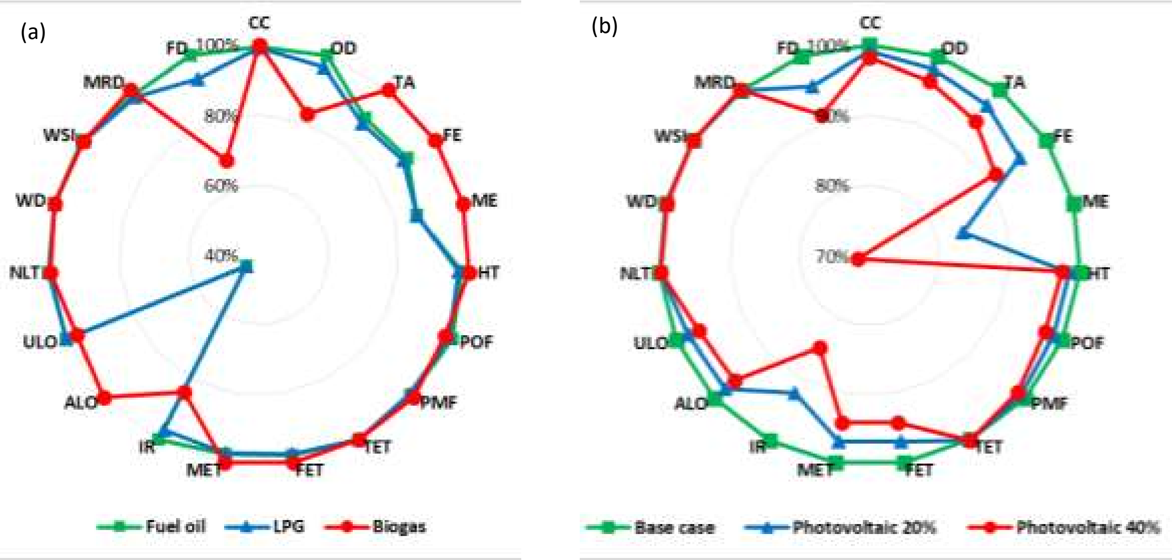


Figure 4: Sensitivity analysis at midpoint level: (a) different fuels used in the heat exchangers; (b) introduction of photovoltaic panels

In particular, substituting the fuel (Figure 4a), it can be noticed that:

1) the use of LPG implies a moderate lowering of all the emissions compared to the base case (fuel oil);

2) the use of biogas is more advantageous than fuel oil or LPG for some categories (OD, IR, ULO and FD), detrimental for some others (TA, FE, ME and ALO), whereas the emissions using the different fuels are comparable in terms of CC, HT, POF, PMF, TET, FET, MET, NLT, WD, WSI and MRD.

The effect of the substitution of part of the electricity source at ReCiPe midpoint level is reported in the radar chart shown in Figure 4b. It is evident that the substitution of a portion of the electricity source using photovoltaic panels lowered the emissions for all the midpoint categories. On the basis of the performed analysis, two improved scenarios are proposed: in both of them, the substitution of the 40 % of the electricity grid with electricity produced by photovoltaic panels is considered, whereas the use of LPG or biogas is taken into account. In Table 10, the emissions at midpoint level of improved scenarios and their comparison with the corresponding base case are reported.

Table 10: Improvement opportunities at midpoint level and their comparison with the base case

Impact category	Emissions			Emissions' reduction	
	Fuel oil (a)	LPG (b)	Biogas (c)	LPG $\frac{b-a}{a}\%$	Biogas $\frac{c-a}{a}\%$
CC	7.24x10^{-1}	7.10x10^{-1}	7.17x10^{-1}	-2%	-1%
OD	4.74x10^{-8}	4.41x10^{-8}	3.74x10^{-8}	-7%	-21%
TA	8.40x10^{-4}	7.75x10^{-4}	8.91x10^{-4}	-8%	+6%
FE	1.68x10^{-5}	1.51x10^{-5}	1.70x10^{-5}	-10%	+2%
ME	2.82x10^{-4}	1.93x10^{-4}	2.36x10^{-4}	-32%	-16%
HT	2.67x10^{-2}	2.58x10^{-2}	2.66x10^{-2}	-4%	+0%
POF	9.85x10^{-4}	9.50x10^{-4}	9.37x10^{-4}	-4%	-5%
PMF	1.13x10^{-3}	1.11x10^{-3}	1.13x10^{-3}	-2%	+0%
TET	2.09x10^{-3}	2.09x10^{-3}	2.09x10^{-3}	+0%	+0%
FET	3.53x10^{-3}	3.31x10^{-3}	3.40x10^{-3}	-6%	-4%
MET	2.94x10^{-3}	2.76x10^{-3}	2.83x10^{-3}	-6%	-4%
IR	1.50x10^{-2}	1.22x10^{-2}	1.04x10^{-2}	-18%	-31%
ALO	1.29x10^{-2}	1.24x10^{-2}	2.85x10^{-2}	-4%	+120.2%
ULO	1.00x10^{-3}	9.72x10^{-4}	9.38x10^{-4}	-3%	-7%
NLT	3.00x10^{-3}	2.99x10^{-3}	2.98x10^{-3}	+0%	-1%
WD	3.92x10^{-2}	3.91x10^{-2}	3.91x10^{-2}	+0%	+0%

