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Published Version:
Ingrao, C., Faccilongo, N., Valenti, F., De Pascale, G., Di Gioia, L., Messineo, A., et al. (2019). Tomato puree in the Mediterranean region: An environmental Life Cycle Assessment, based upon data surveyed at the supply chain level. JOURNAL OF CLEANER PRODUCTION, 233, 292-313 [10.1016/j.jclepro.2019.06.056].

Availability:
This version is available at: https://hdl.handle.net/11585/935082 since: 2023-07-17

Published:
DOI: http://doi.org/10.1016/j.jclepro.2019.06.056

Tomato puree in the Mediterranean region: An environmental Life Cycle Assessment, based upon data surveyed at the supply chain level

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Abstract

Tomato supply chain as all other agricultural systems is responsible of a set of environmental impacts, in every composing phase: from cultivation, through processing and distribution, to consumption. Assessing and improving those impacts with a life cycle approach would enable enhancing the related sustainability and management quality issues, and could be done using valid methodologies like Life Cycle Assessment.

In this context, this study investigates production of tomato puree in Apulia (Italy), to highlight environmental hotspots and potential improvements.

From the study – and in line with previously published literature - it emerged that jar production is the major contributor to the environmental damage associated with the whole supply chain, followed by the agricultural phase. These are, so, the critical parts of the investigated supply chain requiring priority in the identification and implementation of improvement solutions. The latter could be developed through optimisation of soil management, fertilisation and irrigation, as well as of identification of alternative packaging materials, so reducing the environmental impact/damage associated overall with the supply chain investigated. These and related aspects will be the object of a further researches that the authors will conduct as the future perspectives of this study.

Keywords

Agri-food industry; Tomato Supply chain; Packaging; Environmental Sustainability; Life Cycle Assessment

1. Introduction

Traditional crop production strategies had the main goal of only achieving maximum production, paying little or no attention to the associated environmental impacts. By contrast, modern crop production systems have to take into account new issues and redefine new strategies for environmental friendly consumer-oriented production (Lo Giudice et al., 2014). In fact, agriculture and food sectors have become two main priority areas within the European Sustainable Production and Consumption policies (European Commission, 2008). This is because, though contributing to human health and prosperity (Ingrao et al., 2015), they are main contributors to environmental impacts, like global warming, eutrophication, acidification, land degradation, and water depletion (Beccali et al., 2009; Notarnicola et al., 2015; Tamburini et al., 2015). Due to human population growth in number and wealth, an increasing demand for food is expected in the following decades, putting more pressures on land and requiring other inputs for food production, whilst climate change will pose challenges to agricultural production (van der Werf et al., 2014; Ingrao et al., 2015). Agriculture covers about 40% of the global land area; 70% of global water withdrawal is for agriculture; 30% of Greenhouse Gas (GHG) emissions comes from agricultural activities (Foley, 2005).

An important role within the agri-food industry is played by tomato Supply Chain (SC), with approximately 37.8 million tons of tomatoes processed annually at the global level (WPTC, 2018). During the 13th World Processing Tomato Congress, held in June 2018, it has been shown that since 1994 the tomato production and processing has grown worldwide by 59%. Nowadays, California, Italy and China are the biggest tomato producers of the world followed by Spain, Turkey and Portugal (Ismea, 2017). Actually, the whole Mediterranean area is strongly characterised by tomato production and processing. At the European level, Italy contributes 48% of total production with 5.2 million metric tons of tomato produced (WPTC, 2018). Amongst Italian regions, 30-40% (2 million tons/year) of the Italian tomato production comes from Apulia, especially from the province of Foggia, which represents the highest surface area dedicated to this cultivation (20,000 hectares).

However, tomato SC as all other agro-systems, is responsible for a set of environmental impacts, from cultivation, through processing and distribution, to consumption. Assessing and improving those impacts with a life cycle approach would make it possible to enhance sustainability and management quality issues, so being in line with the concept of Environmental Supply Chain Management (ESCM) (Cellura et al., 2012). The latter can be considered as a "set of supply chain management policies held, actions taken, and relationships formed in response to concerns related to the natural environment with regard to the design, acquisition, production, distribution, use, reuse, and disposal of the firm's goods and services" (Zsidisin and Siferd, 2001; Cellura et al., 2012). Cleaner production is an approach to environmental management which is aimed at encouraging new processes, products and services which are cleaner and more resource efficient. It emphasises preventive approaches to environmental management taking into account impacts over the whole life cycle of products and services (Jackson, 2002). In this context, Life Cycle Assessment (LCA) is potentially one of the most instructive management tools to gain insights into product-related environmental impacts (Frankl, 2002) and stimulate implementation of cleaner production and management systems. LCA is considered as a complementary and more comprehensive tool to support effective integrations of environmental aspects in business and economy (Frankl, 2002). It allows, indeed, decision makers to gather data and other technical information on SCs-related environmental issues, so enabling restructuring of those SCs and, overall, optimisation of ESCM systems (Hagelaar and van der Vorst, 2001; Cellura et al., 2012). This can be achieved through identification of the environmental hotspots associated with the SC and of the improvement opportunities (Berlin, 2008; Almeida, 2014). In particular, according to UNEP/SETAC (2011), LCA is highly effective to raise awareness of decision makers about which life cycle stages are the most sustainable, to:

- provide more efficient and sustainable manners of utilising resources and energy, also through valorisation of agricultural residues and food wastes (Valenti et al., 2018a; 2018b);
- guide against environmental degradation; and
- support companies and stakeholders in being conscious about implications of a product/process for environment.

This study attempts contributing achievement of those objectives for the case of Tomato Puree (TP) production in the Apulian region (Italy). In particular, the study discusses application of an environmental LCA to a tomato SC in the province of Foggia and reports upon results as the base to find potential improvements for a more sustainable SC.

For this purpose, apart from this introductory section, the study was developed according to the framework shown in Fig. 1.

Fig. 1. The figure shows the framework that has been followed for development of the study.

2. Review of previously published literature on tomato production and processing systems

LCA takes a holistic approach, quantifying the various forms of resource use and emissions to air, soil, and water that occur during the different stages of production, use and disposal. Although initially applied to industrial products and systems, LCA has also been applied to agricultural systems since the 1990s. It has, indeed, become established as an important technique for integrated environmental assessment of agroecosystems, with case study applications in many countries (Liang et al., 2018).

Several LCAs were found by this author team to address environmental issues related to tomato SCs, by considering two different types of cultivation, i.e., greenhouse or open field cultivation. In the current specialised literature, most of tomato life cycle studies were related to greenhouse tomato cultivation. To the authors' knowledge, the first study that could be considered a precursor of LCA, as the whole SC of tomato production was included, was that reported by Jolliet (1993), in which the energy consumption and environmental emissions were evaluated in seven different glasshouses in Switzerland. Van Worden (2001) applied LCA in a Dutch glasshouse and showed that the use of energy was responsible for about 75% of the total environmental impact of the crop. Later, Torellas et al. (2012) assessed the environmental impacts of tomato crop in a multi-tunnel greenhouse in Almeria, with the aim of suggesting alternative cleaner productions in greenhouse areas. New impact categories linked to water consumption, land use, and pesticides and fertilisers use were included by Antòn et al. (2014) during their environmental impacts assessment. Life cycle analysis was also applied by Payen et al. (2015) to compare local and imported tomatoes and a life cycle perspective on the sustainability of Ontario greenhouse tomato production was proposed by Dias et al. (2017). Technological improvements such as hydroponics, heating systems and double-layer walls were suggested as key factors to reduce the environmental burden for greenhouse tomato production. With regard to open field cultivation, there are few studies in the literature. For example, Page et al. (2012) compared the case of tomato open-field cultivation with greenhouse one, highlighting how the growing seasons and the systems adopted influenced the overall impact. Martinez-Blanco et al. (2011) analysed the fertilisation strategy, by demonstrating that open-field production had the lowest environmental impacts when mineral fertilisers were utilised compared to the use of compost and mineral fertilisers that revealed the highest impacts.

As previously stated, the environmental impact should be considered along the entire production chain, from the cultivation phase, the food processing and the distribution phase to the end-of-life. Many research works have analysed LCA of the agricultural production of tomato, but only few studies investigated the processing steps of tomato derivative productions. Amongst them, Karakaya and Oziligen (2011) calculated energy utilisation and carbon dioxide emissions during production of tomato products, such as fresh, peeled, diced and juiced tomatoes. The authors highlighted that product transport to distribution centres is the most important source of carbon dioxide emissions, emphasising the logistic phase as the most impactful phase. In another study, Del Borghi et al (2014) performed LCA of tomato products (i.e., TP, chopped and peeled tomatoes). In this case, the most impactful steps were cultivation and packaging phases. Another LCA analysis conducted by Manfredi and Vignali (2014) on glass jar packaged TP, showed that packaging followed by cultivation and processing steps were the main responsible for the growth of impact categories. Garofalo et al. (2017), in their LCA on 480g canned whole-peeled tomato, documented that the most impactful steps were for landfill disposal, packaging, processing and cultivation steps. Results from Garofalo et al. (2017) are with De Marco et al. (2017) who highlighted packaging to be the most environmentally impactful phase in tomato SCs. In another study, Bosona and Gebresenbet (2018) analysed environmental burdens of organic tomato produced and distributed in Sweden, by investigating how the drying process influences the environmental impact of the organic tomato SC investigated. For this purpose, fresh and dried tomatoes were considered. Results indicated that the agricultural phase is highly energy-intensive, mainly due to the heating of the greenhouse system utilised, as the consequence of the cold climate conditions which are typical of Sweden. Heated greenhouse conditions were, however, documented to generate increase not only in tomato yield to values ranging between 35-57 kg/m^2 but, also, in electricity consumption (Bosona and Gebresenbet, 2018). To the share for farming, the one for processing is added, overall representing one major environmentally burdening item of the SC (Bosona and Gebresenbet, 2018): this is amplified when tomato drying is accounted for. In this regard, as an important finding from the study, the authors documented that the drying process increases energy demand in the tomato processing phase, but reduces the climate change impact when all SC phases are considered. This is because dried tomatoes are of lower weight than the fresh ones, which is reflected in reduction of the transport volume and of the related environmental impact. In addition to this, the drying process was highlighted by the authors to enable reduction of the product losses, and extension of the shelf life of the product, overall contributing to enhancing sustainability of locally-grown organic tomatoes.

Recently, De Marco et al. (2018) has investigated two improved scenarios as possible alternatives in terms of electricity source and fuel, by demonstrating that a global reduction of 33.3% of the emissions could be obtained compared to the basic case.

Selection of the aforementioned papers was performed by accessing the Scopus database, because it is globally acknowledged to be the largest abstract and citation database of peer-reviewed literature. In operational terms, the bibliographical search in Scopus was conducted by using a combination of key-words connected with – and most representative of - the research field investigated, namely: tomato cultivation; TP production; LCA; environmental impact; and GHG emissions. Papers addressing just agricultural and industrial issues associated with tomato SCs were neglected because, though being relevant and useful for deepening the authors' knowledge on tomato SCs, they seemed to be not consistent with the objective and function of this study. Thirteen papers were found to be published from 2011 to 2018: they were classified in Table 1, based upon a set of methodological issues that were selected by this author team to best describe those studies. The most relevant outcomes from those studies were used for discussion and interpretation of results produced in this study.

Table 1.

In this table, papers reviewed were classified based upon the most relevant methodological issues.

The review performed enabled understanding that limited attention was payed upon the industrial part of tomato SCs. In fact, major attention was found to be focussed upon the agricultural phase, also because in several studies the industrial one was often considered as a "global box" without detailing the merits of each single unit operation (Sanjuan et al., 2014; De Marco et al., 2018).

By contrast, this study evaluates TP SC through in-depth investigation of each step of the way in both the agricultural and the industrial part of it, with lots of details given about input/output data, as well as about all the methodological choices, the assumptions, and the elaborations made for the system modelling and assessment. To the authors' knowledge, such an approach is not common in LCAs and so can be considered as one important aspect of novelty and added-value making the study a valid, reproducible tool to contribute enhancing the knowledge on how LCA should be developed in this particular agro-industrial field of research.

3. Tomato puree: production trend analysis at the global, Italian and regional scale

With an increase of around 14% compared to 2012, the world volumes of tomatoes destined to processing amount to approximately 38 million tonnes. Tomato industry can be considered as very concentrated, if one thinks that the United States, Italy and China cover almost 60% of the total production.

Looking at data as of 2017, the latest World Processing Tomato Council (WPTC) forecasts describe a situation of substantial stability in volumes collected worldwide (+ 0.4%), with positive signs for China (+ 6.8%), Spain

(+ 8.5%), Iran (+ 30.4%) and negative ones for the other main producers, including the United States (-8.3%) and Italy (-3.5%)[1].

Fig. 2. In the figure, tomato production by country was depicted (WPTC, 2017)

Italy, therefore, plays a key role in tomato SCs, with special regard to the transformation step. In 2016, the estimated turnover, including the two national production basins (North and Central-South) amounted to 3.2 billion euros.

The Nielsen-Ismea data show that, in 2016, the negative trend in retail sales was interrupted after a decade. Compared to 2015, sales of tomato-based products remained mostly stable in volume and Economic Income (EI), equal to + 0.3% and -0.4%. Data on tomato cultivation are encouraging with a 0.9% increase by EI and a 3.8% increase by volume. By contrast, consumption of peeled tomatoes is undergoing a drastic decrease equal to 10% in EI and 6.4% in volume, as well as of pulps (-3.2% in EI and -3% in volume) (Iotti and Bonazzi, 2018).

Tomato SCs are characterised by a strong dependence upon an extremely marked seasonality that shortens the production window to only 50-60 days a year. A further limit to its development is represented by an extremely weak and unorganised logistics.

Tomato processing is gathering increasing importance in the Italian manufacturing scenario and, over time, has enabled creating a sector with a total of 30 thousand employees and even more: over 5 million tons of tomato were processed in 2017. Only in 2016 the tomato preserves sector achieved a turnover of over 3.2 billion euros.

This should be also attributed to macroeconomic problems, such as: the expansion and competition of emerging countries like China); the recent economic crisis; the excessive power of the large-scale retail trade, which in fact has full control of the supply chain through aggressive policies such as the "under-cost"; and the fragmentation of companies in the sector, which prevents them from competing in international markets (Ciconte, 2017).

The escalation of the water problem in Puglia, and in particular in Capitanata (Foggia, Italy), is now leading the sector to question the problems related to the high water needs of the crop and to put forward the need to define more effective water saving techniques and methodologies than those practiced up to now. These environmental elements are joined by the difficulties of the supply chain in the management of production waste and the management of logistics processes, which greatly reduce the overall efficiency of the sector in both environmental and economic terms.

The tomato industry chain is highly complex and is characterised by complex functional, technological and organisational relationships amongst its various components. In particular, the increased agronomic needs of the crop (diffusion of more productive hybrid varieties and irrigation) are accompanied by an increasingly pressing need for coordination between the agricultural phase and the industrial transformation phase. The

[1] As of https://www.wptc.to. Accessed Jan 17, 2019

combination of these two evolutionary paths has led to the creation of real production-transformation poles. The cultivation of industrial tomatoes in Italy is concentrated in two geographically well-defined basins: the northern basin, consisting of Emilia-Romagna - above all the provinces of Piacenza, Ferrara and Parma - Piedmont and Lombardy; and the southern basin, formed by Campania and Puglia - above all the provinces of Bari and Foggia - plus some areas of Molise and Basilicata.

The two production district, as depicted in Fig.3, are characterised by a different organization and structure of production (Cuna et al., 2018):

- in the northern district, the average size of the tomato-growing companies is higher than the national one. Furthermore, these are companies with a high level of mechanisation, which make extensive usage of external work and land rental. Those companies have succeeded in gradually reducing production costs, so that the cultivation of tomato from industry guarantees a good level of profitability compared to potential alternatives; on the other hand
- the southern district is characterised, on an average base, by smaller companies that are characterised by lower capitals invested and by greater labour resources - often coming from outside the EU, available in those areas at very low costs - especially for harvesting operations.

Fig. 3. The figure shows tomato production by country (Cuna et al., 2018).

Due to the high incidence of transport costs on the price of agricultural raw materials, the economic advantage of SC, and especially for the processing companies, leads the sector to operate in restricted geographic areas by tightly linking producers and processors. Therefore, the two production basins are flanked by two industrial poles: the northern pole, with a rather limited number of processing plants of relatively large size, traditionally oriented to the production of semi-finished products (above all concentrated tomato); and the southern pole presenting, instead, numerous plants (about 200) of decidedly lesser dimensions, in which the production of peeled tomatoes prevails. The southern pole is characterised by a strong delay in terms of production and logistics structures, whilst companies in the north show signs of weakness in terms of commercial strategies: they operate on the semi-finished market and have not invested, with some exceptions, in the development of own industrial brands, being particularly sensitive to international price competition.

