Life Cycle Assessment of organic and conventional conserved crushed tomatoes for the Swedish market

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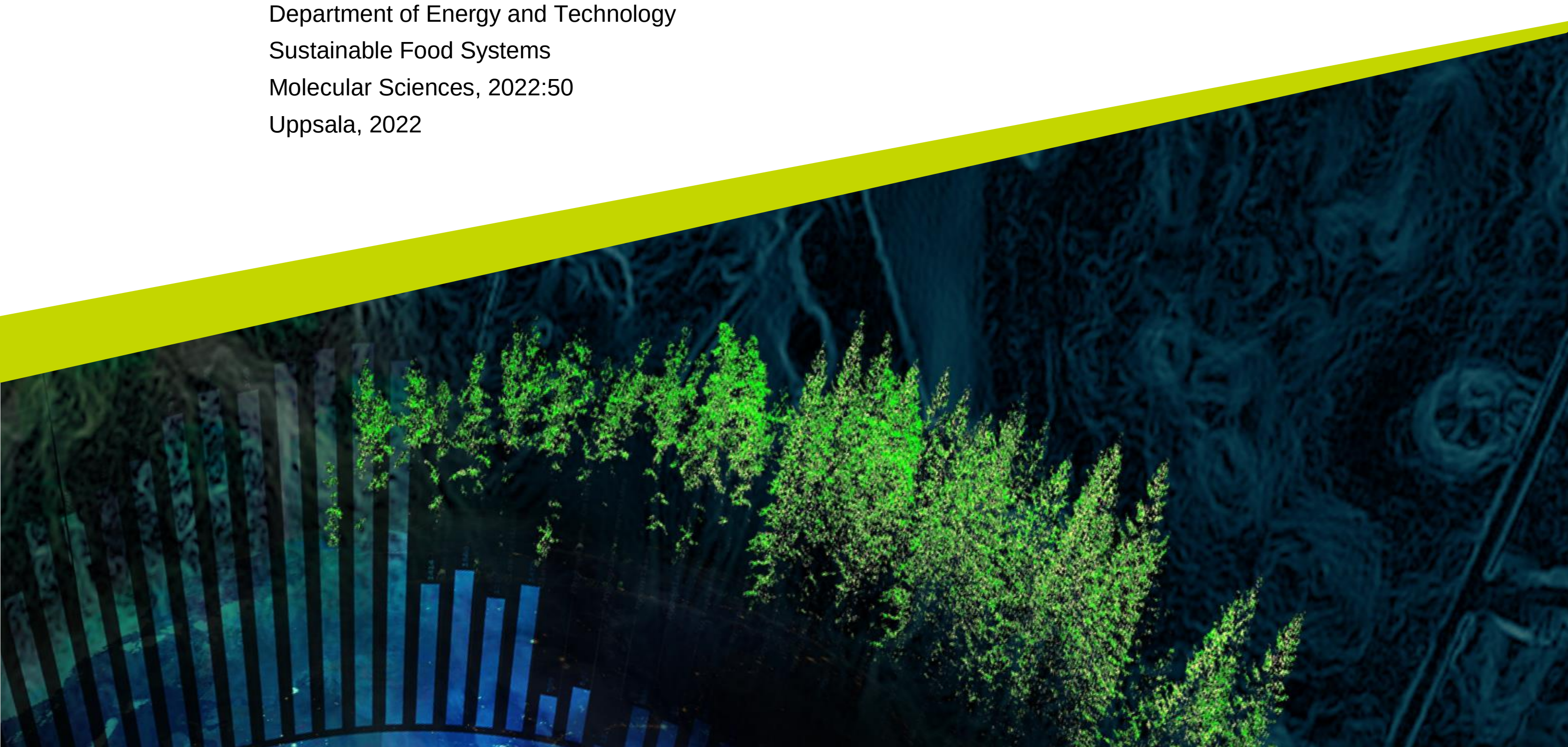

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Abstract

The current global food system has been identified as responsible for a large part of global environmental impact, and the environmental impact of agriculture has significantly increased mainly due to its production practices and activities included in the entire product supply chain. The tomato supply-chain has an important role in the global agri-food industry, identifying California, Italy, China, Spain, Portugal and Turkey as the leading producers globally, and Italy and Spain among the main exporters of tomato products in Europe.

The aim of this study was to investigate the production phases of packed crushed tomato, and to identify the hot-spots along the supply chain. In particular, information on global warming potential and energy demand was collected. As regards the packaged crushed tomato imported to Sweden, a simplified LCA based on a LCA review was conducted to identify the hot-spots of the supply chain. To identify the origin of the products, 16 different packages of crushed tomato organic and conventionally produces were collected, available in the main grocery stores in Stockholm. The information regarding the production activities were obtained through contact with some of the processing companies of the collected products and through published studies. Carbon footprint and energy use were calculated for the agriculture, processing, packaging and transport phases. The calculations did not include activities related to seeds production and transportation, the consumption level, secondary/tertiary packaging and waste disposal.

The results show that the products collected come from Southern Europe, especially from Italy. None of the products selected were produced in Sweden or contain tomatoes with Swedish origin, this underlines that the Swedish consumption of crushed tomato product is currently totally dependent on imports from southern Europe. Six out of sixteen are certified organic products through the European organic logo, some of these also show KRAV logo certification. The results of the simplified LCA show the transport and process phase to be the main environmental burden among the phases considered in terms of carbon footprint and energy use. Furthermore, by analyzing the total impact of both conventional and organic products, the impact of the two systems is very similar. Indeed, the carbon footprint obtained is 0.32 kg CO_2-eq and 0.31 kg CO_2-eq and the energy use is 5 MJ and 4.9 MJ for the organic and conventional product respectively, considering 400 grams of packed crushed tomato as a functional unit. The values obtained in the cultivation phase are those that determine the slight difference between the two systems, both carried out in the open field. The most important measures to reduce the impacts in terms of global warming potential and energy use strongly depend on the cultivation systems used, the type of energy used in the process, the packaging, and the type of vehicle chosen for the transport route.

Keywords: tomato, crushed tomato, supply chain, carbon footprint, energy use

Popular science summary

Organic or conventional tomatoes? Tin cans, glass bottles or Tetra Pak? Faced with the variety of tomato-based products available in grocery store shelves, have we consumers ever wondered how much each package of crushed tomatoes we buy affects the environment?