WSI	2.37×10^{-2}	2.36×10^{-2}	2.36×10^{-2}	+0%	+0%
MRD	4.68×10^{-3}	4.64×10^{-3}	4.78×10^{-3}	-1%	+2%
FD	4.61×10^{-2}	3.89×10^{-2}	2.76×10^{-2}	-16%	-40%

Looking at the results shown in Table 10, neither of the two solutions seems to be the preferred one. Indeed, the improved solution using biogas has, in the case of ALO, much higher emissions than the base case, but high reductions in terms of OD, IR and FD. The high emissions obtained in this latter case in terms of ALO are due to the fact that the biogas is obtained from agricultural waste and, therefore, its attainment implies the occupation of land. In the improved solution using LPG, the emissions' reduction on the majority of the midpoint categories is lower than in the improved solution using biogas.

4.4 Emissions at endpoint level and improved scenario

In order to choose the most eco-friendly solution, they were compared at endpoint level. The damages on human health (HH), ecosystem diversity (ED) and resources availability (RA) are reported in Table 11.

Table 11: Improvement opportunities and base case emissions at endpoint level

Impact category	Unit	Base case	Biogas	LPG
Human health	DALY	1.33×10^{-6}	1.12×10^{-6}	9.74×10^{-7}
Ecosystem diversity	species.yr	1.21×10^{-8}	1.39×10^{-8}	9.17×10^{-9}
Resource availability	$	7.97×10^{-3}	3.14×10^{-3}	5.86×10^{-3}

It is possible to observe that:

- the damage to human health, with respect to the base case, is reduced for both the improved solutions; the lower emissions are generated by the process using LPG;
- the damage to ecosystem diversity, with respect to the base case, is reduced in the case of LPG and increased in the case of biogas;
- the damage to resource availability, with respect to the base case, is reduced for both the improved solutions; the lower emissions are generated by the process using biogas.

In order to choose the best scenario between the two under analysis, the emissions at endpoint level were normalised, according to the ReCiPe method (Goedkoop et al., 2009); after the normalization, the impacts on different damage categories can be added up. The results are shown in Figure 5. It is evident that, from the environmental point of view, both the improved solutions are more convenient than the base case. The higher difference is due to the impact on the resource availability, which in the base case is equal to 26.15 mPt, in the case of the solution using biogas is equal to 10.31 mPt, and in the case of the solution using LPG is equal to 19.23. The total impact, evaluated as the sum of the three impacts on endpoint categories, is equal to 47.71 mPt for the base case, 31.83 mPt for the solution using biogas and 35.19 mPt for the solution using LPG. Therefore, the global saving of the two proposed scenarios with respect to the base case was calculated; in the case of the LPG based scenario, the saving is equal to 26.3 %, whereas in the case of the biogas based scenario, it is equal to 33.3 %.

To sum up, this analysis allows identifying the best improved scenario: the use of using biogas can lead to a global saving equal to 33.3 % with respect to the base case.