4. Materials and Methods

4.1 Application of Life Cycle Assessment

Environmental issues of TP production in the Apulia region were assessed in this study, through application of Environmental LCA (E-LCA). The latter was used, because it is acknowledged as playing multiple key roles for evaluation and improvement of environmental sustainability issues in the fields of agriculture and food industry (Notarnicola et al., 2012; van der Werf et al., 2014).

Therefore, this assessment was developed according to the ISO 14040-44:2006 (ISO, 2006 a,b), and so includes the following phases: Goal and scope definition; Life Cycle Inventory (LCI); Life Cycle Impact Assessment (LCIA); and life cycle interpretation.

4.1.1 Goal and scope definition

The study arises with the aim of investigating TP production in Apulia (Italy), to highlight environmental hotspots and potential improvements. It was focalised upon TP production because tomato SC is highly representative of the Region and contributes significantly to its agro-economic growth, with huge amounts of tomatoes produced and processed every year (see section 3 of this manuscript). Studies investigating environmental sustainability of tomato production and processing systems in the Apulia region have already been developed by Del Borghi et al. (2014), Garofalo et al. (2017) and De Marco et al. (2017, 2018). However, research is still needed to deepen the knowledge in this field and contribute further to production and marketing of typical, locally-grown agri-food products (like fresh tomatoes and derivatives in the Apulian region) that are characterised by high standards of healthiness, safety and sustainability.

According to the subject International Standards (ISO, 2006 a,b), the Functional Unit (FU) and the system boundaries were defined to: be consistent with the aim and function of this assessment; best describe the system investigated; and enable comparisons with other similar products (Ingrao et al., 2019). The function of the investigated SC is based upon production and packing of TP; therefore, in line with Manfredi and Vignali (2014) and Del Borghi et al. (2014), the output product to best fulfil and represent that defined function was considered to be 685g TP (packed in a 300g-heavy glass jar, with a 700g-puree maximum capacity). This was chosen as the FU of the SC investigated (FU_{SC}), and was modelled as 1p.

In addition, in line with previously published literature as reviewed in this paper, four Sub-Systems (SS) were considered as composing the SC investigated: for each of them a specific FU (FU_{SS}) was chosen, for due computation of mass and energy flows throughout the SC itself. In Table 2, those sub-systems were reported together with their FUss, using absolute values as well as values referred to the FU associated with the whole SC investigated (FU_{SC}), with the related Units of Measure (UM).

Table 2

This table shows the classification of sub-systems that was adopted for development of this study

In Fig. 4, those SSs were depicted along with the related inputs and outputs and subsequently interconnected, thereby outlining the boundaries of the system investigated. From both the Table and the Figure, there is evidence that the SC was modelled, so that: each SS encompasses the previous one; and the FU_{SC} (1p) is delivered through SS-4. In particular, it is clarified that seed production as upstream to the nursery phase (SS-1) was not accounted for due to both site-specific and Background Data (BD) being not fully available. However, considering the amount per FU_{SC}, as reported in Table 2, lower environmental impacts were expected from seed production compared to the other phases within the system boundaries. In addition to this, the phase of

TP pack distribution was excluded, because considered as going beyond the gate of the SC investigated. The same observation holds for- the TP consumption phase (with the subsequent disposal of the glass container) which was, indeed, excluded from the system and so not accounted for in the assessment.

Moreover, in the flow-chart of Fig. 4, biomass waste is represented: by the tomato losses and the plant bodies generated from the harvesting activity; and by the peels generated in the pressing stage during tomato processing.

Fig. 4. In the figure, the boundaries of the system investigated were depicted.

To integrate both Table 2 and Fig. 4, Fig. 5 was conceived to show the reference flow throughout the SC investigated.

Fig. 5. The figure shows the main reference flow throughout the entire SC, as investigated in this study.

4.1.2 Life cycle inventory

The Life Cycle Inventory is characterised by compilation, qualification and quantification of the input and output data associated with the system investigated: to the authors' opinion, this is what makes it the most time and effort demanding phase in any LCA. The inputs are represented by the resources, materials, fuels, and energy that get to be utilised in the system investigated. Whilst, outputs are intended as the material emissions in air, water and soil, as well as the exploitation of natural and primary-energy resources (Ingrao et al., 2018). In cases like this when the system investigated is a specialised one, for creation of a system model to be the most representative possible of the real system, it is desirable that due importance is given to site-specific data (primary data) on the typologies and amounts of the aforementioned inputs and outputs.

For development of this study, following the standard practice, Primary Data (PD) were received from first-hand sources such as face-to-face interviews that were self-administered to farmers, producers, technicians, and managers operating in the SC investigated. To that end, check-lists were implemented for the case and were filled in during investigations of each SC-SS and related local sites. Data collected are referred only to 2017. However, this does not generate problems related to reliability and usability of results because, according to the farmers and producers involved in the investigated SC, those data are well representative of the production trends both at the agriculture and food-industry level. In addition, cultivation is carried out according to – and so well represents - the standardised regional practise. PD collected were then combined with BD, extrapolated from databases of acknowledged scientific value and relevance, like Ecoinvent v.3.3 (Ecoinvent, 2016). The latter was used because it is recognised worldwide to accommodate most of the background materials and processes often required in LCAs (Frischknecht and Rebitzer, 2005) and, overall, is quite suited for the modelling of agriculture and food-industry systems. In fact, the authors found in it the supportive data to best model the system, though adjustments were needed to be made, mostly in the farming activity modules. For details, the reader is referred to the Tables 3 – 9, where the authors reported data inventoried and related UM, as well as general comments and discussions on the elaborations performed.

Table 3

This table reports inventories related to the seedling production phase (SS-1).

Table 4

This table reports inventories related to the farming step (SS-2).

PD related to each activity in the farming step, including seedling planting, were summarised in Table 5, with regard to: FTT; diesel consumption; and agricultural machinery.

Based upon values in Table 5, CFs were calculated to adjust the emissions: to air of GHGs and other pollutants resulting from diesel combustion; and to soil from tyre abrasion during tractor handling. Those factors were calculated referring PD on DCA and TM to the corresponding background values contained in the Ecoinvent modules utilised, according to the following equations:

$$CF_{DCA} = {}^{DCA_{(PD)}}\!/_{DCA_{(BD)}} \quad (7)$$

$$CF_{TM_{FTT}} = {}^{TM_{FTT(PD)}}\!/_{TM_{FTT(BD)}} \quad (8)$$

Further elaborations were so made for due computation of the aforementioned primary emissions, as of equations 9 and 10.

$$E_{1(PD)}\,[kg] = CF_{DCA} \times E_{1(BD)} \quad (9)$$

$$E_{2(PD)}\,[kg] = CF_{TM_{FTT}} \times E_{2(BD)} \quad (10)$$

In these equations: $E_{1(PD)}$ and $E_{2(PD)}$ are the emissions resulting from diesel combustion and tyre abrasion, respectively, based upon primary values on diesel consumption and TM_{FTT} as provided by the farmer; whilst, $E_{1(BD)}$ and $E_{2(BD)}$are the corresponding secondary values contained in the Ecoinvent modules utilised. The emission values obtained from calculations were summarised in Table 6.

Table 5

This table reports primary data inventoried for each farming activity modelling. Values are expressed as per ha of cultivated field.

In Fig. 6, diesel consumption values were depicted as to be referred to the SS-2 FU, using values reported in Table 4: 3.153E-7 ha for soil preparation; and 6.61E-6 ha for the other farming activities.

Fig. 6. Diesel consumption per each farming activity considered for the modelling of SS-2. Values are expressed as kg per FU_{SS-2}.

Table 6

This table reports primary emissions associated with each activity considered as part of the cultivation phase. Values are expressed as per ha of cultivated field.

Then, emissions in Table 6 were referred to FU_{SS-2} (1kg gross biomass, as output from cultivation), using conversion factors like 3.153E-7 ha/FU_{SS-2} and 6.61E-6 ha/FU_{SS-2} (as of Table 4), depending upon whether it comes to soil preparation or to one of the key farming activities considered. Those emissions were then depicted in Fig. 7 and Fig. 8, on a 0-100% scale.

Fig. 7. The figure shows to-air emissions from diesel combustion per each faming activity on a 0-100% scale, using values referred to FU_{SS-2}

Fig. 8. The figure shows to-soil emissions from tyre abrasion per each faming activity, on a 0-100% scale, using values referred to FU_{SS-2}

From Tables 5 and 6 there is evidence that, per ha of managed soil, soil preparation is the most diesel demanding and pollutant emitting activity. However, this changes drastically if values are related to the SS-2 FU (1kg gross biomass, as of Table 4): soil preparation turns out to be, indeed, the minor contributor to the total diesel consumption and the total emissions associated with the farming phase, due to the lower CF utilised (3.173E-7 ha/FU_{SS-2}). This brings to highlight that, per kg of gross biomass outlet from cultivation (FU_{SS-2}), ploughing, planting and hoeing are the most diesel demanding and pollutant emitting activities (Fig. 7 and Fig. 8). By contrast, those most contributing in terms of tyre-abrasion derived emissions are ploughing, fertilising and PPP application, mainly because they require longer (4 h) to be completed, compared to the other activities. Despite of the greater time required (5.5 h), soil preparation is confirmed to be the least contributor to the tyre-abrasion derived emissions of the whole farming phase. In addition to this, using the classification proposed by Jolliet et al. (2013), from Table 6 it was found that the most significant substances in terms of emitted amounts per ha of cultivated soil, are:

- in Climate Change (CC): carbon dioxide (fossil);
- in Human Health (HH): nitrogen oxides; carbon monoxide (fossil), particulate matter, NMVOCs, and sulphur dioxide; and
- in Ecosystem Quality (EQ): nitrogen oxides; and sulphur dioxide.

Through the LCIA, those substances will be characterised and weighed and, so, it will be highlighted which the most impacting (on the same equivalent-indicator scale) and the most damaging (on the same point scale) are.

Table 7
This table reports inventories related to the tomato harvesting phase (SS-3).

Table 8
This table reports primary emissions associated with the combine harvesting activity from diesel combustion. Values are referred to 1kg harvested tomato, namely the SS-3 FU.

Finally, Table 9 summarises inventories considered in the ultimate step of TP production and packing.

Table 9
This table reports inventories related to the final step of the investigated SC, namely TP production and packing (SS-4).

Fig. 9. The mass balance associated with the tomato flow throughout the SC was depicted in this figure.

Primary inventory values were found to be well in line with those from subject literature studies investigating TP SCs in Apulia, as of Table 1. Existing differences should be attributed to different soil and climate conditions, as well as to farming and processing practices.
Finally, developed like this the inventory analysis can enhance the knowledge on issues related to TP SC management and assessment, by providing detailed descriptions of primary data inventoried, as well as of methodological choices, assumptions and elaborations made for the entire system modelling.

4.1.3 Life cycle impact assessment

According to De Benedetto and Klemes (2009), this phase was developed by aggregating the material and energy output inventories in a limited set of Impact Categories (ICs), also known as '*midpoint categories*'. To that end, the classification/characterisation scheme of Impact 2002+ (Jolliet et al., 2003) in Simapro 8.1.1.16 was considered. So, this method was used for the assessment because, in agreement with De Marco et al. (2017), it was considered by the authors of this paper as valid to assess and highlight the environmental burdens that best represent the SC investigated both at the midpoint and endpoint level. In the midpoint approach, LCIA results were expressed by means of equivalent indicators, such as: kgCO_2 eq for '*Global Warming*', MJ primary for '*Non-renewable Energy*', and kg$PM_{2.5}$ eq for '*Respiratory Inorganics*'.
Thereafter, the ICs were grouped into Damage Categories (DCs), with the aim of describing the environmental compartments being damaged by the product in its life cycle. According to Jolliet et al. (2013), the classification scheme provided by Impact 2002+ was shown in Table 10.

Table 10
In this table, the ICs and the DCs provided by Jolliet et al. (2003) in the Impact 2002+ method were listed.

Therefore, as done in several of the papers reviewed in this paper, like De Marco et al. (2017), the phases of '*normalisation*' and '*weighing*' were included in the assessment, as part of the endpoint approach. As is known, the latter provides results to be estimated using equivalent numerical parameters, so that they can be expressed as '*weighing points*' or '*damage points*' or '*eco-points*' or, more simply, '*points*'. Therefore, the end-point approach was used by the authors of this paper to represent quantitatively the environmental damage associated not only with the system investigated but, also, with all the included materials, energies, processes, and phases. This made it possible: to highlight the most significant ones; and to use the related findings as the base to identify potential improvements.

Finally, the weighing points were obtained through multiplication of the dimensionless results from the normalisation phase by 1 pt: as is known, the latter represents the factor (equal for all DCs and ICs) to convert results from normalisation to weighing, according to the Impact 2002+ method.

5. Discussions and interpretations of obtained results

Results discussed in this phase refer to inventories reported in Table 9. The study highlighted that the environmental damage associated with the SC investigated is equal to 373.19 µpt, which is due to:

- the production of a 300g-heavy glass jar to contain 685g TP (36.15%);
- the agricultural phase, from seedling production to tomato harvesting (24.31%);
- the total of transports (18.64%); and
- the production of 67g citric acid, as required for 685g TP production (18.05%).

The remaining 2.85% should be attributed to the other materials and processes shown in Table 9: 45.89% of that percentage is contributed by the composting of 0.314kg residual biomass from tomato processing. Therefore, based upon LCIA results, it emerges that jar production is the major contributor to the environmental damage associated with the whole SC, followed by the agricultural phase.

In Fig. 10, most damaging processes were depicted per DC, using endpoint assessment results.

Fig. 10. In this figure, the authors showed weighing results per DC. Personal elaboration from Impact 2002+ LCIA, expressing results as per FU_{SC} (1 TP pack).

From Fig. 10, it seems that the most affected DCs are: Human health; Climate change; and Resources. This is, indeed, confirmed by Fig. 11 where the percentage distribution of the total damage per DC was depicted; additionally, damages-assessment results can be found in Table 11.

Fig. 11. The figure shows the percentage distribution of the total damage (373.19 $\mu pt/FU_{SC}$) amongst the DCs considered by Impact 2002+. Values were elaborated from endpoint results.

Table 11

This table shows 'Damage-assessment' values for each damage category considered. Values were extrapolated from Impact 2002+ LCIA, as referred to FU_{SC}.

The damage produced by each of the aforementioned DCs was contributed by the substances emitted and resources consumed shown in Table 12. Substances and resources contributing for ≤ 1% (each) were excluded: such has brought to considering substance and resources with damage percentage ranging from 80.65%, in the case of EQ, to 99.50% for CC.

Table 12

This table reports environmental hotspots related to the SC investigated in terms of substances emitted and resources consumed, with emphasis on the most contributing materials, processes, and phases. The percentage values reported here were elaborated using weighing results referred to FU_{SC}, as of the endpoint approach.

From Table 12, there is evidence that:

- In HH, the substances reported contribute a total of 93.29% of the related damage (133.73 µpt). For all of them but for ammonia, jar production is the most environmentally burdening process, with an average incidence of 52.65%. In the case of ammonia, however, the greatest contribution comes from the agricultural phase, with a 77.1% contribution. This is due to the combined effect of the on-field N_2O-N emission computed according to Brentrup et al. (2000) and the composting of the harvesting residues, as of Table 7. Furthermore, the contribution played by the other processes is largely higher in this substance (11.9%) compared to the others, because of the composting of the tomato processing waste (see Table 9) which represents 98.32% of that contribution.
- In CC, the substances considered represent 99.50% of the associated damage (108.84 µpt), with CO_2 contributing the greatest damage (94.80 µpt). It should be observed that, as expected, for CO_2 and fossil CH_4 production of the package is the most damage process. By contrast, for the reasons previously explained, in the case of N_2O and biogenic CH_4 the agricultural phase is the most significant one. Furthermore, also in this case, greater contributions were found as related to the other processes (5.94% and 18.61%) due to tomato transformation waste composting representing 95.96% and 99.41% of those contributions.
- In R, the overall contribution given by the resources considered, to the damage associated with this DC, was equal to 99.04%. Jar production is the most environmentally damaging process for natural gas and hard coal with comparable contributions (47.5% and 41.7%). Whilst, in the case of crude oil, as expected, the greatest contribution derives from the transport section mainly because of the diesel consumption in the operational phase. Finally, with regard to uranium and brown coal, citric acid production is the most significant step, with similar contributions equal to 48.5% and 54.3%, mainly because of the consumption of fuels and energies in the processing step. This is the reason why

significant contributions (35.2% and 31%) from citric acid production were recorded also in the case of natural gas and hard coal.