We consumers are increasingly aware of the fact that everything we do and consume has an impact on the environment, and we increasingly need to have the information necessary to understand the best choices to preserve our planet. All the activities included in the production process of what we buy and consume have a certain impact, it is therefore necessary to find suitable solutions that allow us to reduce as much as possible greenhouse gas emissions that damage the environment. The dietary transition towards more plant-based foods often leads us to buy products from other countries, also to increase the variety of products we consume.

The tomato supply-chain, including both fresh and processed tomatoes, has an important role in the global agri-food industry, and approximately 38 million tons are processed per year. In Sweden, the consumption of tomato products has significantly increased over the past 10 years, reaching a value of imported products of around 410 million SEK. All the crushed tomato products that we find in the main Swedish grocery stores are imported from the Mediterranean regions, mainly from Italy, followed by Spain, Greece and Portugal. The products are generally packaged in Tetra Pak® or tin cans, with an average container size of 400 grams.

This study focuses on the evaluation of the energy use and the carbon footprint of crushed tomato packaged for Swedish consumption. Tomatoes are grown organically or conventionally in open fields or greenhouses, processed, packaged and transported to Sweden by articulated lorry or by multimodal transport. Due to the lower productivity in the field, the organic product has a slightly more impact in terms of energy use and greenhouse gas emissions, but it does not seem to be the most important data. In fact, it must be considered that production activities such as packaging and transport are those that allow to have a greater influence on the impact, considering the entire supply chain. The choice of packaging is crucial and choosing a retortable cardboard packaging is the most convenient choice from an energy point of view. As for transport, however, in comparing distance travelled, the type of vehicle used affects the total emissions. Choosing to adopt electric trains for a large part of the route, in the case of multimodal transport, could be a good solution. In this case, however, it is necessary to consider how the energy is produced, e.g. wind and hydropower, coal, biomass, gas.

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Abbreviations

CED	Cumulative energy demand
CS	Conventional system
FU	Functional unit
GWP	Global warming potential
LCA	Life cycle assessment
OS	Organic system

1. Introduction

The current global food system has been identified as responsible for a large part of the environmental impact of the total consumption recorded (Cucurachi *et al*., 2019; Manfredi & Vignali, 2013). The environmental impact of agriculture includes issues caused by both expansion and intensification of production that have increased significantly over the past 60 years (Foley *et al.,* 2011). The intensification of production has not only caused the doubling of the irrigated cropland area but has also led to a 500% increase in fertilizers used (*Ibid*). In Europe, land use for agriculture amounts to 45%, with a water consumption of 30% (Tamburini *et al.*, 2015). The necessity to intensify production, also caused by a rapid demographic increase, has outlined a very critical situation in terms of energy used, water degradation and widespread pollution (Foley *et al.*, 2011). This is also associated with the contribution of agriculture to climate change causing 35% of global greenhouse gas emissions, such as CO_2, N_2O, CH_4, fertilizer use and deforestation (Foley *et al.*, 2011; Garofalo *et al.*, 2016).

The tomato supply-chain, including both fresh and processed tomatoes, has an important role in the global agri-food industry, and approximately 38 million tons are processed per year (Ingrao *et al.*, 2019). California, Italy, China, Spain, Portugal, and Turkey are the main tomato producers in the world, but at a European level, Italy covers 48% of production with 5.2 million metric tons of tomatoes produced (*Ibid*). In Sweden, the consumption of fresh tomatoes has undergone small fluctuations in the last ten years, recording an annual consumption per capita of approximately 10 kg (Ridder, 2022), 86% of the fresh tomatoes on the market are imported, mainly from the Netherlands and Spain (Gren *et al*., 2019). From 2011 to 2020 the value of imported fresh tomatoes in Sweden increased reaching a value of over 1.5 billion SEK in 2020 (Sabanoglu, 2021). An increase was also recorded in the value of processed tomatoes imported into Sweden in the last decade, going from a value of 225 million SEK in 2010 to 407 million SEK in 2020 (Sabanoglu, 2021). Most of the conserved crushed tomatoes on the Swedish market have southern European origins and, to date, there is no literature available regarding the environmental impact of its entire supply chain, from cultivation (conventional and organic), production, packaging and transport to Sweden. Given the large consumption of preserved crushed tomatoes in Sweden, a Life Cycle

Assessment (LCA) which includes production and transport is therefore important to have a better knowledge for improving the supply chain towards an increasingly sustainable process.

1.1. Aim

The aim of this study was to investigate the global warming potential and energy use of packed crushed tomato imported into the Swedish market, and to identify the hot-spots along the supply chain.

The objective was achieved by primarily:

- Conducting a simplified LCA based on published studies to identify what may be the significant burdens in the supply chain, and for both organic and conventional products.
- Investigating the origin of crushed tomatoes in the major Swedish grocery stores.

Furthermore, overall information regarding sustainable food systems and information about how to conduct a life cycle assessment were presented to have a better contextualization of the topic.

2. Background

This chapter briefly presents the challenges and possible solutions for the sustainability of food systems and presents life cycle assessment as a methodology for evaluating the environmental impact.

2.1. Food system sustainability

Providing enough healthy food for the growing population is one of the most important challenges facing the global food system (Allen & Prosperi, 2016) as parts of the world population either have insufficient food resources or are on an inappropriate calorie, nutrient-poor diet (Willet *et al.,* 2019). In fact, to achieve the Paris Agreement and the United Nations Sustainable Development Goals, the transition from an unhealthy and unsustainable diet to a healthy diet from a sustainable food system is necessary (United Nations, n.d.). For this reason, food policies that aim to improve environmental and social well-being are increasingly important (Eakin *et al.,* 2016), and several measures are needed to maintain the food system within the planetary boundaries (Rockström *et al*., 2009), this means focusing on food changes, on reducing food waste, but also on improving the agricultural system towards the use of good practices (Springmann *et al.,* 2018). Food systems involve different interactions between man and nature, which is why they can be defined as socio-ecological systems (Willet *et al*., 2019). A sustainable food system should be able to keep ecosystems healthy, allowing to provide food to the current and future generation while limiting the impact on the environment as much as possible and ensuring the fair treatment of workers within the system (Story *et al.,* 2009). As already mentioned, there are several problems that the current food system and its food supply chains cause to the environment. To the emissions of greenhouse gases, expressed as carbon dioxide equivalents (CO_2eq) originating from human activities, 78% of eutrophication and 32% of global terrestrial acidification caused by food production are added (Poore & Nemecek, 2019). This undermines the ecological robustness and alters the species composition of natural ecosystem reducing its biodiversity (*Ibid*).