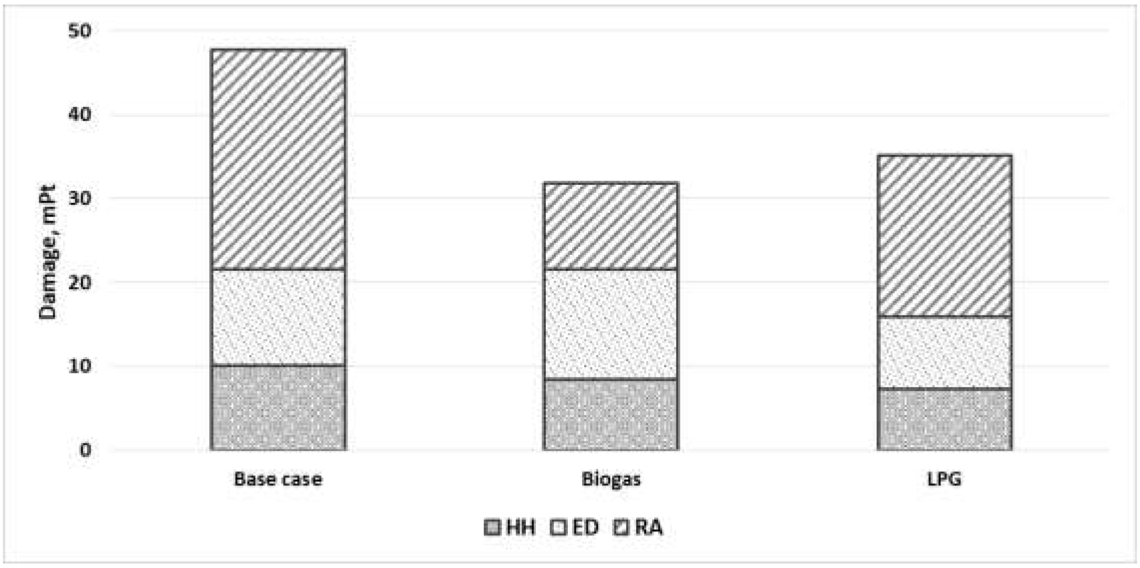


Figure 5: Total environmental impact according to the damage categories of ReCiPe method on relative scale (point, Pt).

5. Conclusions

In this work, a “from cradle to grave” LCA analysis of mashed tomato production, considering the uncertainty of input parameters, was performed. Primary crop inventory data were supplied from fifty Apulia (Southern Italy) farmers, whereas primary processing data were provided by a local company. Data related to the end of life of packaging materials were obtained from specific Italian consortia. A Monte Carlo simulation was used to take into account the variability of input data and it was possible to observe that, for the different midpoint indicators, the coefficients of variation were low, indicating that data had good reliability. Quantitative evaluations showed that cultivation is the main contributor to the majority of the midpoint categories; processing steps are the main contributors to marine eutrophication, ionizing radiation and fossil fuel depletion; eventually, the packaging step generates the highest emissions in terms of freshwater eutrophication and agricultural land occupation. Therefore, an in-depth analysis allowed to understand that the steps that have a major contribution to the majority of the impact categories are blanching, concentration and pasteurization. In order to evaluate the effect of the modification of some parameters, a sensitivity analysis was performed considering the variation of part of the electricity source and the variation of the fuel used in the heat exchangers. Two improved scenarios based on the combination of the possible alternatives (in terms of electricity source and fuel) were evaluated and compared at endpoint level, with the result that the use of photovoltaic panels and of biogas instead of fuel oil generated a global reduction of 33.3 % of the emissions affecting human health, ecosystem diversity and resource bioavailability with respect to the base case.

REFERENCES

Al-Salem, S.M., Evangelisti, S., Lettieri, P., 2014. Life cycle assessment of alternative technologies for municipal solid waste and plastic solid waste management in the Greater London area. Chem Eng J 244, 391-402.

Andræ, A.S.G., Zou, G., Liu, J., 2004. LCA of electronic products: An environmental assessment of Gallium Arsenide Monolithic Microwave Integrated Circuit System-In-a-Package (SIP) Switch Product. Int J Life Cycle Assess 9, 45-52.

Antón, A., Torrellas, M., Núñez, M., Sevigné, E., Amores, M.J., Muñoz, P., Montero, J.I., 2014. Improvement of agricultural life cycle assessment studies through spatial differentiation and new impact categories: Case study on greenhouse tomato production. Environ Sci Technol 48, 9454-9462.

Beccali, M., Cellura, M., Iudicello, M., Mistretta, M., 2010. Life cycle assessment of Italian citrus-based products. Sensitivity analysis and improvement scenarios. J Environ Manage 91, 1415-1428.

Berlin, J., 2002. Environmental life cycle assessment (LCA) of Swedish semi-hard cheese. International Dairy Journal 12, 939-953.