- In EQ, the greatest contribution to the damage associated with this DC (40.89 μpt) comes from the occupation of arable lands under intensive-cultivation and irrigation regime, which is almost entirely due to the cultivation phase. Significant damage values are associated with the emission to soil of zinc and aluminium, respectively deriving from:
    - utilisation of tractors and agricultural machineries in the agricultural phase, as well of transport means for supply of material inputs and distribution of biomass and inert waste (for a total of 93%); and
    - industrial systems, like those involved in the production of the glass jar (34.1%) and of the citric acid (30.4%) utilised for TP production.

The other substances affecting EQ contribute by lesser percentages in the range of 1%-4.5%.

Furthermore, substances and resources from Table 12 were detailed in Table 13 in terms of results from: output inventory analysis; characterisation; and damages assessment. Weighing points were not reported to avoid double information provided, considering that those can be calculated, for each substance, by applying the related percentage to the damage associated with the given DC.

Focussing attention upon ICs, based upon endpoint results the most environmentally significant ones amongst those considered by Impact 2002+ (Table 10) are: respiratory inorganics; global warming; and non-renewable energy. However, much less impactful but significant ICs can be found in: land occupation; terrestrial eco-toxicity; carcinogens; non-carcinogens; and terrestrial acidification/nitrification. The most representative and significant ICs were selected and were listed in Table 14, based upon results from midpoint and endpoint assessments. Additionally, Fig. 12 shows all ICs considered by Impact 2002+, with evidence of the materials and processes characterising the SC investigated.

Table 13

In this table, substances and resources from Table 12 were classified based upon: amounts from output inventory analysis; characterisation; and damages assessments. All values reported were referred to $FU_{SC.}$

Table 14

In this table, most representative and impactful ICs were reported, based upon results from characterisation (midpoint) and weighing (endpoint). All values reported were referred to the $FU_{SC.}$

Fig. 12. In this figure, results from single-score evaluation per IC are depicted. Personal elaboration from Impact 2002+ LCIA, with results expressed as per FU_{SC} (1 TP pack).

According to this author team, the output inventory pack discussed in Table 12 and Table 13, as well as the ICs reported in Fig. 12 and Table 14, can be considered as environmental aspects being highly significant and representative of the SC investigated. Therefore, they could serve as the starting base to identify environmental impact indicators usable for potential improvements of labelling systems currently available for tomato SCs.

Results from this study agree with previously published papers as reviewed in section 2 and, in particular, with Manfredi and Vignali (2014), Del Borghi et al. (2014), Garofalo et al. (2017), and De Marco et al. (2017, 2018), who investigated TP SC and documented that jar production is the most environmentally burdening phase in the tomato SC, followed by cultivation. Furthermore, the percentage contribution (34.28%) exhibited by production of the package to the total Global Warming Potential (GWP) of the TP SC investigated was found in this study to be highly comparable with values from Del Borghi et al. (2014) and Licciardello (2017). Differences should be attributed to methodological issues in the application of LCA, like those related: to FU and system border definition; to choices and assumptions made for the modelling of the system and of the related inventory dataset; and to methods used for the impact assessment phase.

Del Borghi et al. (2014) documented, however, that the environmental damage generated by production of this type of package is drastically reduced in case of usage of alternative ones like carton-based containers, and cultivation would turn out to be the most environmentally damaging phase.

Such a finding will be taken into consideration by this author team for development of future studies aimed at identifying and assessing solutions for improvement of the environmental sustainability associated with TP SC, by operating at the level of tomato production and packing. Following Del Borghi et al. (2014), a valid solution in this regard could be the usage of carton-based containers, whether this resulted to be feasible and in line with the firm policy and strategy. With regard to the agricultural phase, major solutions to be considered could be the usage of organic fertilisers in ways to partly or totally replace the mineral ones, and the shift to conservative agriculture practices.

Finally, in line with findings from the studies reviewed, it is confirmed that the most environmentally impactful midpoint categories are RI, GW and NRE, so mostly affecting endpoint categories like HH, CC and R.

6. Conclusions and future perspectives

System perspectives are by now recognised to be essential for design, development and improvement of sustainable food SCs and for support to decision-making, in an industrial-ecology context. This would make it possible to avoid narrow analyses, that could overlook important variables and, more importantly, lead to unintended consequences.

The effort to use a system perspective is reflected in the application of formal methods like LCA, to examine the environmental impact/damage of products, processed, facilities or services from resource extraction and acquisition for raw material preparation through manufacture and consumption to waste management (Lifset and Graedel, 2002).

In this context, the study here-presented has investigated TP SC in the Apulia region through application of LCA, to highlight environmental hotspots as the starting point for potential improvement identification, and has achieved the proposed objectives. As a matter of fact, it enabled understanding that, for the majority of the ICs considered, the environmentally-critical parts in the TP SC investigated stay in the agricultural and processing subsystems. In particular, the study highlighted that the major contributor to the environmental damage associated with the TP SC investigated is the manufacturing of the TP containing jar, followed by the agricultural phase. Their contributions were found to cover together a total of around 60% of the total damage, and to imply huge consumption of NRE sources, as well as emissions of GHGs and other pollutants damaging HH and EQ.

Potential improvement measures can, therefore, be developed in the agricultural and packing phases, by optimising soil management, fertilisation and irrigation, as well as packaging materials, so contributing to the reduction of the environmental impact/damage associated overall with the TP SC investigated. In addition to this, as also recommended by Bosona and Gebresenbet (2018) in their study, utilisation of renewable energy sources could be a valid solution to reduce the environmental burdens arising from consumption of electricity both at the farming and processing stage. These and related aspects will be the object of further researches that will be conducted by this author team as the outlooks of this study.

In a system perspective context, based upon findings from this study as well as from the specialised literature, it is recommended to involve all related stakeholders in the agri-food sectors, like farmers, transformation companies, policy- and decision-makers, retailers and consumers. This is because their joint cooperation may facilitate the implementation and the application of strategies for SCs generating food products with enhanced rates of health, safety, and sustainability.

Moreover, for this paper development great importance was given to discussing in details not only LCIA results, but also the methodological choices, the assumptions and the elaborations that were made for creation and assessment of the most system-representative possible input/output dataset. Such an approach is not often present in LCAs and so is recommended by this author team to make studies valid, reproducible tools to contribute enhancing the knowledge on LCA application as in this research field as in others.

Finally, in line with the studies reviewed in section 2, in the way it was set up and developed the study could favour comparison with similar studies and, in turn, support the search for - and the assessment of – strategies to improve quality and sustainability of locally-grown tomato SCs, that are highly representative of regional territories like the Apulian ones.

Acronyms

AMM: Mass of the Agricultural Equipment used in the farming step

AMM_{FTT}: AMM implied in the given FTT

AMSS: Service life of the agricultural machinery

BD: Background Data(um)

CBB: Corrugated Board Box

CC: Climate Change

CF: Correction Factor

DCA: Diesel Consumption Amount

DW: Demolition Waste

EI: Economic Income

E-LCA: Environmental Life Cycle Assessment

EQ: Ecosystem Quality

EVA: Ethylene Vinyl Acetate

FT: Farming Treatment

FTT: Farming Treatment Time, namely the time needed to perform a given FT

FU: Functional Unit

FU_{SC}: FU associated with the supply chain investigated

FU_{SS}: FU of each sub-system in which the entire system investigated was broken down

$(GB_{SS\text{-}2})_{SS\text{-}3}$: Gross biomass outlet from SS-2 entering SS-3 in the amount required for production of the related FU

GHS: Greenhouse System

GPCS: Greenhouse Plastic Covering Sheet

GW: Global Warming

GWP: Global Warming Potential

HH: Human Health

LCA: Life Cycle Assessment

LCI: Life Cycle Inventory

LCIA: Life Cycle Impact Assessment

LDPE: Low-Density Polyethylene

NMVOCs: Non-methane volatile organic compounds

NRE: Non-Renewable Energy

PAHs: Polycyclic Aromatic Hydrocarbons

PD: Primary Data(um)

PPP: Plant Protection Product

PVC: Polyvinyl Chloride

RI: Respiratory Inorganics

SC: Supply Chain

$(SI_{CH})_{SS\text{-}3}$: Surface involved in the combine harvesting stage in the amount referred to $FU_{SS\text{-}3}$

$SI_{SS\text{-}2}$: Surface invested for production of 1kg gross biomass ($FU_{SS\text{-}2}$)

$(SI_{SP})_{SS\text{-}2}$: Surface involved in soil preparation activities as referred to $FU_{SS\text{-}2}$

TEG: Tri Ethylene Glycol

TM: Mass of the 4-wheel Tractor used in the farming step

TM_{FTT}: TM implied in the given FTT

TP: Tomato Puree

TSS: Tractor Service Life

UM: Unit of Measure

WPS: Water Piping System

WPTC: World Processing Tomato Council

Nomenclature

C_2H_3Cl: Vinyl chloride

$Ca(NO_3)_2$: Calcium nitrate

CH_4: Methane

$CuSO_4$: Copper sulphate

K_2O: Potassium oxide

MgO: Magnesium oxide

N: Nitrogen

N_2O: Dinitrogen monoxide

NOx: Nitrogen oxides

P_2O_5: Phosphorus pentoxide (or phosphoric anhydride)

PAHs: Polycyclic Aromatic Hydrocarbons

SO_2: Sulphur dioxide

Acknowledgements

Dr. Carlo Ingrao has been in charge with design, development, coordination and supervision of this study and he has contributed development of the full LCA, including life cycle inventory analysis, as well as he has written sections 4 and 5 of this manuscript.

However, this study would have not been possible without the invaluable commitment and work by his co-authors. In particular, he would like to thank:

- Dr. Nicola Faccilongo, for collecting on site all primary data needed for the study development, and for contributing section 3 of this document, together with Dr. De Pasquale and Dr. Di Gioia;
- Dr. Francesca Valenti, for contributing section 2 of this manuscript to review ad build upon previously published literature studies on tomato production and processing systems, as well as for acting as corresponding author for this submission;
- Prof. Antonio Messineo, for his inputs to the study development, and for contributing the conclusive section of this document; and, finally,
- Prof. Claudia Arcidiacono, for her multiple key roles in the development of this study, including the computation of the on-field emissions due to fertiliser application, and for her in-depth revision of the final version of this document before submission.

Furthermore, the authors wish to thank the anonymous experts who have reviewed an earlier version of this manuscript for providing invaluable inputs that have contributed to improvement and upgrade of the manuscript itself.

Finally, special thanks are conveyed to Prof. Maria Teresa Moreira for her kind and prompt handling of this paper submission.