What are the possible solutions and strategies to be adopted to cut greenhouse gas emissions, limit the loss of biodiversity and habitat losses as much as possible, reduce emissions caused by the overuse of pesticides and reduce water withdrawals used in production processes? According to Foley *et al.* (2011), stopping the expansion of agriculture, closing the yield gaps by increasing the efficiency of the agricultural resources already available, increasing food delivery by changing diets and reducing waste are among the most valid strategies. To these the continuous search for practical solutions more suited to those already in existence is added, with the aim of fulfilling the objectives of the Paris Agreement and the United Nations Sustainable Development Goals (United Nations, n.d.).

Quantification of the environmental impact generated by supply chains can be the bases for the implementation of practical solutions that aim to make processes more sustainable (Poore & Nemecek, 2019). There are various tools that allow to focus on production systems, which aim to monitor and identify the phases with the greatest environmental impact with the aim of finding solutions that are more sustainable. One of these tools is Life Cycle Assessment (LCA), which in recent years has been widely used in the food sector for assessing and communicating the environmental performance of food products along their supply chain (Tidåker *et al.,* 2020).

2.2. Life Cycle Assessment

Life Cycle Assessment (LCA) is a methodology that evaluates the environmental impact of a product or a system throughout its life cycle (Roy *et al.,* 2009), considering, theoretically, all phases of the supply chain, from cradle to grave, and the related relevant activities within each phase (Farahani *et al*., 2018; Sonesson *et al.*, 2017). The evaluation through this methodology allows to stimulate the implementation of more sustainable production systems (Garofalo *et al.,* 2016). The data relating to the life cycle of a process or product allow decision makers to identify which are the critical phases of the process (De Marco *et al.*, 2017), and to raise awareness on which phases of the life cycle are the more or less sustainable (Ingrao *et al.,* 2019). Based on the data obtained, this information makes it possible to support the companies and stakeholders involved to be aware of the implications that the supply chain entails for the environment, to provide a guide to limit environmental degradation by providing the appropriate skills to make the best use of energy and resources towards sustainable systems (Notarnicola *et al.,* 2016). The goal is to identify the possible options for improvement with respect to the impact categories considered (Ibid.).

Life cycle assessment focuses on the quantification of environmental issues such as climate change, freshwater use, land occupation and transformation, aquatic eutrophication, toxic impacts on human health, depletion of non-renewable resources and eco-toxic effects from metals and synthetic organic chemicals (Haushild *et al.*, 2018). In the food sector, LCA identifies the life cycle stages that affect the global food industry's environmental impacts, including food waste and transport/shipping distance (Virdegar *et al.*, 2020). However, there are limitations regarding the measurements. Calculation of the environmental impacts obtained through the life cycle methodology can be considered as the calculation of impact potentials, as it is strictly related to the area taken into consideration, aggregated over time and space (Ibid). Furthermore, it is rare that all categories are analysed in one study because it is a very complex process (Notarnicola *et al.*, 2016).

2.2.1. Methodology of Life Cycle Assessment

The standards ISO 14040/14044 defines the methodology to be adopted to conduct an LCA (Klöpffer, 2012), which consists of four main phases as shown in *Figure 1*.

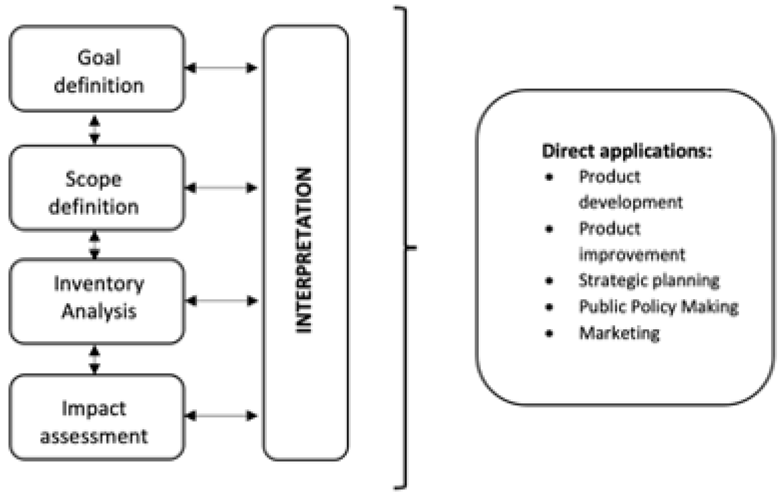

Figure 1 Life Cycle Assessment framework, adapted from ISO 14040 standard.

2.2.2. Phases of an LCA

Goal and scope definition

The goal is the first phase of an LCA and defines the context in which the study is carried out but also the later steps of the LCA which must be consistent with the goal definition (Hauschild *et al.,* 2018). In this phase, the intention of the application and the reason that led to conducting the study are declared, to whom it is addressed and whether the results can be useful for a comparative evaluation (Del Borghi *et al.,* 2020).

Based on the established goal, the purpose determines the product system involved in the study and its function. In addition, the system boundaries are specified, which include all stages selected and included in the study. This will help map the flow production (De Marco *et al*., 2017). At this stage it is important to determine the functional unit (FU), which represents the product used as a reference and must therefore be measurable and quantified through a unit - *i.e.*, tons, kilograms (Del Borghi *et al.,* 2020). Defining which impact categories will be considered in the study, the next step concerns the definition of what data will be collected for the research and what the data will come from, also defining how the assessment should take place (Hauschild *et al.*, 2018).

Inventory Analysis phase: Life Cycle Inventory

The Life Cycle Inventory - LCI - represents the most complex section of the study as it contains all the information for the collection and interpretation of data relating to the input and output flows selected in the observed system and necessary for the environmental assessment (Del Borghi *et al.*, 2020; De Marco *et al.,* 2017). The data collected refer to process inputs, such as resources, material and semi-products, output of emissions and waste of the process (Hauschild *et al.,* 2018).