Berlin, J., Sonesson, U., Tillman, A.-M., 2007. A life cycle based method to minimise environmental impact of dairy production through product sequencing. J Clean Prod 15, 347-356.

Biswas, W.K., Naude, G., 2016. A life cycle assessment of processed meat products supplied to Barrow Island: A Western Australian case study. J Food Eng 180, 48-59.

Bojacá, C.R., Gil, R., Casilimas, H., Arias, L.A., Schrevens, E., 2012. Modelling the environmental impact of pesticides sprayed on greenhouse tomatoes: A regional case study in Colombia, Acta Horticulturae, pp. 61-68.

Cellura, M., Ardente, F., Longo, S., 2012a. From the LCA of food products to the environmental assessment of protected crops districts: A case-study in the south of Italy. J Environ Manage 93, 194-208.

Cellura, M., Longo, S., Mistretta, M., 2012b. Life Cycle Assessment (LCA) of protected crops: An Italian case study. J Clean Prod 28, 56-62.

COMIECO, 2016. 21° Rapporto Raccolta, Riciclo e Recupero di carta e cartone.

COREPLA, 2016. Rapporto di sostenibilità 2015 del consorzio nazionale per la raccolta, il riciclaggio e il recupero degli imballaggi in plastica.

De Marco, I., Iannone, R., 2017. Production, packaging and preservation of semi-finished apricots: A comparative Life Cycle Assessment study. J Food Eng 206, 106-117.

De Marco, I., Miranda, S., Riemma, S., Iannone, R., 2015. Environmental assessment of drying methods for the production of apple powders. Int J Life Cycle Assess 20, 1659-1672.

De Marco, I., Miranda, S., Riemma, S., Iannone, R., 2016. Life Cycle Assessment of Ale and Lager Beers Production. Chem Eng Trans 49, 337-342.

De Marco, I., Riemma, S., Iannone, R., 2017. Environmental Analysis of a Mashed Tomato Production: an Italian Case Study. Chem Eng Trans 57, 1825-1830.

De Marco, I., Riemma, S., Iannone, R., 2018. Life cycle assessment of supercritical CO2 extraction of caffeine from coffee beans. J Supercrit Fluids 133, Part 1, 393-400.

Del Borghi, A., Gallo, M., Strazza, C., Del Borghi, M., 2014. An evaluation of environmental sustainability in the food industry through Life Cycle Assessment: the case study of tomato products supply chain. J Clean Prod 78, 121-130.

Dias, G.M., Ayer, N.W., Khosla, S., Van Acker, R., Young, S.B., Whitney, S., Hendricks, P., 2017. Life cycle perspectives on the sustainability of Ontario greenhouse tomato production: Benchmarking and improvement opportunities. J Clean Prod 140, 831-839.

Garofalo, P., D'Andrea, L., Tomaiuolo, M., Venezia, A., Castrignanò, A., 2017. Environmental sustainability of agri-food supply chains in Italy: The case of the whole-peeled tomato production under life cycle assessment methodology. J Food Eng 200, 1-12.

Gazulla, C., Raugei, M., Fullana-I-Palmer, P., 2010. Taking a life cycle look at crianza wine production in Spain: Where are the bottlenecks? Int J Life Cycle Assess 15, 330-337.

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., van Zelm, R., 2009. ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level.

Guinée, J., Heijungs, R., De Koning, A., Van, L., Geerken, T., Van Holderbeke, M., Vito, B.J., Eder, P., Delgado, L., 2006. Environmental Impact of Products (EIPRO) Analysis of the life cycle environmental impacts related to the final consumption of the EU25.

Guo, M., Murphy, R.J., 2012. LCA data quality: Sensitivity and uncertainty analysis. Science of the Total Environment 435-436, 230-243.

Iannone, R., Miranda, S., Riemma, S., De Marco, I., 2016. Improving environmental performances in wine production by a life cycle assessment analysis. J Clean Prod 111, 172-180.

ISO, 2006a. Environmental management - Life cycle assessment - Principles and framework. International Organisation for Standardisation, Geneva, Switzerland, 14040.

ISO, 2006b. Environmental management - Life cycle assessment - Requirements and guidelines. International Organisation for Standardisation, Geneva, Switzerland, 14044.

Jiménez-González, C., Kim, S., Overcash, M.R., 2000. Methodology for developing gate-to-gate Life Cycle Inventory information. Int J Life Cycle Assess 5, 153-159.