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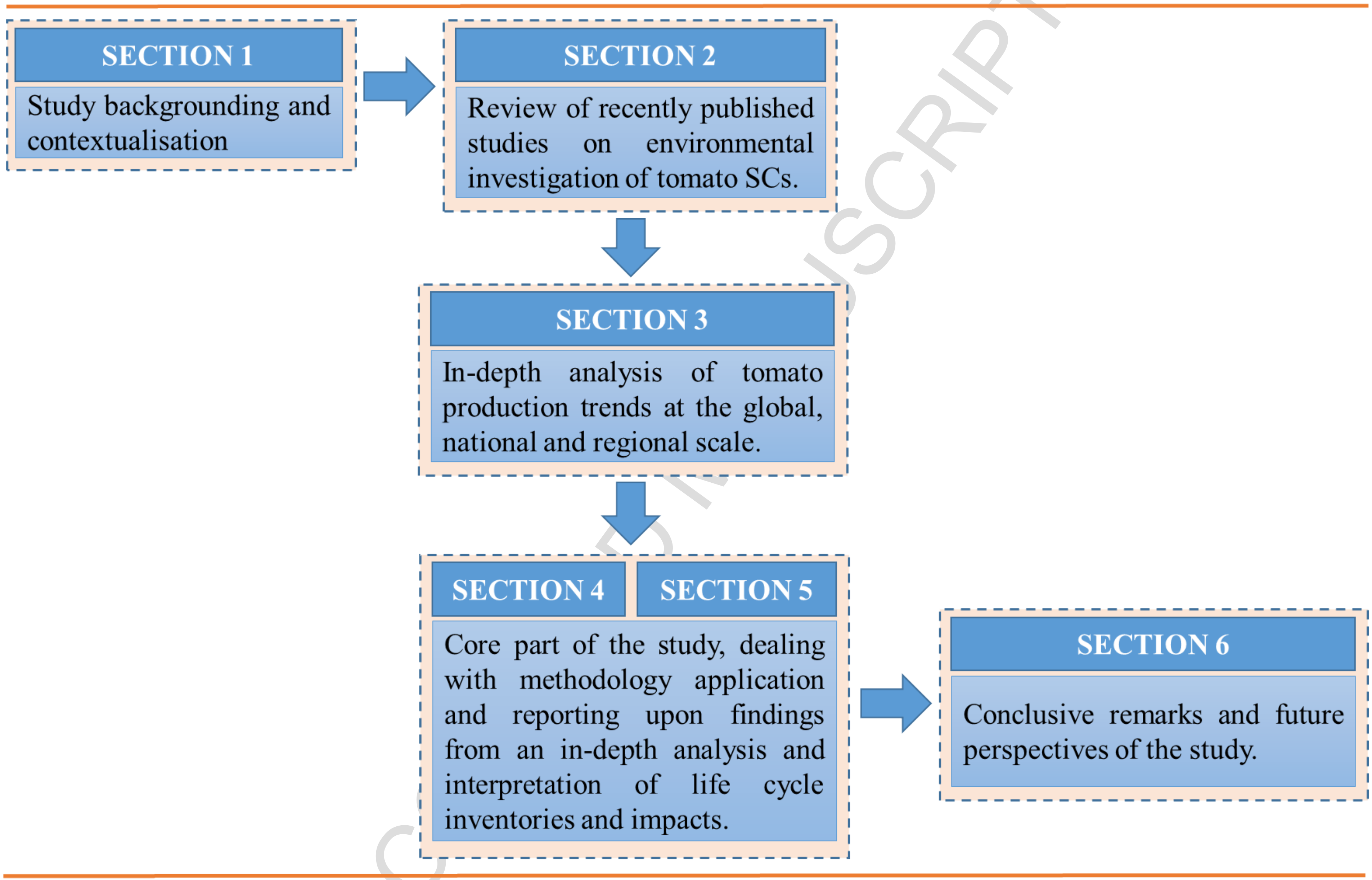
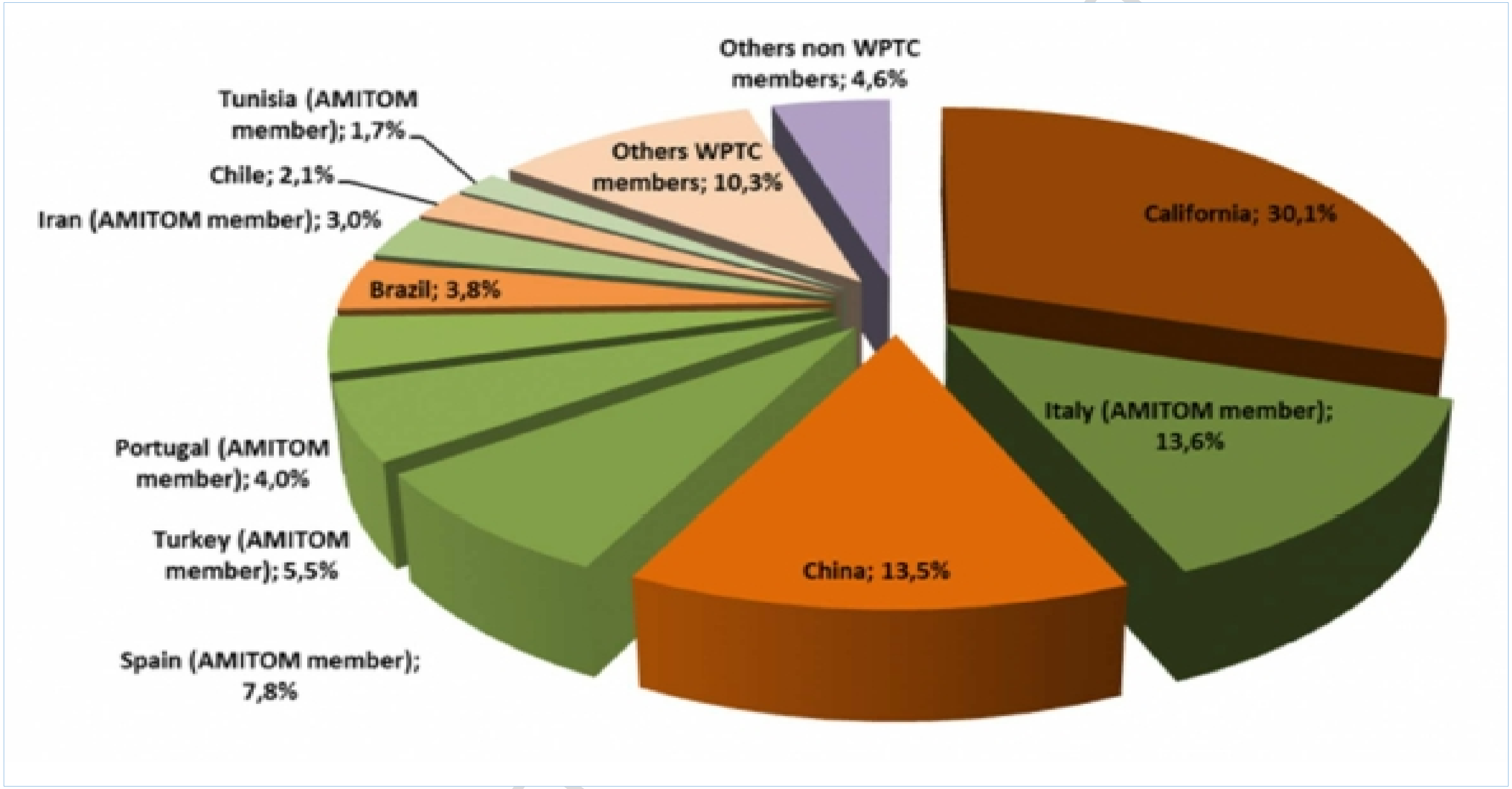
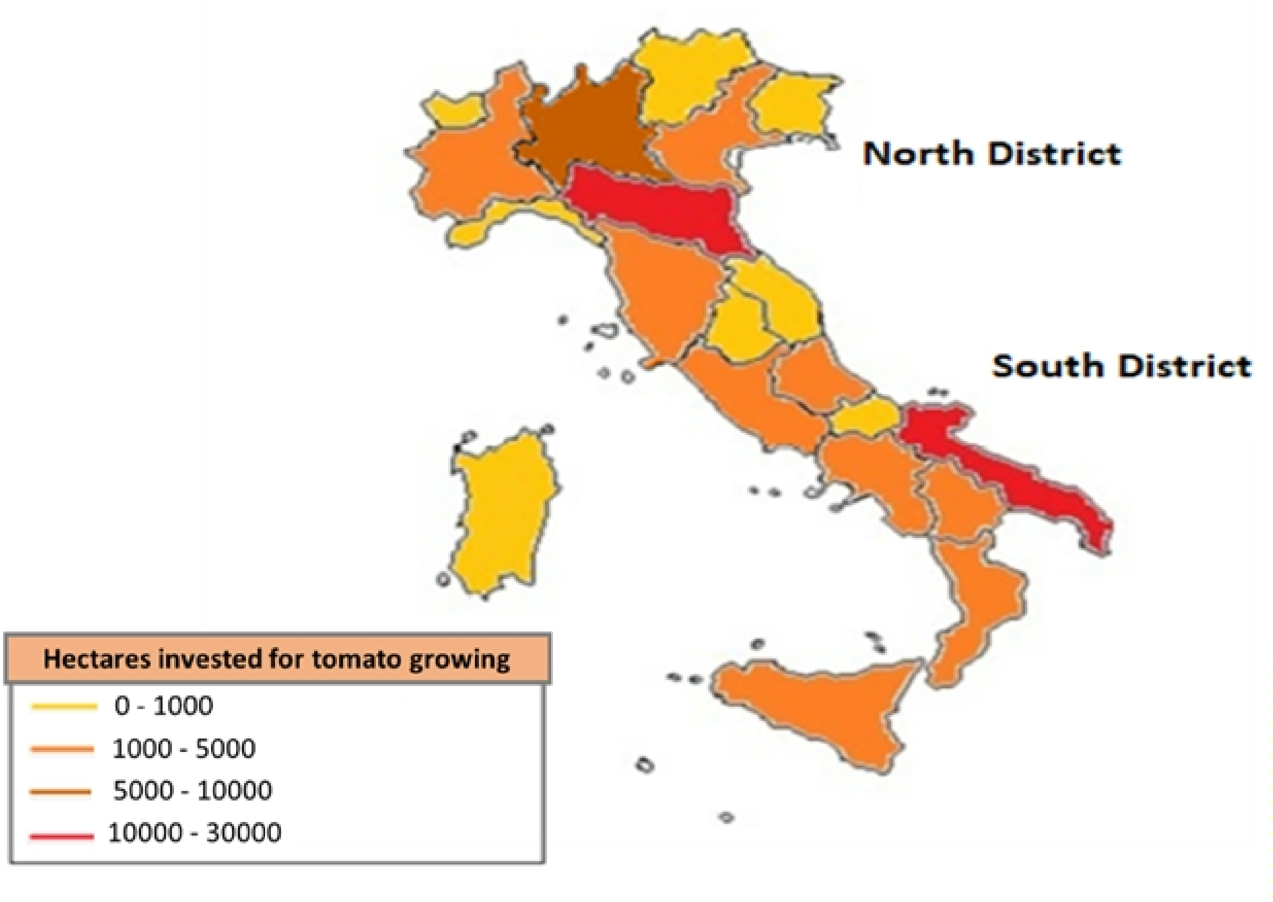
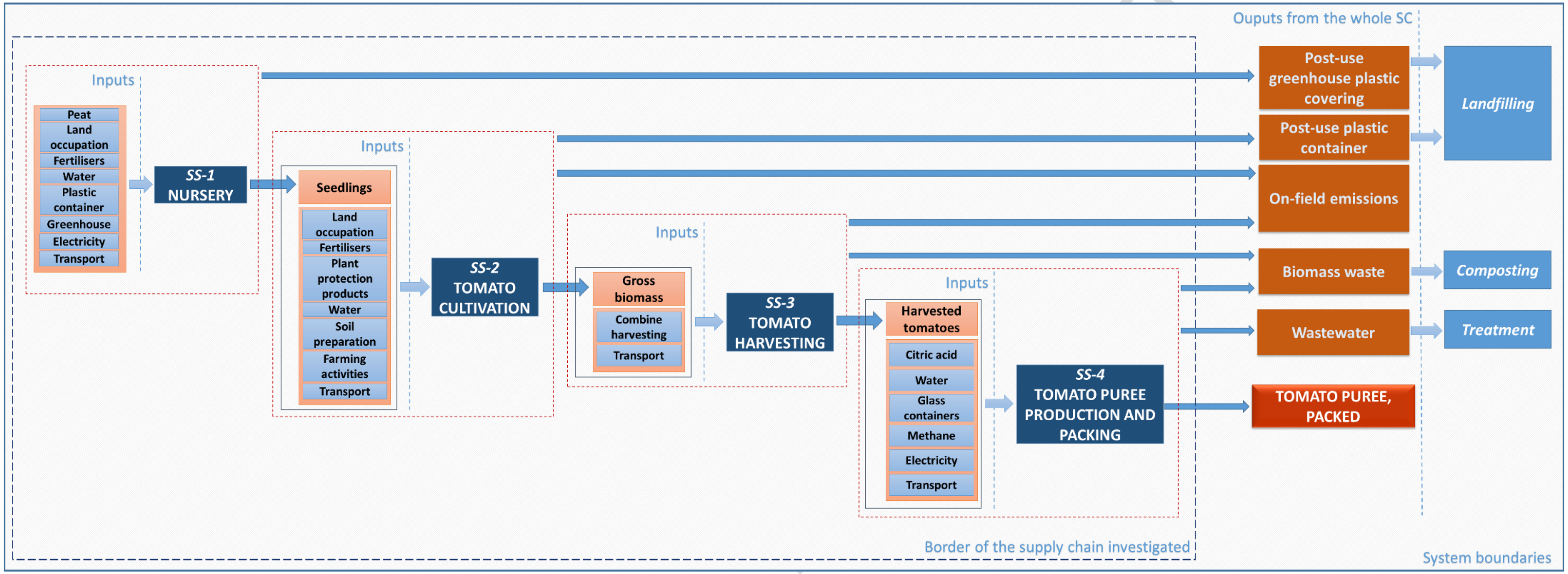
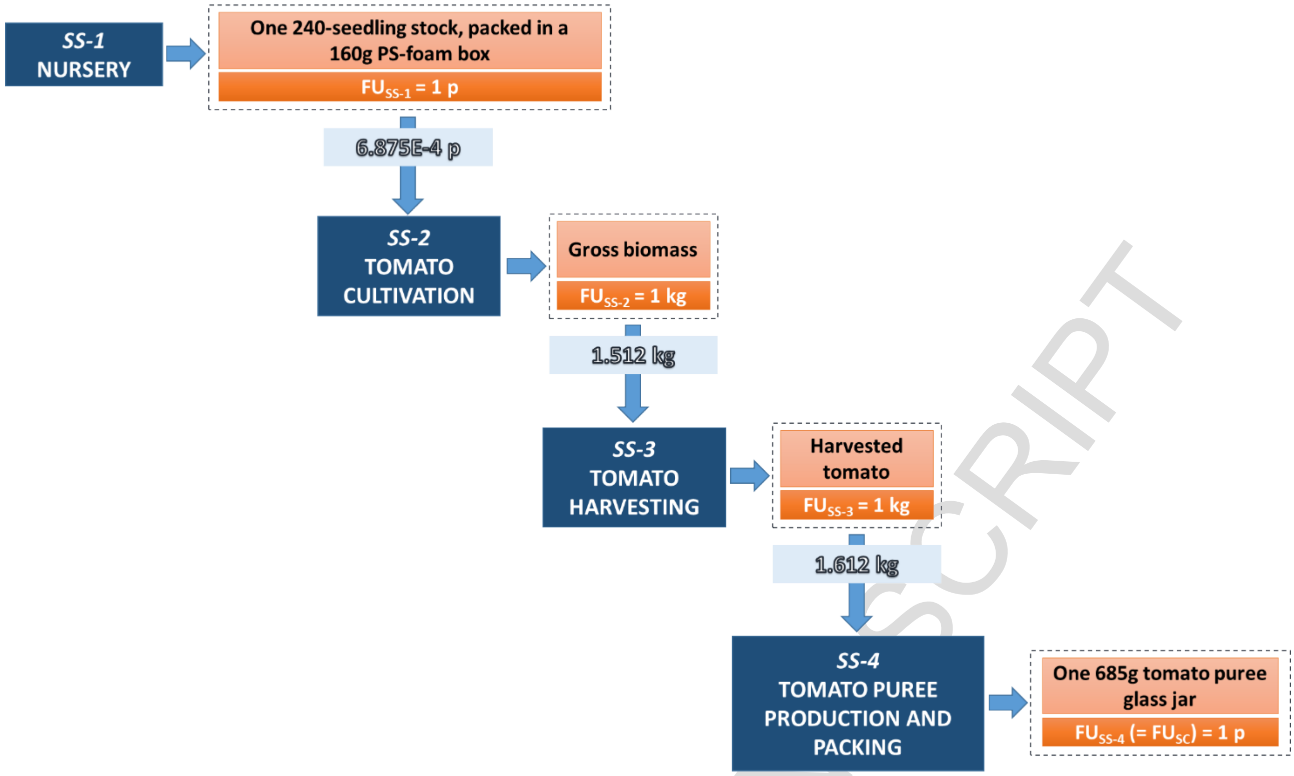

SECTION 1
Study backgrounding and contextualisation
SECTION 2
Review of recently published studies on environmental investigation of tomato SCs.
SECTION 3
In-depth analysis of tomato production trends at the global, national and regional scale.
SECTION 4
SECTION 5
Core part of the study, dealing with methodology application and reporting upon findings from an in-depth analysis and interpretation of life cycle inventories and impacts.
SECTION 6
Conclusive remarks and future perspectives of the study.

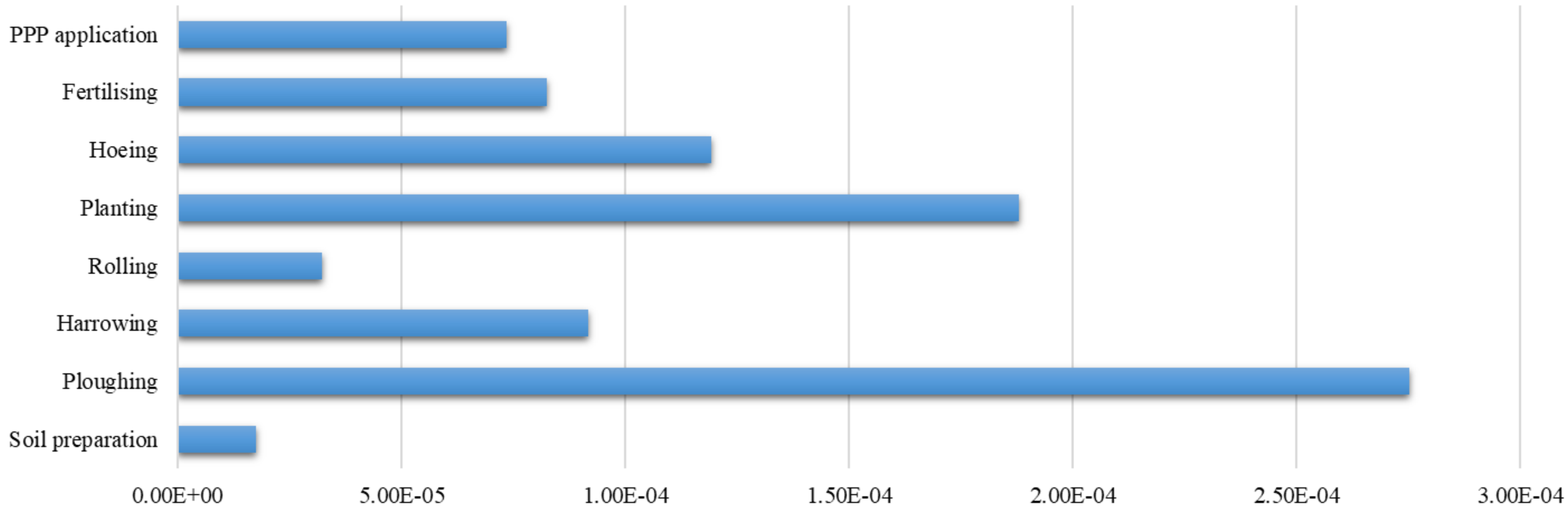

Others non WPTC members; 4,6%
Tunisia (AMITOM member); 1,7%
Others WPTC members; 10,3%
Chile; 2,1%
Iran (AMITOM member); 3,0%
California; 30,1%
Brazil; 3,8%
Italy (AMITOM member); 13,6%
Portugal (AMITOM member); 4,0%
Turkey (AMITOM member); 5,5%
China; 13,5%
Spain (AMITOM member); 7,8%


North District
South District
Hectares invested for tomato growing
0 - 1000
1000 - 5000
5000 - 10000
10000 - 30000