Impact assessment

The life cycle impact assessment phase processes the data collected in the previous phase, translating them into "environmental impact scores" (Hauschild *et al.*, 2018), these data might be processed through a LCA software (Del Borghi *et al.,* 2020; Notarnicola *et al.,* 2016). The ISO 14040/14044 standards determines which are the mandatory and optional steps of this phase. The mandatory steps require that it be defined which impacts it is necessary to evaluate, which impacts does the LCI result contribute to and define how much each LCI result contribute (Hauschild *et al.,* 2018). The optional steps require to group the different impact indicator results and define if the values obtained are relevant (Ibid).

2.3. Major producers and exporters of tomato products in Europe

European Commission (2021) published the report *The tomato market in the EU*, which provides data on the main exporters of fresh tomatoes on the EU market, the Netherlands, Spain and Belgium are among the main exporters of fresh tomatoes intended for use as such. The *Short-term outlook for EU agricultural markets in 2021* (European Commission, 2021) states that European production of fresh tomatoes has been on decline since 2016 and consumption is expected also to decline by 2030, but production of tomatoes for processing has instead increased due to the strong demand. According to Eurostat, *Agriculture, forestry and fishery statistics* (Eurostat, 2020), Italy and Spain produced two thirds of the tomatoes destined for processing and of processed tomato products in the EU in 2019. The *Short-term outlook for agricultural market in 2019 and 202*0 released by the European Commission recorded also a significant increase in EU imports of processed tomatoes, in particular preserved tomatoes, from China, Chile and Ukraine.

3. Material and method

This chapter describes how the study was conducted and the methods used, including information regarding data collection and literature review. It also includes information regarding the simplified LCA, its scope and system boundaries, impact categories and functional unit.

3.1. Literature review and data collection

The information collected was based on primary and secondary data. Data regarding the land of origin of the product was obtained by collecting 16 packaged crushed tomatoes of different brands in the main grocery stores in Stockholm (COOP, ICA, Willys, Hemköp), in spring 2022. The products were purchased canned packaged in Tetra Pak® or steel cans. All the products collected in this study were listed in Table 3, and more in detail in Table 10 in Appendix. Information regarding production and transport were collected by phone with the various customer services of each food actor marketing the product through their own brand or with private label.

Since it was not possible to have all the necessary primary data, a literature review of published studies was carried out in order to better understand the production processes and have more information regarding the environmental impacts. Some of the published studies were used as a reference for the compilation of the simplified LCA. The literature review was carried out in various databases such as Scopus, Web of Sciences, Google Scholar and following some criteria such as the year of publication, from 2010 to 2022. The key words used were *tomato, life cycle assessment, LCA, carbon footprint, GWP, energy use, tomato product, Mediterranean area, Sweden*. Only articles in English and relevant to the purpose of this paper were selected.

3.2. Life cycle assessment

System boundaries

The system boundary selected for this study included agriculture stage (production of purchased inputs, soil tillage, fertilizers and pesticides application), processing, packaging in Tetra Recart ®[1], and transport from the farm to the processing plant, and from the latter to Sweden. The carbon footprint and energy use were assessed on these aforementioned phases. The calculations did not include activities related to seeds production and transportation, the consumption level, secondary/tertiary packaging and waste disposal.

Impact categories

To evaluate the effects on the environment caused by a product supply chain, impact categories are selected. The focus was on **energy demand** (ED) expressed in MJ and the amount of greenhouse gas emissions that translates into the **carbon footprint** - expressed as kg CO2 equivalent (kg CO2-eq) - which considers the global warming potential (GWP) of various emissions in the stages of the supply chain considered.

Functional unit

The functional unit (FU) selected for this study was the amount of conserved crushed tomatoes corresponding to 400 grams. According to the information obtained from some producers, about 650 grams of incoming fresh tomatoes are required to produce 400 grams. The remaining part corresponds to water, seeds and peel eliminated during the process. The unit considered was chosen as it is a convenient unit for comparing different products available on the market. The product, which can be purchased by choosing between different brands, can be found in the main Stockholm supermarkets, packed in brick or tin can.

Data collection

The calculations carried out for each phase of the LCA were based on previous studies, and the values concerning the energy use and GWP considered were then related to the functional unit selected in this study. The article by Ronga *et al.* (2019) was the reference for the agricultural phase, which bases its values on a functional unit equal to one ton of marketable fresh tomatoes. The process phase was based on the data provided in the study by Manfredi & Vignali (2013) which

[1] Tetra Recart® is a more sustainable and innovative retortable cardboard packaging designed by Tetra Pak® that allows to package food products by replacing cans or glass bottles.

consider 700 grams of tomato puree as a functional unit. The study by Tidåker *et al.* (2021), which bases the calculations on 1 kg of pulse, was considered as a reference for the packaging phase. Finally, for the transport phase from field to the processing plant, the data provided by Garofalo *et al.* (2017) based on 480 g of canned whole-peeled tomato; as regards transport from Italy to Sweden, the study conducted by Sundin (2020) based on 1 kg of canned pulse in Tetra Pak® is the reference for this study.

3.3. Delimitations

Data obtained from the simplified LCA were based on data from published studies. The results are therefore to be considered as a good starting point on what could be a future evaluation based on more primary data, strictly connected to the products found on the Swedish market.

4. Results

In this section, a literature review of previous LCA-studies concerning the environmental impact of the tomato and tomato products supply chain is presented. A list of products retrieved in the main Stockholm grocery stores is presented followed by an overview regards the production process of crushed tomatoes, from cultivation to the transport phases. The section ends with a simplified LCA of packaged crushed tomato.

4.1. Previous LCA studies on tomato and tomato products

This section presents previous studies concerning the production of fresh tomatoes and tomato products. For the phases considered in the supply chain, the hot spots are identified with reference to the energy use and global warming potential impact categories.