Karakaya, A., Özilgen, M., 2011. Energy utilization and carbon dioxide emission in the fresh, paste, whole-peeled, diced, and juiced tomato production processes. Energy 36, 5101-5110.

Lassaux, S., Renzoni, R., Germain, A., 2007. Life cycle assessment of water from the pumping station to the wastewater treatment plant. Int J Life Cycle Assess 12, 118-126.

Manfredi, M., Vignali, G., 2014. Life cycle assessment of a packaged tomato puree: a comparison of environmental impacts produced by different life cycle phases. J Clean Prod 73, 275-284.

Meneses, M., Torres, C.M., Castells, F., 2016. Sensitivity analysis in a life cycle assessment of an aged red wine production from Catalonia, Spain. Science of The Total Environment 562, 571-579.

Ntinas, G.K., Neumair, M., Tsadilas, C.D., Meyer, J., 2017. Carbon footprint and cumulative energy demand of greenhouse and open-field tomato cultivation systems under Southern and Central European climatic conditions. J Clean Prod 142, 3617-3626.

Núñez, M., Pfister, S., Vargas, M., Antón, A., 2015. Spatial and temporal specific characterisation factors for water use impact assessment in Spain. Int J Life Cycle Assess 20, 128-138.

Payen, S., Basset-Mens, C., Perret, S., 2015. LCA of local and imported tomato: An energy and water trade-off. J Clean Prod 87, 139-148.

Pfister, S., Koehler, A., Hellweg, S., 2009. Assessing the environmental impacts of freshwater consumption in LCA. Environ Sci Technol 43, 4098-4104.

Prosapio, V., Norton, I., De Marco, I., 2017. Optimization of freeze-drying using a Life Cycle Assessment approach: strawberries' case study. J Clean Prod 168C, 1171-1179.

Reap, J., Roman, F., Duncan, S., Bras, B., 2008. A survey of unresolved problems in life cycle assessment. Part 2: Impact assessment and interpretation. Int J Life Cycle Assess 13, 374-388.

Romero-Gámez, M., Antón, A., Leyva, R., Suárez-Rey, E.M., 2017. Inclusion of uncertainty in the LCA comparison of different cherry tomato production scenarios. Int J Life Cycle Assess 22, 798-811.

Rossi, V., Cleeve-Edwards, N., Lundquist, L., Schenker, U., Dubois, C., Humbert, S., Jolliet, O., 2015. Life cycle assessment of end-of-life options for two biodegradable packaging materials: Sound application of the European waste hierarchy. J Clean Prod 86, 132-145.

Roy, P., Nei, D., Orikasa, T., Xu, Q., Okadome, H., Nakamura, N., Shiina, T., 2009. A review of life cycle assessment (LCA) on some food products. J Food Eng 90, 1-10.

Sanjuán, N., Stoessel, F., Hellweg, S., 2014. Closing data gaps for LCA of food products: Estimating the energy demand of food processing. Environ Sci Technol 48, 1132-1140.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., Smith, J., 2008. Greenhouse gas mitigation in agriculture. Philosophical Transactions of the Royal Society B: Biological Sciences 363, 789-813.

Tetrapak, 2010. Bilancio Ambientale e Sociale (http://www.tetrapak.com/it)

Tillman, A.M., Svingby, M., Lundström, H., 1998. Life cycle assessment of municipal waste water systems. Int J Life Cycle Assess 3, 145-157.

Torrellas, M., Antón, A., López, J.C., Baeza, E.J., Parra, J.P., Muñoz, P., Montero, J.I., 2012. LCA of a tomato crop in a multi-Tunnel greenhouse in Almeria. Int J Life Cycle Assess 17, 863-875.

Torrellas, M., Antón, A., Montero, J.I., 2013. An environmental impact calculator for greenhouse production systems. J Environ Manage 118, 186-195.

Tukker, A., Goldbohm, R.A., De Koning, A., Verheijden, M., Kleijn, R., Wolf, O., Pérez-Domínguez, I., Rueda-Cantuche, J.M., 2011. Environmental impacts of changes to healthier diets in Europe. Ecological Economics 70, 1776-1788.

Valsasina, L., Pizzol, M., Smetana, S., Georget, E., Mathys, A., Heinz, V., 2017. Life cycle assessment of emerging technologies: The case of milk ultra-high pressure homogenisation. J Clean Prod 142, 2209-2217.

WPTC, 2016. World production estimate of tomatoes for processing. http://www.wptc.to (October 2016).