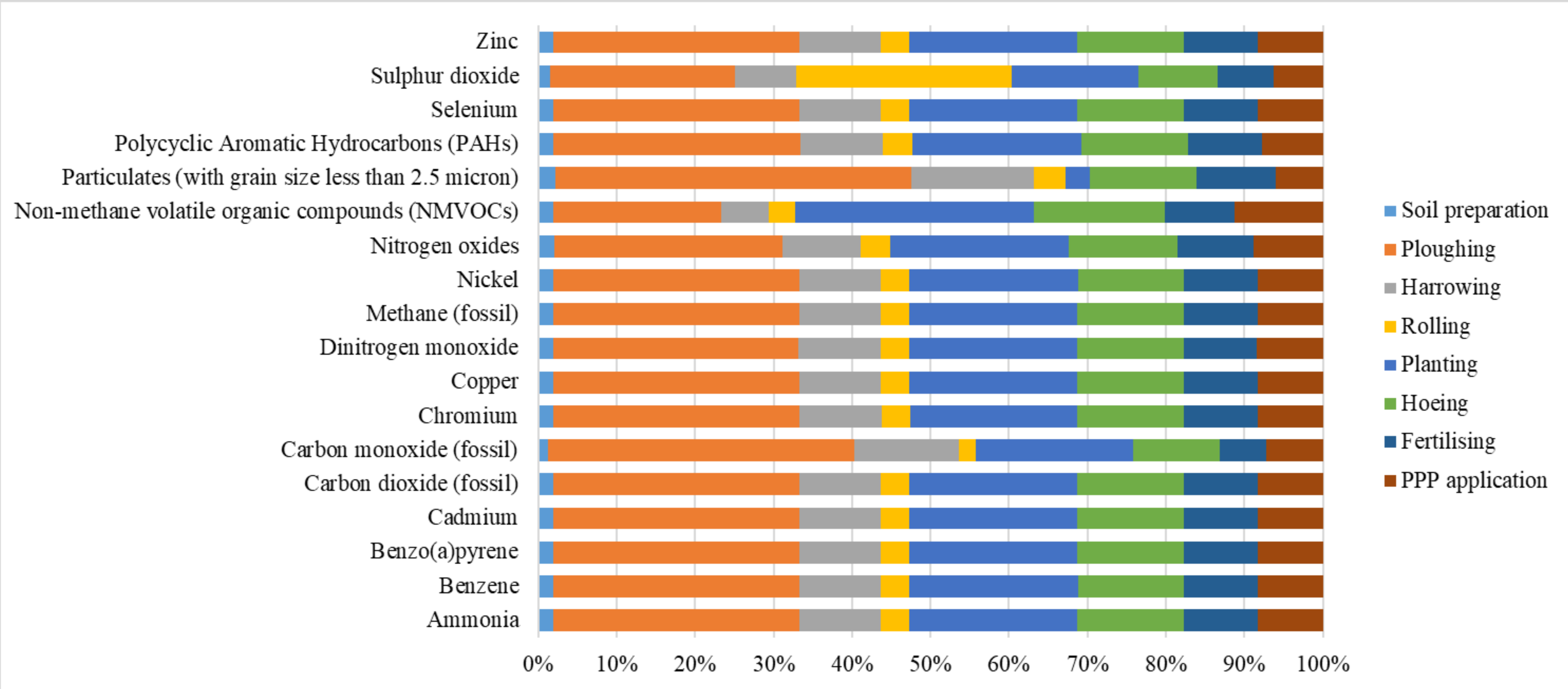


Ouputs from the whole SC
Inputs
Peat
Land occupation
Fertilisers
Water
Plastic container
Greenhouse
Electricity
Transport
SS-1
NURSERY
Inputs
Seedlings
Land occupation
Fertilisers
Plant protection products
Water
Soil preparation
Farming activities
Transport
SS-2
TOMATO CULTIVATION
Inputs
Gross biomass
Combine harvesting
Transport
SS-3
TOMATO HARVESTING
Inputs
Harvested tomatoes
Citric acid
Water
Glass containers
Methane
Electricity
Transport
SS-4
TOMATO PUREE PRODUCTION AND PACKING
Post-use greenhouse plastic covering
Post-use plastic container
On-field emissions
Biomass waste
Wastewater
TOMATO PUREE, PACKED
Landfilling
Composting
Treatment
Border of the supply chain investigated
System boundaries

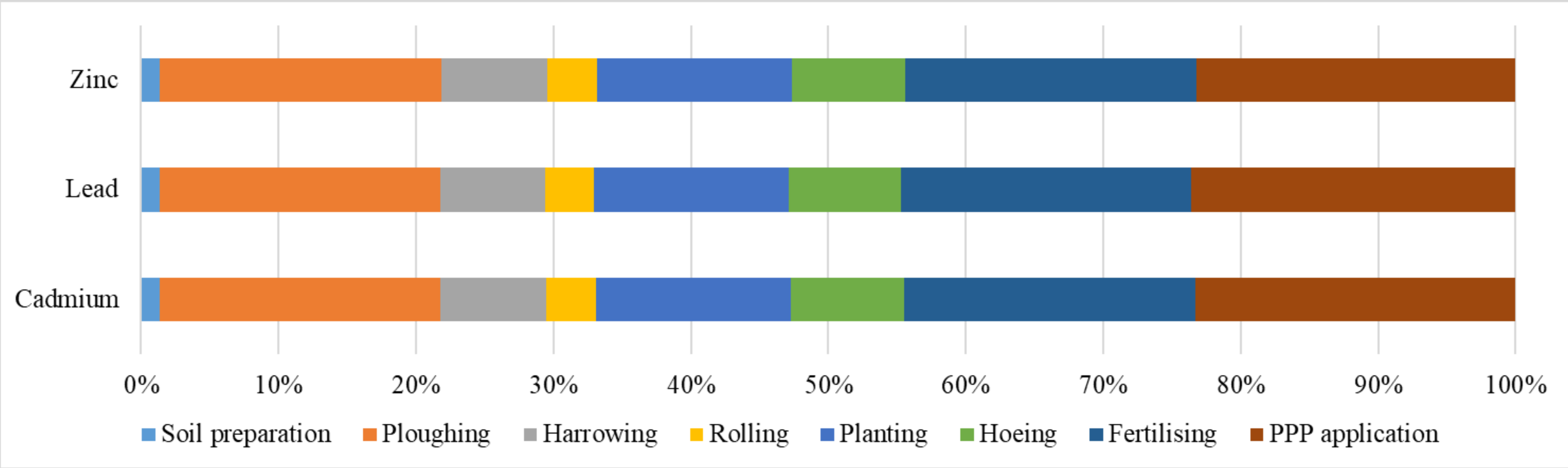

SS-1
NURSERY
One 240-seedling stock, packed in a 160g PS-foam box
FU$_{SS-1}$ = 1 p
6.875E-4 p
SS-2
TOMATO CULTIVATION
Gross biomass
FU$_{SS-2}$ = 1 kg
1.512 kg
SS-3
TOMATO HARVESTING
Harvested tomato
FU$_{SS-3}$ = 1 kg
1.612 kg
SS-4
TOMATO PUREE PRODUCTION AND PACKING
One 685g tomato puree glass jar
FU$_{SS-4}$ (= FU$_{SC}$) = 1 p

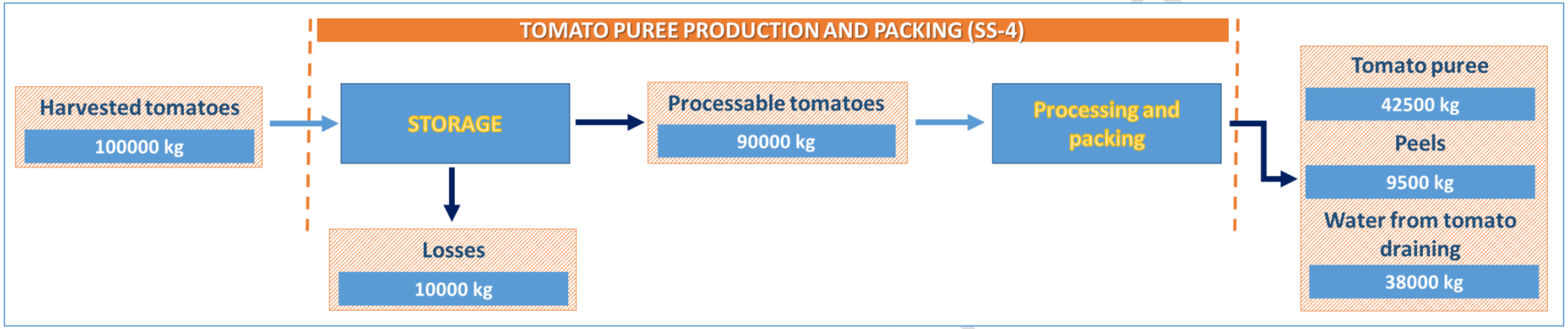


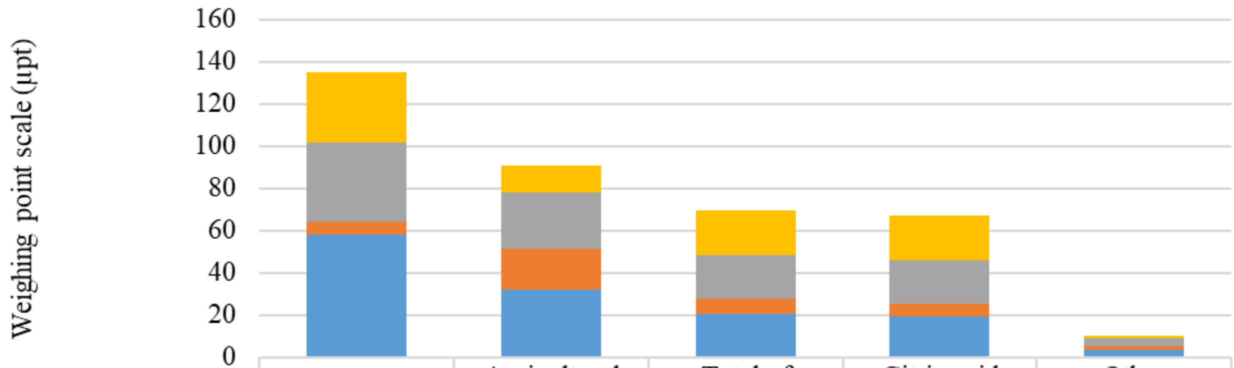
	Soil preparation	Ploughing	Harrowing	Rolling	Planting	Hoeing	Fertilising	PPP application
Diesel consumption	1.75E-05	2.75E-04	9.18E-05	3.21E-05	1.88E-04	1.19E-04	8.26E-05	7.34E-05



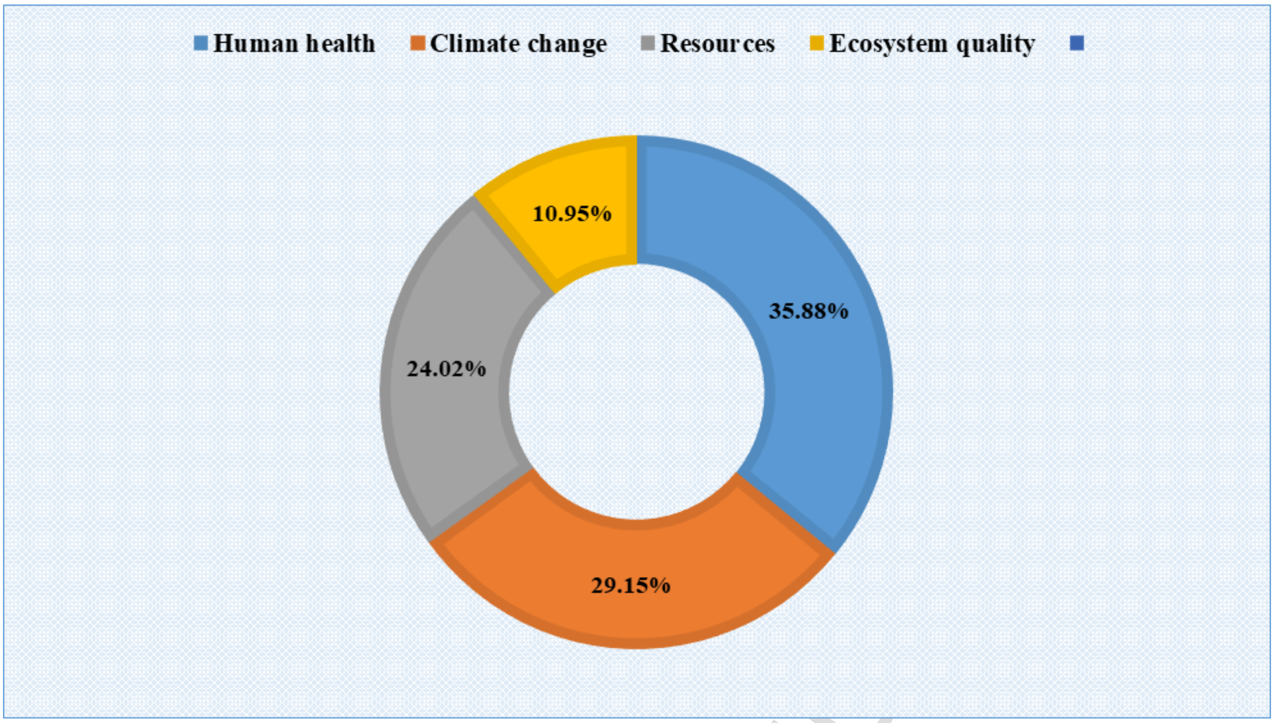
Zinc
Sulphur dioxide
Selenium
Polycyclic Aromatic Hydrocarbons (PAHs)
Particulates (with grain size less than 2.5 micron)
Non-methane volatile organic compounds (NMVOCs)
Nitrogen oxides
Nickel
Methane (fossil)
Dinitrogen monoxide
Copper
Chromium
Carbon monoxide (fossil)
Carbon dioxide (fossil)
Cadmium
Benzo(a)pyrene
Benzene
Ammonia
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Soil preparation
Ploughing
Harrowing
Rolling
Planting
Hoeing
Fertilising
PPP application

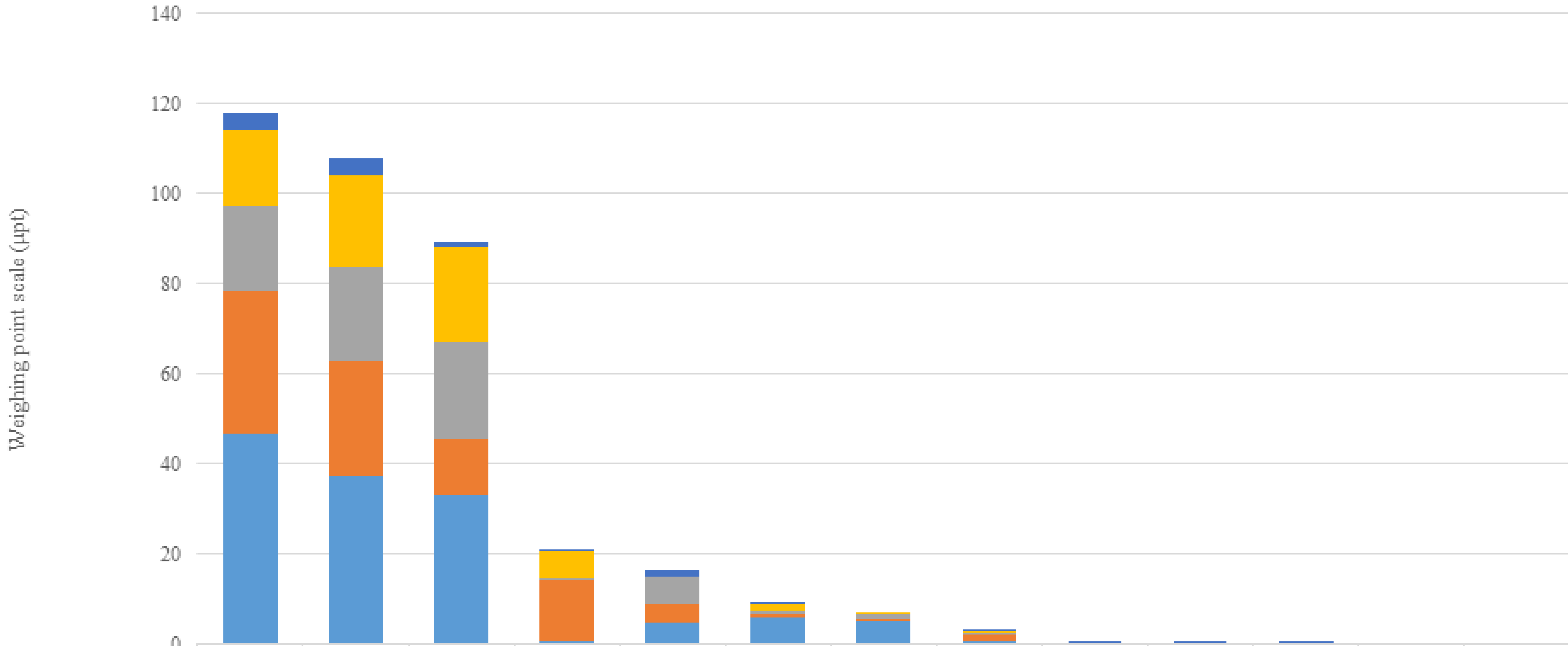

Zinc
Lead
Cadmium
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Soil preparation
Ploughing
Harrowing
Rolling
Planting
Hoeing
Fertilising
PPP application


TOMATO PUREE PRODUCTION AND PACKING (SS-4)
Harvested tomatoes
100000 kg
STORAGE
Losses
10000 kg
Processable tomatoes
90000 kg
Processing and packing
Tomato puree
42500 kg
Peels
9500 kg
Water from tomato draining
38000 kg



	Jar production	Agricultural phase	Total of transports	Citric acid production	Other processes
Resources	33.38	12.40	21.41	21.47	1.06
Climate change	37.31	26.90	20.64	20.24	3.75
Ecosystem quality	6.48	19.37	6.86	6.51	1.67
Human health	57.97	32.13	20.77	19.16	3.70


Human health
Climate change
Resources
Ecosystem quality
10.95%
35.88%
24.02%
29.15%