4.1.1. Energy use and carbon footprint in fresh tomatoes production

To date there are several LCA-studies dedicated to tomato and tomato products. Some of these studies focus mainly on fresh tomatoes, using LCA to calculate the environmental impact in the various phases, taking into account mainly emissions of greenhouse gases, water consumption, use of pesticides and energy (Bosona & Gebresenbet, 2018; Martínez-Blanco *et al.,* 2010; Ntinas *et al.,* 2016; Payen *et al.,* 2014; Ronga *et al.,* 2019). Other studies concern tomato products as tomato puree, crushed tomato, whole-peeled tomato, focused mainly on the Mediterranean area (Del Borghi *et* al., 2014; De Marco *et al.,* 2017; De Marco *et al.,* 2018; Farahani *et al.,* 2018; Garofalo *et al.,* 2016; Ingrao *et al.,* 2019; Manfredi *et al.,* 2013;). Therefore, system boundaries considered and selected environmental impact considered vary. Among the selected studies, one focuses on the life cycle analysis of organic tomato production and supply in Sweden (Bosona & Gebresenbet, 2018). It focuses on production and the supply chain, aiming to understand what the environmental impact of organic tomatoes is and what are the environmentally hotspots stages of its value chain (Bosona & Gebresenbet, 2018).

Table 1 shows five studies concerning the LCA of fresh tomato production. The studies conducted by Bosona & Gebresenbet (2018) and Payen *et al.* (2014) focus on organic and conventional production systems, both in greenhouses. Payen *et al.* (2014) focuses also on fresh tomato produced in Morocco and exported to France, therefore long transport distances are considered. Studies conducted by Martínez-Blanco *et al.* (2010) and Ntinas *et al.*, 2016 focus on both open field and greenhouse tomato cultivation. Finally, Ronga *et al.* (2019) compare organic and conventional production both carried out in the open field, focusing on global warming potential and energy used for both systems.

Table 1 Previous studies focused on fresh tomatoes production

Author(s) and year	Area of origin	Product	Impact categories[a]	Functional unit (FU)	System boundaries	Some results
Bosona & Gebrensenbet (2018)	Sweden	Fresh and dried organically produced tomatoes, produced and distributed in Sweden.	CED, GWP	1-ton fresh tomato	Agricultural production; post-harvest process; transport.	Agriculture, transport hot spots for GWP. Agriculture, post-harvest hot spots for CED.
Martínez-Blanco *et al*. (2011)	Spain	Fresh tomatoes produced in open field and greenhouse.	ADP, AP, EP, GWP, OLDP, POP, CED.	1-ton fresh tomato	Mineral and organic fertilizers production and transport. Agricultural production.	Greenhouse systems increase yield, lower CED compared to open-field.
Ntinas *et al*. (2016)	Greece, Germany	Fresh tomatoes produced in Greece and Germany in greenhouse and open field.	GWP, CED, WUE	1 kg of fresh tomatoes	Agricultural production.	Lower GWP and CED in open field, but higher WUE.
Payen e*t al.* (2014)	Morocco	Fresh tomatoes for French and Moroccan market.	GWP; CED, TA; FE; ME; TET; FET; MET; ALO; FD; MD[a].	1 kg fresh bulk tomato	Seeds and tomatoes production, greenhouse manufacture, packaging, transport.	Production contributes to FE, FET and MD. Long transport main contributor to GWP, TA, FD, ME.
Ronga *et al.* (2019)	Italy	Organic and conventional fresh tomatoes	GWP, CED	1-ton fresh tomato	Agricultural production.	Organic system greatest impact. Pesticides and fungicides application, soil tillage have the highest impacts among management inputs on GWP and CED.

[a] ***ADP:** abiotic depletion potential; **ALO**: agricultural land occupation; **AP**: acidification potential; **CED**: cumulative energy demand; **EP**: eutrophication potential; **FD**: fossil fuel depletion; **FE**: freshwater eutrophication; **FET**: freshwater ecotoxicity; **GWP**: global warming potential; **MD**: metal depletion; **ME**: marine eutrophication; **MET**: marine ecotoxicity; **OLDP:** ozone layer depletion potential; **POP:** photochemical oxidation potential; **TA**: terrestrial acidification; **TET**: terrestrial ecotoxicity, **WUE**: water use efficiency.*

Bosona & Gebrensenbet (2018) focus on fresh and dried tomato value chain including cultivation, post-harvest process and transport stages in southern Sweden. According to the results obtained, cumulative energy demand (CED) calculated for both production of fresh and dried tomatoes is 45 MJ and 49 MJ, respectively, per 1 kg of fresh product. Agricultural production stage in greenhouse is energy intensive, in fact it contributes the most to environmental impact. A greenhouse requires a certain energy input for its heating, especially if is located in cold areas. Bosona & Gebrensenbet (2018) identified the washing, sorting, drying and packaging phases as major contributors to CED compared to the transport phase, which is instead identified as a hot spot for the global warming potential, GWP. The impacts regarding the transport depend strongly on the modality and the distances with which the transport takes place. The GWP calculated is equal to 0.54 kg CO_2-eq and 0.46 kg CO_2-eq per kg for fresh and dried tomatoes respectively. Results show how dried tomato value chain could be generally more sustainable in terms of GWP and CED compared to fresh tomato value chain considering these system boundaries. The energy required for drying is greater than the energy required in the fresh tomato process. On the contrary, inputs and resources required for dried tomatoes packaging and transport is lower than those required for fresh tomatoes. It is also important to consider that the drying process allows to increase the product shelf-life and therefore decrease food losses.

Payen *et al.* (2014) compare the greenhouse production of tomatoes in Morocco and transported to France with tomatoes off-season production in France. The study focuses on the production of fresh tomatoes considering different impact categories and 1 kg of fresh tomatoes as a functional unit. Considering the GWP, transport appears to be the main contributor mainly due to long distances, contributing 44% of the impact of the entire supply chain. Transport alone recorded 0.240 kg CO_2-eq out of 0.546 kg CO_2-eq throughout the system boundary. As concern the CED, 9.13 MJ are required from the production to the market-gate in France. An interesting fact concerns the local French fruit and vegetable market. Payen *et al.* (2014) point out that sourcing local tomatoes during the winter period is not the best choice from GWP and CED point of view. The export of tomato grown in unheated greenhouses has a minor impact, especially in terms of CED, compared to local French tomatoes grown in heated greenhouses (*Ibid*). Therefore, relying only on the distances travelled does not provide accurate data, it is also necessary to understand the techniques used along the entire supply chain (*Ibid*).

Ronga *et al.* (2019) compares the conventional cultivation system with the organic one in the production of tomatoes in the Mediterranean area, through the carbon footprint evaluation and energetic analysis. Considering 1 ton of marketable tomatoes, the GWP of the conventional system turns out to be lower than the organic one - respectively about 55 kg CO_2-eq t^{-1} and 67.5 kg CO_2-eq t^{-1} (0.055 kg

CO2-eq and 0.067 kg CO2-eq per 1 kg of marketable tomatoes). This result is in contrast with the results obtained considering instead one hectare of cultivated land, which sees the conventional system with a higher GWP than the organic one - respectively about 3155 kg CO_2-eq and 5290 kg CO_2-eq. As for the CED, considering a ton of marketable tomatoes the conventional system required 618 MJ compared to the organic one which required 794 MJ (0.62 MJ and 0.8 MJ per kg of marketable tomatoes). However, considering one hectare of cultivated land, the result changes and the biological system requires less energy. What makes the difference in this case are the yields, which is only 50% in the organic system compared to the conventional system. Furthermore, in the conventional system soil tillage has the highest impact in terms of kg CO2-eq, followed by pesticides and fungicides application.

Finally, Ntinas et al. (2016) focus the LCA on different scenarios that consider both open-field and greenhouse conventional cultivation located in Greece and Germany. The study investigates the environmental impact and the energy demand and considers one kilo of tomato and a square meter of cultivated land as functional units. Each scenario presented a variation with respect to the other, such as in irrigation methods, in the type of heating for the greenhouse, cultivation techniques in or out of the soil. The system with the least emissions of kg CO_2-eq and energy used per kilo of tomatoes is the open-field cultivation system, 0.1 kg CO_2-eq and 0.8 MJ. The main hot spots in this scenario were electricity for irrigation, water and fertilizers used. The system with the most impact was instead identified in the greenhouse cultivation system, where about 10 kg CO_2-eq and 160 MJ were calculated for each kilo of tomato produced. The main hot-spots for both impact categories were identified in fuel and electricity used to heat the greenhouse. In this case, the heating and the electricity requirement are the main problem in terms of high consumption and type of fossil fuels and are identified as the key to the environmental impacts that must be reduced. Martínez-Blanco *et al.* (2010) conducted a similar study, which also considers open-field and greenhouse production and treating the soil with compost plus mineral fertilizers, or just with mineral fertilizers. From this study it emerges that considering the yields in both systems, the greenhouse system operating with compost and mineral fertilizers is more sustainable in terms of CED but not in terms of GWP. Considering the GWP, the open field system operating with compost and mineral fertilizers has a much lower impact than the same system in the greenhouse. This is because in the greenhouse system, the greenhouse stage covers a high impact contribution mainly due to the production of its components.

4.1.2. Energy use and carbon footprint in tomato products production

Table 2 shows some studies carried out in the tomato-based products production sector, which are processed and packaged.

Table 2 Previous studies about packaged tomato products.

Author(s) and year	Area of origin	Product	Impact categories[b]	Functional unit (FU)	System boundaries	Some results
Del Borghi *et al.* (2014)	Italy	13 different tomato packaged products.	HT; TET; MET; FE.	1 Kg of packaged product.	Cultivation, transport, processing, packaging, end of life.	Agriculture and packaging production highest impact in all categories.
De Marco *et al.* (2017)	Italy	Mashed tomato in Tetra Pak.	C; NC; RI; IR; RO; FET; TET; TA; LO; GWP; NRE; ME.	500 g of mashed tomato.	Processing and packaging.	Packaging main contributor in all categories. Processing is hot-spot for GWP.
De Marco *et al.* (2018)	Italy	Mashed tomato in Tetra Pak.	GWP; TA; TET; FET; MET; ULO; NLT; WD; FD; HH; ED.	500 g of mashed tomato.	Cultivation, processing, packaging, transport.	Cultivation, blanching, concentration, pasteurization main contributors to environmental impacts.
Farahani *et al*, (2019)	Iran	Tomato puree.	D(abiotic); AC; EU; GWP; OLD; HH; ET; FET; TET; PO.	500 g of tomato puree.	Cultivation, transportation, processing, transport.	Packaging and cultivation hot spots for most impact categories.
Garaofalo *et al.* (2016)	Italy	Whole-peeled tomato	GHGs.	480 g of canned whole-peeled tomato.	Cultivation, transport, processing, packaging, waste treatment.	Waste disposal main contributor.
Ingrao et al. (2019)	Italy	Tomato puree.	GWP; HH; RD: EQ.	685 g tomato puree.	Cultivation, processing, packaging, transport, waste disposal.	Production, agricultural stages major contributors.
Manfredi & Vignali (2013)	Italy	Tomato puree.	GWP; CED; NRE; TA; FE; ME; TET; FET; MET; ALO; FD; WD.	700 g tomato.	Cultivation, transport, processing, packaging, distribution.	Packaging, cultivation and transport major contributors.

[b] ***AC**: acidification; **ALO**: agricultural land occupation; **C**: carcinogens; **CED**: cumulative energy demand;, **ED**: ecosystem diversity, **EU**: eutrophication; **EQ**: ecosystem quality**;** **FD**: fossil depletion; **FET**: freshwater ecotoxicity; **GHG**: greenhouse gas; **GWP**: global warming potential; **HH**: human health; **HT**: human toxicity; **IR**: ionizing radiations; **LO**: land occupation; **MET**: marine ecotoxicity; **NLT**: natural land transformation; **NRE**: non-renewable energy; **PO**: photochemical oxidation; **RD:** resource depletion **RI**: respiratory inorganics; **RO**: respiratory organics; **TA**: terrestrial acidification; **TET**: terrestrial ecotoxicity; **ULO**: urban land occupation; **WD**: water depletion*