	Respiratory inorganics	Global warming	Non-renewable energy	Land occupation	Terrestrial ecotoxicity	Carcinogens	Non-carcinogens	Terrestrial acidification/ nitrification	Aquatic ecotoxicity	Ionizing radiation	Mineral extraction	Respiratory organics	Ozone layer depletion
Other processes	3.6308	3.7537	1.0591	0.0329	1.3595	0.1223	-0.0590	0.2414	0.0324	0.0040	0.0001	0.0017	0.0002
Citric acid production	17.1199	20.2381	21.3918	5.9044	0.1938	1.5248	0.3669	0.3314	0.0821	0.1306	0.0819	0.0136	0.0041
Total of transports	18.5582	20.6436	21.3611	0.4602	5.9987	0.7861	1.3389	0.3450	0.0573	0.0488	0.0527	0.0285	0.0053
Agricultural phase	31.6217	25.7221	12.2935	13.5303	4.1459	0.9477	0.4265	1.6735	0.0529	0.0534	0.1067	0.0194	0.0026
Jar production	46.9013	37.3051	33.3094	0.8336	4.8542	5.8534	5.0934	0.6755	0.1206	0.0914	0.0712	0.0265	0.0051

- The paper deals with Life Cycle Assessment of tomato puree supply chain
- The functional unit was 685g tomato puree packed in a 300g-heavy white-glass jar
- Primary and secondary data were inventoried for the study development
- Major environmental impacts were in the packaging and agricultural phases
- Potential improvements were identified

Publication year	Paper reference	Study area	Methodological issues			
			Assessment description	FU	System boundaries	Impact assessment method
2011	Karakaya and Oziligen	Tokat region (Turkey)	Energy utilisation and carbon dioxide emission in the fresh, paste, whole-peeled, diced, and juiced tomato production processes.	one metric ton (1000 kg) of fresh tomatoes	Growth and transportation of tomatoes; Tomato paste production; Whole-peeled and diced-tomato production; Tomato juice production. Including packaging.	Non specified
2011	Martinez-Blanco et al.	County of Maresme (Spain)	LCA to determine agricultural and environmental differences of four cultivation options characterised by greenhouse or open-field cultivation using compost plus mineral fertilisers or only mineral fertilisers.	1 ton of commercial tomato	Compost production (including collection and transport of organic waste); mineral fertiliser production; Transport; Cultivation process in the open field; Cultivation process under greenhouse (including greenhouse structure).	CML2001
2012	Page et al.	Sydney (Australia)	Carbon and water footprints of tomato production.	1 kg of fresh tomato	Pre-farm processes (often referred to as ‘cradle’) such as the extraction of raw materials, production, and transport of inputs.	IPCC
2012	Torellas et al.	Almeria (Southern Spain)	LCA of a tomato crop in a multi-tunnel greenhouse in Almeria	1 ton of loose classic tomatoes	Crop production. Manufacture of greenhouse components, transport of materials, materials disposal and greenhouse management were accounted.	CML2001
2014	Anton et al.	Almeria (Southern Spain)	LCA of greenhouse tomato production to provide a detailed evaluation of new impact categories method, by comparing it with commonly used methods	1 hectare of cultivated field for tomato production	From raw material extraction to the farm gate including material waste disposal	LC-IMPACT (new impact method)
2014	Del Borghi et al.	Provinces of Ferrara and Modena; Emilia Romagna region, Tosco-Laziale Maremma area; Salento, and Provinces of Parma, Piacenza; Basilicata; and Foggia.	LCA to evaluate the environmental impacts of 13 tomato based products	1kg packaged tomato-based product	Cultivation; Transportation to the processing factory; Food processing; Package manufacture; Food packing; End-of-life	CML 2001

2014	Manfredi and Vignali	Emilia Romagna region (Italy)	LCA to: evaluate the environmental impacts of the various stages of tomato cultivation and processing; and to assess possible actions to improve the environmental sustainability of the whole supply chain.	700g of jar-packaged tomato puree	Cultivation; transportation to the factory; tomato processing and packaging; and distribution.	CML 2001 CED ReCiPe
2015	Payen et al.	Souss-Massa region (Southern Morocco)	LCA including freshwater deprivation and identification of the environmental hotspot of off-season tomato production in Morocco and delivery to the French market in winter.	1 kg of fresh bulk tomato	Seedling production; greenhouse manufacture; tomato production, packaging and transportation to the French market.	ReCiPe
2017	De Marco et al.	Southern Italy	LCA to evaluate the environmental impacts of the production and packaging of mashed tomato.	500 g of mashed tomato	Tomato acquisition, processing and packaging	Impact 2002+
2017	Dias et al.	Ontario	LCA to quantify cradle-to-gate environmental impacts of average greenhouse tomato productions in Ontario, by suggestion improvements to operations.	1 kg of packaged tomatoes at the greenhouse gate	Greenhouse infrastructure; seeding production; climate control; tomato cultivation; on-site packaging.	TRACI 2.1 LCIA
2017	Garofalo et al.	Apulia region (Southern Italy)	LCA to evaluate the environmental impact due to GHG emissions of canned tomato at the different production steps in Apulia region (Southern Italy); and to define material and energy flows causing the highest environmental impact and identify potential mitigation strategies throughout this supply chain.	480 g of canned whole-peeled tomato	Tomato cultivation; transport to the processing plant; tomato processing and packing; waste treatment	LCD 2011 Midpoint
2018	Bosona and Gebresendet	Sweden	LCA to assess the environmental burdens of organic tomato produced and distributed in Sweden, by investigating the effect of tomato drying process on environmental impact of organic tomato value chain.	1 ton of fresh tomato	In both cases, the product life cycle consists of three major stages: agricultural production (farming), post-harvest process, and transport activities.	ReCiPe
2018	De Marco et al	Apulia region (Southern Italy)	LCA to evaluate the environmental impacts, through an in-depth "from cradle to grave" analysis, of the production and packaging of mashed tomato (Italian"passata")	500 g of mashed tomato produced and packaged in Tetra Pak® by a Southern Italy company	Tomato cultivation, processing, and packaging. Transports are included	ReCiPe

Sub-system		FU_{SS}		Reference flow (FU_{SS}/FU_{SC})	*UM*
N.	*Description*	*Description*	*Amount*	*Amount*	
1	Nursery	One 240-seedling stock, packed in a 160g PS-foam box	1	1.678E-3	p
2	Tomato cultivation	Gross biomass outlet from 1-year cultivation, represented by tomatoes (67%) and plant bodies (33%).	1	2.437	kg
3	Tomato harvesting	Harvested tomatoes (net production)	1	1.612	
4	TP production and packing	685g TP, packed in a 300g 700g-capacity glass jar	1	1	p

Outputs			
Product	*Amount*	*UM*	*Comment*
Seedlings	1	p	The FU of this first SS was chosen to be a 240-seedling stock, packed in a 160g holed PS-foam container.
Waste streams	*Amount*	*UM*	*Comment*
LDPE film	6.891E-4	kg	Both waste commodities are generated from GPCS unpacking in the seedling production site and, then, are sent to recycling plants.
CBB	1.307E-3	kg	
Post-use GPCS	0.0624	kg	As is known in such cases, the GPCS cannot be recycled after application because it is damaged by agricultural activities and climate conditions. Therefore, it is treated in a sanitary landfill.
Inputs			
Resources	*Amount*	*UM*	*Comment*
Peat	2.4	kg	This is the amount of peat used as seedling substrate in the PS-foam container.
Material and energy commodities	*Amount*	*UM*	*Comment*
Water	500	g	This is water consumed for dilution of fertilisers and subsequent administration through drip irrigation. In this study, water was modelled as a raw material, because the Ecoinvent dataset considers 1kg tap water production under pressure at facility gate, ready for distribution in network. It represents average operation of tap water from underground water without further treatments. Water is pumped from aquifer and pressurised for distribution: which is what occurs in this system, actually. From there on, the Water Piping System (WPS) for drip irrigation with micro-irrigators, hydraulic fittings and so on was not accounted for, due to the difficulty of collecting reliable primary and secondary data. Therefore, to avoid excessive uncertainty risk, the WPS was excluded from the system boundaries. This choice was also supported by the fact that, considering its service life (20 years for the pipes and 10 years for the micro-irrigators), low environmental impacts were expected compared to the other materials, processes and phases, on the equal FU base (FU_{SS-1} and FU_{SC}).
N-fertiliser	50	mg	Values alongside were provided by the seedling production manager as referred to the single 240-seedling stock.
P_2O_5-fertiliser	3.75		
K_2O-fertiliser	35		
Foamy polystyrene (PS) containers	160	g	Production of these containers was modelled combining primary information collected on site with secondary one from Ecoinvent, choosing 1kg container as the FU of the process. In particular, the model created contains 1.05kg expandable PS-granules to be foamed first and then thermoformed with calendaring. Overall, the process generates 0.05kg scraps that are transported to and treated in an industrial plant for plastic mix recycling.
Electricity	1.166	kWh	This is the electricity spent in the germination phase. Estimation of the alongside value was done considering that almost 208 of those 240-hole boxes, initially containing just peat with the seed within, are inserted in the

			germination chamber and stay for an average time of 54 h. In addition to this, a 4.5kW power is installed and utilised for the working of the chamber: that was accounted for in the calculation of the value alongside.
Greenhouse System (GHS)	*Amount*	*UM*	*Comment*
Concrete/steel structure life cycle	1.518E-4	p	In agreement with several authors in this field like Martinez-Blanco et al. (2011) and Torellas et al. (2012), the GHS utilised in the nursery phase was taken into account for the assessment. The value alongside was computed considering that: the entire GHS stands on a 2ha land, has a 30-year service life and generally contains 50000 tomato-seedlings with a 15-day long stay within the GHS itself. In addition to this, in the calculations it was computed that this GHS is used for tomato seedling production just 2 months a year, corresponding to 16.67% of its yearly service time. The GHS is composed by 14 serially-placed, joint tunnel-greenhouse modules; each with a ground surface equal to 1428 m^2 and the following dimensions: width (14.28 m); length (100 m); and height (2.5 m) Each module life cycle was modelled as 1p, through the accounting of its installation, inclusive of the raw material preparation and acquisition phase, and its dismantling. The use phase was not taken into account, because the greenhouse is un-heated and marginal operations are carried out with negligible environmental impacts; for instance, no lighting system is installed within the greenhouse, because all activities including those for the marketing of the seedlings are developed during the light hours. Metric calculations from the design phase were provided by the farmer and used for the modelling of the production/assembly phase. To this end, the following inputs were taken into account for each GHS module: 37.38m^3 ready-mixed concrete for the foundation plinths; 867.62kg reinforcement steel; 9.22t low-alloyed tubular steel for the framed structure; and a total 2.28ktkm transport flow. The installation phase was modelled considering a 40.89m^3 soil excavation by means of a hydraulic digger, consuming 5.336kg diesel. Ready-mixed concrete was assumed to be poured through a bucket at the end of the mixer truck utilised for its transport to the GHS installation site. In addition to this, steel elements composing the GHS structure were considered as being mounted manually by around 5 workers in the time calculated according to equation 1. $8\ {}^{h}/_{d} \times 3\ {}^{d}/_{GHS\ module} \times 14\ {}^{modules}/_{GHS} = 336\ h$ (1) This is because each GHS module is characterised by a 2.5m height, which makes it possible that all components are assembled on the ground utilising battery-equipped screwdrivers (each worker has one) and then manually lifted and installed. Therefore, no significant environmental impacts were worth to be accounted but the electricity consumption associated with the screwdriver usage. For electricity computation, based upon information provided by specialised workers, it was reasonably considered that screwing was done in half of the overall time required for GHS installation. Screwdrivers have batteries being characterised by 18V voltage and 1.5A amperage and chargeable in 45 minutes: therefore, each battery requires 20.25Wh electricity consumption for being charged and then gives an 8h usage duration to the screwdriver. Subsequently, considering the screwing time in the GHS assembly, each battery requires charging a total of 21 times for a total of ~16h; hence, the overall electricity consumption for charging was obtained through equation 2.

			$(20.25\ Wh \times 21) \times 5 = 2.126\ kWh$ (2) The end-of-life was modelled starting from the GHS demolition with usage of: a hydraulic digger for dismantling the concrete plinths and loading the resulting waste on the means for its transport to the treatment plant. Whilst, in the case of the GHS steel structure, both disassembly and loading on the means for transport to the related treatment were done manually, so meaning that no environmental impacts were taken into account. Finally, included in this phase was the treatment of the Demolition Waste (DW): in particular, the structural steel was considered to be fully recyclable, and a combination of PD and BD was used for its modelling. In doing so, the substitution approach was applied and so the related avoided product (1kg virgin steel per kg of steel waste treated) was considered. In this way, the environmental gains resulting from steel recycling were duly considered, thereby making recycling environmentally advantageous. By contrast, with regard to treatment of the waste reinforced concrete, the latter is disposed of in an inert material landfill, according to the local practice.
Greenhouse Plastic Covering Sheet (GPCS), packed	0.0644	kg	The GPCS considered is manufactured through co-extrusion of a set of plastic polymers, in the following percentages: LDPE, 37.27%; Linear-LDPE (LLDPE), 45.32%; Polyvinyl Chloride (PVC), 10%; and Ethylene Vinyl Acetate (EVA), 7.5%. The alongside value is given by: the covering, for 96.90%; and the package, for 3.10%. In particular, the covering sheet is packed with an LDPE-film (6.891E-4 kg), and then with a Corrugated Board Box (CBB) (1.307E-3 kg).
Transports (for supply of)	*Amount*	*UM*	*Comment*
Fertilisers	0.12	kgkm	The travelled distance was: 1350 km, for the fertilisers; 490 km, for the container; and 85 km, for the GPCS. In the former case, the transport module used was "Transport, freight, lorry 3.5-7.5 metric ton, EURO 6 {RoW} | transport, freight, lorry 3.5-7.5 metric ton, EURO 6 | Alloc Def, S", whilst in the latter two were "Transport, freight, lorry 3.5-7.5 metric ton, EURO 5 {RoW} | transport, freight, lorry 3.5-7.5 metric ton, EURO 5 | Alloc Def, S".
PS-foam containers	78.4		
GPCS	5.474		
Transports (for disposal of)	*Amount*	*UM*	*Comment*
Post-use GPCS	2.933	kgkm	The following travelled distances were computed: 47 km, for the post-use GPCS; 37.5 km, for the LDPE film; and 129 km for the corrugated board. Considering information provided by the seedling production system manager, the following transport modules were extrapolated from Ecoinvent and used for all the three transport flows: "Transport, freight, lorry 7.5-16 metric ton, EURO 5 {RoW} | transport, freight, lorry 7.5-16 metric ton, EURO 5 | Alloc Def, S"
LDPE film	0.0258		
CBB	0.169		

			Outputs
Product	*Amount*	*UM*	*Comment*
Gross biomass	1	kg	This is the total biomass output from the cultivation phase, just before harvesting. It is composed by: tomato for 67%; and plant body for the remaining 33%. This was calculated considering that: 101300kg is the gross tomato production; whilst 50000kg is the vegetation mass (stems, leaves and roots). The latter was estimated from the consideration that: the mass of a single tomato plant at the final step of cultivation (before tomato harvesting) is around 2kg; and 1ha of cultivated land contains 25000 plants. Based upon those values, the surface invested for production of FU_{SS-2} (SI_{SS-2}) was calculated as of equation 3. $SI_{SS-2} = 1\ ha / 151300\ kg = 6.61E-6\ ha/kg$ (3)
Wastes	*Amount*	*UM*	*Comment*
Post-use seedling-containing PS-foam boxes	0.11	g	This amount was computed by considering that each container has a 160g weight, and that 6.875E-4 p of them are required for production of 1kg gross-biomass.
			Inputs
Resources	*Amount*	*UM*	*Comment*
Occupation of ploughed, irrigated land (intensive cultivation regime)	6.61E-6	ha y	This is the amount of surface invested for FU_{SS-2} production.
Material and energy commodities	*Amount*	*UM*	*Comment*
Seedling stock (output from SS-1)	6.875E-4	p	The value alongside was calculated considering that: around 104 of 240-seedling stocks are used for planting 25000 seedlings in 1ha of cultivated field; and 6.61E-6 ha is the amount of surface invested for production of 1kg total biomass as the FU of this second SS (SS-2). For details related to the seedling production dataset, please check Table 3.
Water	33.05	l	This water is utilised for dilution of fertilisers and subsequent administration through drip irrigation. Please see Table 3 for information related on its modelling, because the same choices were made.
Fertilisers	*Amount*	*UM*	*Comment*
Urea	1.322E-3	kg	This was estimated considering that 200kg urea are used for 1ha field fertilisation.
N-fertiliser	1.983E-3	kg	These fertilisers are applied through ferti-irrigation using the amount of water indicated above; the values alongside were obtained from the amounts used for 1ha land fertilisation, namely: 300 kg_{N}; 80 kg_{P2O5}; 350 kg_{K2O}; 350 $kg_{Ca(NO3)2}$; and 70 kg_{MgO}.
P_2O_5-fertiliser	5.288E-4		
K_2O-fertiliser	2.314E-3		
Calcium nitrate [$Ca(NO_3)_2$]	2.314E-3		
Magnesium oxide (MgO)	4.627E-4		
Plant Protection Products (PPPs)	*Amount*	*UM*	*Comment*