The study conducted by Del Borghi *et al.* (2014) considers the supply chain of thirteen different tomato products of different brands (tomato purée, chopped tomato, peeled tomato), and selecting 1 kg of packaged product as functional unit. The results show that for all types of products, the cultivation and packaging phases are those with the greatest impact, especially about the high consumption of fossil fuel and the use of energy. Production of cardboard-based packaging requires less energy and produces less CO_2 than glass or steel, even if the production of packaging paper produces the greatest amount of biogenic carbon. It also appears that large format packaging exhibits less impact. Carton-based packaged tomato purees products have an average GWP value of about 1 kg CO_2-eq and CED of about 14 MJ per functional unit. As for chopped tomato products packed in glass or steel can, the GWP is 1.54 kg CO_2-eq and the CED is around 22 MJ. Finally, as regards peeled tomatoes paced in steel can, the GWP is about 1.30 kg CO_2-eq and the CED is 18 MJ. What makes the difference is the packaging, which in the case of carton-based has much lower values than glass or steel cans, both in terms of GWP and CED. Garofalo *et al.* (2016) focus on the life cycle assessment of the whole-peeled tomato production by calculating GHG emissions along the entire supply chain in each stage, from cultivation to the waste disposal phase, and considering 480 g of canned whole-peeled tomato as a functional unit. In the stages considered, the hot-spots are identified in the processing phase, in particular in waste management, packaging, processing and cultivation steps.

The LCA of mashed tomato production in Italy by De Marco *et al*. (2017), focuses on GWP and on other impact categories listed in Table 2, and considering 500 g of mashed tomato packed in Tetra Pak® as a functional unit. As already pointed out by Garofalo *et al.*, (2016), packaging appears to be the phase that most affects the emissions of the whole process for most of the impact categories considered. As for the GWP, the preliminary stages such as washing, sorting, grinding, blanching and refining are added to the latter. For all the phases considered, the total GWP is about 0.60 kg CO_2-eq. Similar results were obtained in the study conducted by De Marco *et al.* (2018), which identifies the cultivation phase as a major cause of eutrophication, ionizing radiation, and fossil fuel depletion. The packaging phase, on the other hand, generates the highest emissions in terms of agricultural land occupation and freshwater eutrophication.

Farahani *et al.* (2019) compare different tomato puree production phases from the environmental point of view. In this study 500 g of canned tomato puree is considered as a functional unit. The calculated GWP is equal to 0.34 kg CO_2-eq and only the packaging phase is equal to 0.18 kg CO_2-eq. Also this study confirms the packaging phase as a major contributor in almost all impact categories. The main cause is the type of material used, steel-can and plastic used as a cap. The cultivation phase is the second process hot-spot. This means that by improving the packaging, the cultivation phase would become the main source of impact. A further study concerning tomato puree in the Mediterranean area conducted by Ingrao *et al.* (2019) focuses on impact categories such as GWP, non-renewable energy and respiratory inorganics. The study considers 685 g of tomato puree packed in glass jar as a functional unit. The GWP value for all the phases considered (tomato cultivation, harvesting, production and packaging) is approximately 1 kg CO_2 -eq. Packaging is the phase with the greatest impact for the categories considered, followed by the agricultural phase. These two phases contribute to 60% of the total impact.

Manfredi *et al.* (2013) which focuses on the agricultural, post-harvesting and transportation phase in the entire supply chain, further emphasizes how the packaging phase is the least sustainable due to the high energy demand for its production. The study considers 700 g puree jar as a functional unit and calculates the environmental impact for the categories specified in Table 2 in cultivation, processing, packaging material and transport stages. As for the GWP, the total value corresponds to 0.68 kg CO_2-eq, of which 0.3 kg CO_2-eq refer to the packaging, which is therefore considered a hot-spot. As for the CED, 9.65 MJ are used in the considered system boundary and 5.17 MJ refers to packaging. Not considering the packaging, the cultivation phase would be considered a hot-spot for GWP (0.18 kg CO2-eq) and the processing phase would be considered a hot-spot in terms of CED (1.79 MJ).

The studies considered show that, among the phases in common, packaging and the agricultural phase are the hot-spots of the supply chain in most of the impact categories considered. It denotes how the packaging and cultivation phases have the highest potential for reduction of the environmental impacts. Especially as regards the packaging, it has been noted that the material used is the factor that mainly influences the environmental impact. In this study it is expected not to have packaging among the main hot-spots, as Tetra Pak® will be considered as a container for crushed tomatoes. Transport remains an unknown factor, which in the case of this study will include the entire supply chain: from the transport of tomatoes to processing plant, to transport from the processing plant to Sweden. As reported in the article *Effect of eating seasonal on the carbon footprint of Swedish vegetable consumption* (Röös & Karlsson, 2013), when the food distribution area increases, the environmental burden increases as well, but we must also consider how sustainable the production of packaged tomatoes would be directly in Sweden for an accurate comparison.

4.2. Origin of canned crushed tomato products on the Swedish market

The products collected for this study, data regarding the origin of the product, type of cultivation, weight and type of packaging were identified in major grocery stores (COOP, ICA, Willys, Hemköp) in Stockholm, Sweden, during spring 2022. As listed in Table 3, 16 canned crushed tomatoes have been identified: 13 out of 16 products come from Italy, the remaining three come from Spain, Portugal and Greece. 10 products come from conventional farming and 6 from organic farming. The products were purchased packed in Tetra Pak® or metal cans; different packages contain from 390 grams to a maximum of 500 grams of crushed tomato.

Looking at the information on packaging, for some of the products the origin of the tomatoes and tomato juice coincides with the country in which it is processed. In other cases, however, the origin of tomatoes is specified and coincides with the country where the process takes place, but the origin of the tomato juice is not specified.

Table 3 List of crushed tomatoes in Tetra Pak® or metal can, found in main grocery stores in Stockholm.

Product	Type of production	Origin - Processing country	Container size	Packaging
1	Conventional	Portugal	390	Tetra Pak
2	Conventional	Italy	400	Tetra Pak
3	Organic	Italy	390	Tetra Pak
4	Conventional	Italy	500	Tetra Pak
5	Organic	Italy	390	Tetra Pak
6	Conventional	Spain	500	Tetra Pak
7	Conventional	Greece	390	Tetra Pak
8	Organic	Italy	390	Tetra Pak
9	Conventional	Italy	500	Tetra Pak
10	Organic	Italy	400	Metal can
11	Conventional	Italy	400	Metal can
12	Organic	Italy	400	Metal can
13	Conventional	Italy	400	Metal can
14	Organic	Italy	400	Metal can
15	Conventional	Italy	400	Metal can
16	Conventional	Italy	400	Metal can

Since most of the product have Italian origin, the data collection in the next sections focuses mainly on this area.