Glyphosate	1.322E-5	kg	As for the fertilisers and other inputs in this table, the values alongside were obtained referring to this SS FU for the related amounts per ha of cultivated field, namely: Glyphosate (2 kg); Aclonifen (4 kg); $CuSO_4$ (6 kg); Sulphur (2 kg); other PPPs for a total of 5.25 kg. The latter are represented by: metribuzin; cicloxidin; fenoxaprop-P-ethyl; and D-isomer quizalofop ethyl. As indicated by Nemecek and Kägi (2007), they were modelled as "Pesticides, unspecified {GLO} | market for | Alloc Def, U", because related production modules were not found in Ecoinvent and collecting PD would have been extremely hard to be done. However, considering their rather low amounts per kg of harvested tomato according to the authors, negligible differences in environmental impact and resultant uncertainties were expected. For clearness reason, it is specified that the module used contains in it the module "Pesticides, unspecified {RER} | production | Alloc Def, U", which considers production of 1kg pesticide active-ingredient from preparation and acquisition of raw materials, whose amounts were calculated in a stoichiometric manner. Consumption of energy for the process and overall emission of pollutants were found accounted for in that module.
Aclonifen	2.644E-5		
Copper sulphate ($CuSO_4$)	3.966E-5		
Sulphur	1.322E-5		
Others	3.47E-5		
Agricultural activities	*Amount*	*UM*	*Comment*
Soil preparation	3.173E-7	ha	The soil preparation phase is mainly based upon ploughing related activities. For this reason, it was modelled using ploughing BD but making all required adjustments in: the diesel consumption; the mass-shares of both tractor and agricultural machinery implied in the process; and the resultant emissions. The same was done for the activities considered as characterising the farming phase, based upon information provided by the farmer; they were: ploughing; rotary harrowing; rolling; planting; hoeing; urea application (fertilising); and PPP administration. For the purpose of their modelling, the related Ecoinvent modules were used and accessed, but differences were found. Therefore, adjustments were operated by replacing background Diesel Consumption Amounts (DCAs) contained in those modules with primary values related to the SC investigated. Changes were made also with regard to the amount (in kg) of 4-wheel tractor and agricultural machinery utilised for each single agricultural activity. Related calculations were developed according to the LCI guidelines on Swiss and European agricultural production systems by Nemecek and Kägi (2007): to that end, the time to perform each single farming treatment were considered based upon information provided by the farmer (expressed as h per ha). The following equations were so extrapolated from Nemecek and Kägi (2007) and used to estimate the mass of tractor (TM) and the mass of agricultural machinery (AMM) implied in that Farming Treatment Time (FTT): -for the tractor case $TM_{FTT}[kg] = {}^{TM}/_{TSS} \times FTT$ (4) where: TM is 3000 kg (Ecoinvent, 2016); and TSS is the tractor service life, equal to 7000 h (Ecoinvent, 2016). -for the agricultural machinery case $AMM_{FTT}[kg] = {}^{AMM}/_{AMSS} \times FTT$ (5) where: AMM is 800-1000 kg (Ecoinvent, 2016) and AMSS is the service life of the agricultural machinery, equal to 800-1000 h (Ecoinvent, 2016), both depending upon the farming treatment considered. If it is about tillage-related operations like ploughing, rotary harrowing, rolling, and hoeing, the agricultural machinery contained in those Ecoinvent models is "Agricultural machinery, tillage {GLO}| market for | Alloc Def, U". Whilst, for general cultivation activities like planting, fertilisation, and PPP application, the agricultural machinery model used in Ecoinvent was "Agricultural
Farming	6.61E-6		

			machinery, unspecified {GLO}| market for | Alloc Def, U". For each of the two agricultural machinery models, differences from one farming/tillage activity to the other were described by the different AMM implied. Furthermore, in both cases, the AMM/AMSS ratio was always equal to 1 kg/h, which brings to equal absolute values between AMM and FTT, as it is shown in Table 5. Finally, it should be observed that a different value was used to input soil preparation into the farming phase, because it is carried out every 21 years: therefore, a 0.048 Correction Factor (CF) was calculated and used for due computation of the related input flow. The related alongside value was obtained through equation 6. $(SI_{SP})_{SS-2} = CF \times SI_{SS-2}$ (6) where: - $(SI_{SP})_{SS-2}$ is the surface involved in the soil preparation activity as referred to FU_{SS-2}; - CF is the correction factor used for the case and equal to 0.048; and - SI_{SS-2} is the surface invested for production of this sub-system FU (1kg gross biomass), and is equal to 6.61E-6 ha.
Transports (for supply of)	*Amount*	*UM*	*Comment*
All inputs to this SS-2	0.608	kgkm	The value alongside was calculated from the data provided by the farmer on the amount of diesel consumed for input transport issue: 10.028 kg/ha. According to the information provided by the farmer on the transport means utilised, the Ecoinvent module "Transport, freight, lorry 3.5-7.5t, EURO 5" was accessed for computation of the related transport flow. From that module, the related DCA item (0.109 kg/tkm) was extrapolated and used to calculate the value of 92 tkm/ha, which was then referred to this SS-2 FU through multiplication by the associated surface invested (6.61E-6 ha/FU_{SS-2}): the value alongside was so obtained.
Transports (for disposal of)	*Amount*	*UM*	*Comment*
Post-use seedling-containing PS-foam box	5.5E-3	kgkm	Disposal was in a sanitary landfill located at 50km distance from the farm.

Farming activity	Diesel consumption	FTT	FTT-related agricultural equipment	
			Tractor	Machinery [a,b]
	kg	h	kg	
Soil preparation [a]	55.528	5.5	2.357	5.5
Ploughing [a]	41.65	4	1.714	4
Harrowing [a]	13.88	1.5	0.643	1.5
Rolling [a]	4.862	0.7	0.3	0.7
Planting [b]	28.459	2.7	1.157	2.7
Hoeing [a]	18.044	1.8	0.686	1.8
Fertilising [b]	12.49	4	1.714	4
PPP application [b]	11.107	4	1.714	4
TOTAL	186.02	24.2	10.285	24.2

As clarified in Table 4, in tillage-related activities, the agricultural machinery utilised was modelled using the Ecoinvent module "Agricultural machinery, tillage {GLO}| market for | Alloc Def, U" [a], whilst it was represented with "Agricultural machinery, unspecified {GLO}| market for | Alloc Def, U" [b] for the modelling of the other cultivation activities considered.

Emitted substance	Soil preparation	Key farming activities							TOTAL
		Ploughing	Harrowing	Rolling	Planting	Hoeing	Fertilising	PPP application	
	Amount (kg)								
Emissions to air (from diesel combustion)									
Ammonia	1.109E-3	8.328E-4	2.78E-4	9.71E-5	5.692E-4	3.603E-4	2.5E-4	2.228E-4	3.719E-03
Benzene	4.051E-4	3.047E-4	1.013E-4	3.547E-5	2.084E-4	1.315E-4	9.117E-5	8.142E-5	1.359E-03
Benzo(a)pyrene	1.664E-6	1.25E-6	4.164E-7	1.457E-7	8.538E-7	5.408E-7	3.755E-7	3.339E-7	5.580E-06
Cadmium	5.553E-7	4.164E-7	1.388E-7	4.862E-8	2.846E-7	1.804E-7	1.25E-7	1.111E-7	1.860E-06
Carbon dioxide (fossil)	172.925	129.542	43.09	15.107	88.596	56.11	38.968	34.65	578.988
Carbon monoxide (fossil)	0.22	0.332	0.112	0.0193	0.17	0.0935	0.0496	0.0618	1.058
Chromium	2.776E-6	2.09E-6	6.94E-7	2.431E-7	1.423E-6	9.022E-7	6.259E-7	5.567E-7	9.311E-06
Copper	9.43E-5	7.0833E-5	2.354E-5	8.257E-6	4.845E-5	3.064E-5	2.126E-5	1.893E-5	3.162E-04
Dinitrogen monoxide (N_2O)	6.65E-3	4.99E-3	1.67E-3	5.825E-4	3.422E-3	2.16E-3	1.5E-3	1.338E-3	2.231E-02
Methane (CH_4), fossil	7.16E-3	5.38E-3	1.79E-3	6.27E-4	3.676E-3	2.33E-3	1.61E-3	1.439E-3	2.401E-02
Nickel	3.876E-6	2.92E-6	9.704E-7	3.394E-7	2E-6	1.26E-6	8.74E-7	7.763E-7	1.302E-05
Nitrogen oxides (NOx)	2.427	1.643	0.564	0.213	1.287	0.792	0.546	0.499	7.971
Non-methane volatile organic compounds (NMVOCs)	0.149	0.0814	0.0227	0.0131	0.115	0.0633	0.0337	0.0426	5.208E-01
Particulates (with grain size less than 2.5 micron)	0.218	0.22	0.0757	0.0191	0.0154	0.0654	0.0491	0.0292	6.919E-01
Polycyclic Aromatic Hydrocarbons (PAHs)	1.816E-4	1.37E-4	4.562E-5	1.59E-5	9.368E-5	5.941E-5	4.109E-5	3.361E-5	6.079E-04
Selenium	5.553E-7	4.164E-7	1.388E-7	4.862E-8	2.846E-7	1.804E-7	1.249E-7	1.111E-7	1.860E-06
Sulphur dioxide (SO_2)	0.0559	0.042	0.014	0.049	0.0286	0.0182	0.0126	0.0112	2.315E-01
Zinc	5.553E-5	4.164E-5	1.388E-5	4.862E-6	2.846E-5	1.804E-5	1.25E-5	1.111E-5	1.860E-04
Emissions to soil (from tyre abrasion)									
Cadmium	1.113E-6	8.207E-7	3.084E-7	1.441E-7	5.693E-7	3.296E-7	8.483E-7	9.345E-7	5.07E-06
Lead	4.954E-6	3.595E-6	1.344E-6	6.305E-7	2.49E-6	1.441E-6	3.717E-6	4.165E-6	2.23E-05
Zinc	3E-3	2.17E-3	8.17E-4	3.82E-4	1.503E-3	8.733E-4	2.24E-3	2.46E-3	1.34E-02

Outputs			
Product	*Amount*	*UM*	*Comment*
Harvested tomatoes	1	kg	This is FU_{SS-3}. Based upon the information provided by the farmer, a 100t net-production was considered for data collection and elaboration as part of this assessment.
Waste streams	*Amount*	*UM*	*Comment*
Harvesting residues	0.512	kg	As clarified above, this biomass is treated in a compost plant: this was described through the Ecoinvent module "Compost {RoW} | treatment of biowaste, composting | Alloc Rec, U". However, being considered and modelled as a disposal scenario and not as an organic fertiliser production system, the authors of this paper believed the substitutional approach as reasonably applicable. That module was, indeed, adjusted by incorporating in it the amounts of N-, P_2O_5-, and K_2O-fertiliser avoided per kg of compost produced (7g, 5g, and 6g, respectively), so taking better account of the environmental benefits resulting from this biomass recovery process.
Emissions, from N-fertiliser application	*Amount*	*UM*	*Comment*
Ammonia (to air)	1.98E-4	kg	The emissions generated from N-fertiliser application were calculated using Brentrup et al. (2000) from a total N-input equal to $3.918E-3\ {kg_N}/{FU_{SS-3}}$, which was elaborated as follows: $\left(6.081E-4\ {kg_{N_a}}/{FU_{SS-2}} + 1.983E-3\ {kg_{N_b}}/{FU_{SS-2}}\right) \times 1.512\ {kg_{FU_{SS-2}}}/{FU_{SS-3}}$ (12), where: N_a, is the nitrogen contained in the amount of urea and N_b is the amounted of N in ferti-irrigation, both applied per kg of gross biomass outlet from SS-2. By contrast, those from P_2O_5-fertilisation were estimated through Nemecek and Kägi (2007) using the P_2O_5-input reported in Table 4 but referred to this SS-3 FU, namely $7.995E-4\ {kg_{P_2O_5}}/{FU_{SS-3}}$. In this regard, it should be observed that, for mere modelling reasons, these emissions were associated with this harvesting-related SS, because they are developed during farming but are actually materialised in the harvesting phase. This is with special regard to ammonia leaching because, for its correct computation according to Brentrup et al. (2000), "N-removal with harvested crop" was required to be accounted and was equal to $3.918E-3\ {kg_N}/{FU_{SS-3}}$. This issue clearly occurs - and so was attributed to - the harvesting stage. Finally, N- input and removal have equal values because the whole tomato plantation is harvested and hence removed from the soil.
Nitrogen (to air)	3.35E-4		
Dinitrogen monoxide (to air)	4.65E-5		
Nitrate leaching (emission to groundwater)	1.967E-5		
Emissions, from P-fertiliser application	*Amount*	*UM*	
Phosphorus (to groundwater)	7E-7	kg	
Phosphorus (to surface water/river)	2.1E-6		
Inputs			
Material and energy commodities	*Amount*	*UM*	*Comment*

Gross biomass (output from SS-2)	1.512	kg	As specified in Table 4, this is the total biomass that outlets the cultivation phase: tomato is 67%, whilst the plant body represents the remaining 33%. This was calculated considering that: 101300kg is the gross tomato production; whilst 50000kg is the vegetation mass (stems, leaves and roots). The latter was estimated considering that: the mass of a single tomato plant at the final step of cultivation (before tomato harvesting) is around 2kg; and, based upon primary information provided, 1ha of cultivated land contains 25000 plants. Therefore, 1.013kg tomatoes and 0.499kg plantation waste are obtained from 1.512kg input gross biomass. From harvesting, 0.013kg tomato residues are generated due to unripe and/or over-ripened tomatoes. Those residues along with the plantation waste (harvesting residues) are treated in a compost plant, for a total of 0.512 kg.
Agricultural activities	*Amount*	*UM*	*Comment*
Combine harvesting	9.994E-6	ha	The value alongside was calculated as follows: $(SI_{CH})_{SS-3} = (GB_{SS-2})_{SS-3} \times SI_{SS-2}$ (11) where: -$(SI_{CH})_{SS-3}$ is the surface involved in the combine harvesting stage as referred to the SS-3 FU; - $(GB_{SS-2})_{SS-3}$ is the gross biomass outlet from SS-2 that enters SS-3 in the amount required for production of the related FU, namely 1kg harvested tomatoes. That amount was calculated to be equal to $1.512\ kg_{GB_{SS-2}}/FU_{SS-3}$; -$SI_{SS-2}$ is the amount of land involved in the production of FU_{SS-2} (1kg gross biomass), namely $6.61E-6\ ha/kg_{GB_{SS-2}}$. The harvesting phase was modelled using the Ecoinvent module "Combine harvesting {RoW} | processing | Alloc Def, U" but adjustments were made, due to the differences in terms of: DCA and the amount of agricultural equipment implied (tractor + machinery); and to the emissions resulting from diesel combustion and tyre abrasion. Those adjustments were operated as was done for the activities in the farming step (see Table 4). In particular, the DCA-related BD (33.324 kg/ha) was replaced with the PD provided by the farmer and equal to 43.954 kg/ha: a 1.319 CF was so calculated and used for adjustment of the diesel combustion derived emissions. It goes without saying that the DCA referred to this SS-3 FU is equal to 4.393E-4 kg. The so calculated emissions from diesel combustion were reported in Table 8. With regard to the machinery utilised, a 10000kg harvester with a 1300h service life is contained in that Ecoinvent module and, in agreement with the farmer, was considered by this author team to be representative of the real version implied. Relating the mass to the service life, a 7.692kg/h ratio was calculated. The latter was used, in turn, to estimate the harvester mass employed for 100t/ha tomato harvesting in a 12h time; the following value was resulted: 92.304 kg/ha, corresponding to 9.225E-4 kg/FU_{SS-3}. Great difference was recorded by comparing that value with the background one contained in Ecoinvent and equal to 6.3 kg/ha: a 14.65 CF was so calculated to adjust the tyre-abrasion derived emissions. Emissions to soil from tyre abrasion were found to be equal to: 5.535E-10 kg/FU_{SS-3} (Lead); 1.291E-10 kg/FU_{SS-3} (Cadmium); and 3.488E-7 kg/FU_{SS-3} (Zinc).
Transports (for disposal of)	*Amount*	*UM*	*Comment*

Harvesting residues	25.6	kgkm	To the compost plant, travelling for a 50km distance. Based upon information provided by the farmer, the following Ecoinvent module was chosen to describe this transportation phase: “Transport, freight, lorry 3.5-7.5 metric ton, EURO 4 {RoW} | transport, freight, lorry 3.5-7.5 metric ton, EURO 5 | Alloc Def, S”.

Type	*Amount (kg)*	*Type*	*Amount (kg)*	*Type*	*Amount (kg)*
Ammonia	8.780E-09	Chromium	2.203E-11	NMVOCs	1.909E-06
Benzene	3.203E-09	Copper	7.467E-10	Particulates (with grain size less than 2.5 micron)	1.969E-06
Benzo(a)pyrene	1.318E-11	Dinitrogen monoxide	5.277E-08	PAHs	1.463E-09
Cadmium	4.392E-12	Methane (fossil)	5.667E-08	Selenium	4.392E-12
Carbon dioxide (fossil)	1.359E-03	Nickel	3.074E-11	Sulphur dioxide	4.427E-07
Carbon monoxide (fossil)	4.217E-06	Nitrogen oxides	2.243E-05	Zinc	4.392E-10

Outputs			
Product	*Amount*	*UM*	*Comment*
685g TP, packed in a 300g-heavy glass container	1	p	Each jar is characterised by a maximum capacity of 700 g but is never completely filled: an almost 98% filling rate was, indeed, considered based upon information provided by the producer in agreement with the regular practice: a 685g filling amount was, so, calculated.
Waste streams	*Amount*	*UM*	*Comment*
Residual biomass	0.314	kg	This includes both peels (0.153 kg) and losses from sorting due to storing (0.161 kg). Both are treated in the same compost plant as the one considered for treatment of the biomass residual streams form SS-3 (see Table 7)
Wastewater	3.769	l	In this amount, there are included: the water-serum mix outlet from tomato blanching, in the amount of 0.738l (corresponding to 45800 kg per 100000 kg of processed tomato); 0.613l water that is drained from blanched tomatoes; and the water used for the cleaning of sorted tomatoes (2.418 l). All of them were considered as disposable in an average wastewater treatment plant; based upon the SC location as well as information directly provided by the producer, the Ecoinvent module “Wastewater, average {RoW} | treatment of, capacity 1.1E10 l/y | Alloc Rec” was considered as suitable to describe this activity. Wastewater transport to the treatment plant takes place through connection to the local sewer network.
Inputs			
Material and energy commodities	*Amount*	*UM*	*Comment*
Input tomatoes (from SS-3)	1.612	kg	Amount of fresh tomato required for production of 0.685kg puree to be packed by a 700g capacity glass container. For greater understanding, it is clarified that the value alongside was calculated from the mass balance associated with the processing step (see Fig. 9), in the following elaboration: $^{100000\ kg}/_{42500\ kg} \times 0.685\ kg$ (13) As shown in Fig. 9, 10% losses are generated, on average, from tomato storage: this means that the net amount of workable tomatoes is 90000 kg, corresponding to 1.451 kg as referred to this SS FU.
Water	3.156	kg	This is the sum of the water used for cleaning (2.148 kg) and blanching (0.738 kg) of the input fresh tomatoes. The value alongside was estimated considering that, in the process, cleaning comes after first sorting and the related water demand is 150 m^3. Therefore, water for cleaning was computed as follows: $^{150\ m^3}/_{90000\ kg} \times 1.451\ kg$ (14) Whilst, water demand for blanching 90000kg tomatoes is 45800 kg; so, the amount referred to this SS-FU was calculated as: $^{45800\ kg}/_{90000\ kg} \times 1.451\ kg$ (15) For both cases, the Ecoinvent model used is the same of Table 2, because the same modelling choices were made except for the WPS-related issue which is clearly not pertaining to this case. Therefore, the reader is recommended to refer to that table for related details.

			After usage, the overall amount of water (3.156 kg) is disposed of in a wastewater treatment plant, through the local sewer network.
Citric acid	66.89	g	It is utilised with preservation functions. The value alongside was elaborated according to equation 16, so that it was referred to this SS FU. $(A_{CA})_{SS-4} = (A_{CA}/ TP_{NP}) \times A'_{TP} \times D_{CA}$ (16) In the formula: -$(A_{CA})_{SS-4}$ is the amount of citric acid as referred to FU_{SS-4}; -A_{CA} is the primary data and stands for the amount demanded for production of 42500kg TP, and is equal to 2500 l; -TP_{NP} is the net production of tomato puree outlet from the transformation plant and equal to 42500 kg, as shown in Fig. 9; -A'_{TP} is the amount of packed TP, namely 0.685kg; and -D_{CA} is citric acid density which was found in the specialised literature to be equal to 1.66 g/cm^3 in standard conditions (Apelblat, 2014). For the modelling of citric acid production as part of the raw material preparation step associated with the SC investigated, the Ecoinvent module used is: "Citric acid {RER} | production | Alloc Def, S".
Primary package	300	g	This is represented by: a 300g-heavy white glass jar that is utilised to contain 685g TP, as discussed above; and its cap, with a nearly 10g weight. The latter was not modelled because both primary and secondary data were not available but, following Manfredi and Vignali (2014), in the LCIA phase it will be accounted that caps contribute around 15% of the environmental impacts associated with production of the jars. Whilst, the white glass jar was modelled using the Ecoinvent dataset "Packaging glass, white {GLO} | packaging glass production, white, without cullet | Alloc Def, S", which includes: material and energy inputs; water consumption; emissions to air and water; waste production; and infrastructure. This module was considered by this author team to be well representative of the type of package utilised in the SC investigated because, in this case, 100% virgin glass is utilised for jar manufacturing due, in turn, to 100% transparency and purity required for the glass itself. Finally, any form of label applied to the jar was neglected because of the unavailability of both primary and secondary, but lesser environmental impacts were expected compared to that derived from production of the jar itself.
Secondary package	5.83	g	This is the cardboard box used for the marketing of the tomato jars. The value alongside was calculated considering that each box is 70g heavy and contains 12 jars.
Methane	8.866E-5	m^3	This value was calculated from the amount provided by the producer on the consumption of methane (5.5 m^3) for the processing of 90000kg tomatoes (harvested tomatoes, inlet to the system, net of the storage losses). In particular, 45.45% of that amount is in the tomato blanching stage; whilst, the remaining 54.55% is consumed for pasteurisation. In the light of this, the two following elaborations were needed to be done; results from the two were then summed up, so obtaining the alongside value. 1) blanching of input tomato, after storage and sorting

			$${}^{2.5\ m^3}/_{90000\ kg} \times 1.451\ kg \quad (17)$$ 2) pasteurisation, after tomato pressing (from which TP is obtained) $${}^{3\ m^3}/_{42500\ kg} \times 0.685\ kg \quad (18)$$ Methane supply is developed through the local gas network, which is already accounted for in the Ecoinvent module used, namely "Methane, 96% by volume {GLO} | market for | Alloc Def, S".
Electricity	6.19E-3	kWh	This derives from a total electricity consumption equal to 384 kWh for the processing of 100t input tomatoes into 42.5t output TP (packed in 62000 glass jars). In particular, calculations carried out in this case were the followings: 1) Sorting of stored tomatoes $${}^{120\ kWh}/_{100000\ kg} \times 1.612\ kg \quad (19)$$ 2) Cleaning of sorted tomatoes $${}^{120\ kWh}/_{90000\ kg} \times 1.451\ kg \quad (20)$$ 3) Pressing of blanched tomatoes, to obtain TP. This phase comes after the blanching one, which, however, does not require electricity but heat through methane usage (see table raw above). Input and output tomatoes associated with blanching (fresh vs. blanched) are of the same amount, because mass difference was considered as negligible. $${}^{120\ kWh}/_{90000\ kg} \times 1.451\ kg \quad (21)$$ 4) TP packing. TP from blanched tomato pressing is pasteurised, with no electricity demand but only heat from methane, and then packed by utilising white glass jars, and consuming electricity in the amount calculated below. $${}^{24\ kWh}/_{42500\ kg} \times 0.685\ kg \quad (22)$$
Transports (for supply of)	*Amount*	*UM*	*Comment*
All inputs to SS-4	372.91	kgkm	To the processing plant. Based upon information collected on site with regard to the features of the means utilised, the following Ecoinvent datasets were used for the modelling of the input material transport flow: -"Transport, freight, lorry 3.5-7.5 metric ton, EURO 3{RoW} | transport, freight, lorry 3.5-7.5 metric ton, EURO 3 | Alloc Def, S", for fresh tomatoes (70 km);

			- “Transport, freight, lorry 3.5-7.5 metric ton, EURO 5 {RoW} | transport, freight, lorry 3.5-7.5 metric ton, EURO 5 | Alloc Def, S”, for either of citric acid (500 km), glass jars (750 km) and carton boxes (270 km).
Transports (for disposal of)	*Amount*	*UM*	*Comment*
Residual biomass	39.25	kgkm	To the compost plant travelling for 125 km. In this case the following Ecoinvent module was used: “Transport, freight, lorry 3.5-7.5 metric ton, EURO 4 {RoW} | transport, freight, lorry 3.5-7.5 metric ton, EURO 5 | Alloc Def, S”

Damage category	Impact category
Human health	Carcinogens
	Non-carcinogens
	Respiratory inorganics
	Respiratory organics
	Ionizing radiations
	Ozone layer depletion
Ecosystem quality	Aquatic eco-toxicity
	Terrestrial eco-toxicity
	Terrestrial acidification/nitrification
	Aquatic acidiphication
	Aquatic eutrophication
	Land occupation
Climate change	Global warming
Resources	No-renewable energy
	Mineral extraction

Damage category	Damage-assessment	
	Value	*UM*
Human health	9.48E−7	DALY
Climate change	1.08	kg_{eq} CO_2
Resources	13.6	Primary-energy MJ
Ecosystem quality	0.56	PDF m^2 y

DALY (Disability-Adjusted Life Year): a measure of the overall severity of a disease, expressed as the number of years lost due to illness, disability or premature death.

PDF (Potential Damage Fraction): the fraction of species that have a high probability of not surviving in the affected area due to unfavourable living conditions.

Substance	Emission compartment	Contribution to the damage affected by HH (%, ↓)	Due to: Jar production (%, →)	Agricultural phase	Total of transports	Citric acid production	Other processes
Human health (HH) *(Calculated damage: 133.73 µpt)*							
Nitrogen oxides	air	29.4	35.8	25	24.11	11.9	3.19
Particulates (grain size < 2.5 micron)	air	25.4	48.8	14.6	18.54	17.5	0.56
Sulphur dioxide	air	19.2	60.5	8.61	10.53	20	0.36
Ammonia	air	13.3	3.32	77.1	0.22	7.46	11.9
Aromatic hydrocarbons	air	5.99	65.5	11.4	5.84	15.5	1.76
Climate change (CC) *(Calculated damage: 108.84 µpt)*							
Carbon dioxide, fossil	air	87.1	38.2	18.3	21.32	19.7	2.48
Dinitrogen monoxide	air	6.21	3.62	76.2	1.54	5.94	7.15
Methane, biogenic	air	4.66	0.46	80.8	0.031	0.099	18.61
Methane, fossil	air	1.53	41.6	13.2	13.42	29.8	1.98
Resources (R) *(Calculated damage: 89.73 µpt)*							
Crude oil	---	46.2	31.9	15	43.28	9.26	0.56
Natural gas	---	30.6	47.5	9.9	5.53	35.2	1.87
Hard coal	---	12.7	41.7	13.6	12.33	31	1.37
Uranium	---	7.32	27.1	17.2	5.69	48.5	1.51
Brown coal	---	2.22	21.5	18.4	4.5	54.3	1.3
Ecosystem quality (EQ) *(Calculated damage: 40.89 µpt)*							
Occupation of arable land under intensive-	---	33.1	Negligible	~100	Negligible		

cultivation and irrigation regime							
Zinc	soil	17.1	18.5	42.9	50.1	-16.8[1]	4.3
Aluminium		12.3	34.1	4.99	13.98	30.4	16.53
Aluminium	air	4.32	37.3	17.3	13.78	30.4	1.22
Ammonia		4.13	3.32	77.1	0.22	7.46	11.9
Copper		3.35	12.2	15.5	63.92	8.6	-0.22
Nitrogen oxides		3.18	35.8	25	24.11	11.9	3.19
Zinc		2.12	18.3	19.4	48.5	13.8	0
Occupation, traffic area, road network	---	1.05	7.61	12.1	74.99	4.8	0.5

[1] According to the Ecoinvent module used, citric acid is produced by a submerged fermentation process which employs a strain of the microorganism Aspergillus niger to convert sugar into citric acid. The carbohydrate substrate (glucose syrup or sugar), which is made from European corn or sugar beet, is heat treated and inoculated with Aspergillus niger. After fermentation, the biological solids (mycelium) are removed. Then – and this is what that environmental benefit should be attributed to, according to this author team - citric acid is recovered from the remaining broth and the resulting citric acid solution is purified by ion exchange and carbon treatment. Finally, the citric acid solution is evaporated, and citric acid is crystallised, dried and sieved.

Substance/resource	Output inventory		Characterisation		IC	Damages assessment		DC
	Amount	UM	Value	UM eq		Value	UM	
Nitrogen oxides	3.13	g	3.98E-4	kg $PM_{2.5}$	Respiratory Inorganics (RI)	2.78E-7	DALY	HH
Particulates (grain size < 2.5 micron)	0.346		3.46E-4			2.42E-7		
Sulphur dioxide	3.34		2.61E-4			1.83E-7		
Ammonia	1.48		1.8E-4			1.26E-7		
			7.55E-5	kg C_2H_3Cl	Non-carcinogens			
Aromatic hydrocarbons	5.74E-3		3.04E-9			5.68E-8		
			0.0203		Carcinogens			
Carbon dioxide, fossil	939	g	0.939	kg CO_2	Global Warming (GW)	0.939	kg CO_2	CC
Dinitrogen monoxide	0.429		0.0669			0.0669		
Methane, biogenic	10.4		0.0503			0.0503		
Methane, fossil	1.59		0.0165			0.0165		
Crude oil	138	g	6.3	Primary-energy MJ	Non-Renewable Energy (NRE)	6.3	Primary-energy MJ	R
Natural gas	109	l	4.18			4.18		
Hard coal	90.5	g	1.73			1.73		
Uranium	0.0142		0.998			0.998		
Brown coal	30.6		0.303			0.303		
Occupation of arable land under intensive-cultivation and irrigation regime	0.161	m^2a	0.17	m^2org.arable	Land occupation	0.185	PDF*m^2*y	EQ
Zinc (soil)	2.05E-3	g	12.1	kg TEG soil	Terrestrial eco-toxicity	0.096		
			2.86	kg TEG water	Aquatic eco-toxicity			
Aluminium (soil)	0.0111		8.44	kg TEG soil	Terrestrial eco-toxicity	0.069		
			38.9	kg TEG water	Aquatic eco-toxicity			
Aluminium (air)	0.0236		2.98	kg TEG soil	Terrestrial eco-toxicity	0.0242		
			11.6	kg TEG water	Aquatic eco-toxicity			
Ammonia [a]	1.48		0.0145	kg TEG soil	Terrestrial eco-toxicity	0.0231		
			5.77E-3	kg TEG water	Aquatic eco-toxicity			
			0.0221	kg SO_2	Terrestrial acidification/nitrification			
			2.78E-3		Aquatic acidification			
Copper	1.97E-3		2.34	kg TEG soil	Terrestrial eco-toxicity	0.0188		
			5.81	kg TEG water	Aquatic eco-toxicity			

Nitrogen oxides [a]	3.13		0.0172	kg SO_2	Terrestrial acidification/nitrification	0.0178		
			2.19E-3		Aquatic acidification			
Zinc (air)	1.49E-3		1.5	kg TEG soil	Terrestrial eco-toxicity	0.0119		
			0.303	kg TEG water	Aquatic eco-toxicity			
Occupation, traffic area, road network	0.0702	m^2a	5.41E-3	m^2org.arable	Land occupation	5.9E-3		

[a] Environmental damage from ammonia and nitrogen oxides on EQ was estimated knowing that, according to Impact 2002+ (Jolliet et al., 2003), aquatic acidification is a midpoint indicator only, and therefore it is not included in the damage-oriented evaluation that is part of the endpoint approach. This means that the damage values of those two substances (0.0231 and 0.0178 PDF*m^2*y) were obtained from elaboration of the characterisation results related just to their impact to terrestrial eco-toxicity.

Impact category	Weighing	Characterisation	
	μpt	*Value*	*UM* eq
Respiratory Inorganics	118	0.0012	kg $PM_{2.5}$
Global warming	108.84	1.08	kg_{eq} CO_2
Non-renewable energy	89.4	13.6	Primary-energy MJ
Land occupation	20.8	0.261	m^2org.arable
Terrestrial ecotoxicity	16.6	28.7	kg TEG soil
Carcinogens	9.23	0.0234	kg C_2H_3Cl
Non-carcinogens	7.17	0.0182	kg C_2H_3Cl
Terrestrial acidification/nitrification	3.27	0.043	kg SO_2