4.3. The production system

Information obtained about the production process in the farm and processing plant was difficult to obtain from the food actors. The customer service of each company listed in Table 11 was contacted, in most of the cases no response was obtained. In other cases, the most common replies from non-responders were "*we cannot provide this information*", "we are not aware of this data", "*to find out data about yields it is time consuming and we need a formal request*". In the few cases of response, the information was often generic and vague. A literature review was then conducted to compile data of carbon footprint and energy demand. Data were then extracted from previous studies concerning cultivation, production, packaging, and transport methods.

Production process and transport

The data relating to the agricultural cultivation phase refer to one of the main cultivation sites in southern Europe, Italy. The most likely production methods are described below.

The cultivation systems in Europe are regulated by the internal regulations of the country of production in accordance with the European regulations. The Regulation (EU) 2018/848 of the European Parliament focuses on organic production and related labelling. Conventional farming systems are also defined as intensive farming systems and make use of external factors that make it possible to make the most of the cultivated land and to obtain higher yields. The systematic use of synthetic chemicals for pesticide, herbicide and fertilizer purposes is therefore the basis of this system. On the contrary, organic farming aims to reduce the production costs, to improve soil and ecosystem health ecosystem by not using synthetic fertilizers and pesticides (European Parliament - Regulation (EU) 2018/848), this is done with the aim of safeguarding biodiversity, soil productivity and biological cycles (Dam *et al.*, 2005).

The **agricultural phase** consists of several practices. The tillage of the soil takes place a few months before transplanting; in this phase the soil is ploughed and harrowed. In the case of conventional cultivation, mineral fertilizers are placed in the soil to provide potassium, nitrogen and phosphorus. Often some of these are added to the land both before and after the transplant (De Marco *et al.*, 2017). Based on atmospheric conditions and temperatures, sowing takes place in greenhouses or open fields. Tomato seeds are planted in a seedbed, this phase often takes place in the greenhouse as it is possible to maintain a stable temperature and humidity (Casalasco, pers. comm.), but when temperatures allow it, this phase can take place directly on the soil in May-June (La Doria, pers. comm.).

Transplanting generally takes place in the months of April and May when the seedling is 10-15 cm tall (Casalasco, pers. comm.). Herbicides and pesticides are then added in order to protect the plants, with the aim of maximizing harvest yields. During the development of the plant, the irrigation must be provided regularly, from a few times a week in the months with a mild climate to every day in the hottest and driest months (Dam *et al.*, 2005).

Mechanical harvesting takes place in several steps between July and September in order to better manage the transport and processing of tomatoes for tomato product production (Casalasco, pers. comm.). Tractors take care of soil tillage, transplanting, of the distribution of fertilizers and pesticides on the soil, and of the final harvesting phase. Tomatoes are then arranged in boxes and loaded on trucks.

According to the information provided by some companies interviewed, the travel distance between the farm and the processing plant is about 50 km (Casalasco, pers. comm.). The harvested tomatoes are usually processed on the same day, this allows to optimize the yields as the degradation curve of the tomato is rapid (*Ibid*).

In the **processing plants,** tomatoes are sorted and washed through sorting canals. In large plants where several production lines are planned, tomatoes are placed in the automatic production selection system. The most common tomato products are whole-peeled tomato in tomato juice, tomato purée, chopped and crushed tomato (Del Borghi *et al*., 2014). For the production of crushed tomatoes, a manual and automatic machine take care of sorting, tomatoes are lightly blanched to remove the peel and sent to the automatic cutting machine. Subsequently seeds and peel are eliminated, and a certain quantity of water is evaporated using concentrating machines. At the same time the concentrated tomato is produced, the tomato is shredded, heated and processed in refiners that separate the peel from the juice. The latter is collected and concentrated up to the concentration suitable for the production of crushed tomatoes. Sliced tomatoes and a lightly concentrated tomato juice are fed into a mixing machine, pasteurized, and **canned** in brick e.g., Tetra Recart, cans or glass bottles.

Part of the companies that produce crushed tomatoes destined for the international market distribute the product with private labels, as in the case of most of the crushed tomato packages found in the main Swedish supermarkets. Canned and labelled product is then packed in secondary and tertiary packaging and loaded onto articulated lorry. Goods are generally transported by articulated lorry, which is the most common transport method, or using multimodal transport by lorry, trains and roll-on/roll-off ships to reach Scandinavia (Sundin, 2020).

Only some of the food actors contacted in Italy shared overall information about **transportation routes** within the country, also providing information on the modes of transport used. The production poles in Italy are divided between the north and south of the country (Boccia *et al*., 2019). For companies located in northern Italy, the main production regions are Emilia-Romagna, Lombardy, Veneto, and Piedmont. In Southern Italy, on the other hand, the main production regions are Apulia and Campania. As previously mentioned, tomatoes are transported on articulated lorry for about 50 km, the distance between the farm and the processing plant (Casalasco, pers. comm.).

A comprehensive view of the typical shipping routes from Italy to Sweden is presented in the report *Carbon footprint and energy use of transport in the supply chain of pulses for Swedish human consumption* (Sundin, 2020). The mode of transport seems to be the same for all tomato products. As reported by Sundin

(2020), the transport of goods is often shared by several shippers to limit costs and emissions. A typical route can be exemplified by the transport of products ready for export being transported to Verona or Domodossola, respectively located in the north and northeast. Containers are loaded onto electric trains in the direction of Rostock - Germany. In Germany, containers are put on Roll on - Roll off ships to Sweden (*Ibid*). Containers are then redistributed on articulated lorry or trains and sent to Sweden. Alternatively, the transport takes place through the Brenner pass on the border with Austria exclusively with articulated lorry (*Ibid*).

4.4. Simplified LCA – climate impacts of different stages in the supply chain of crushed tomato production

Considering all the phases described in paragraph 4.3 and the most common place of origin found on the packaging of the collected products (Table 3), it was decided to base the calculations for a system described as follows: the cultivation phase takes place in southern Italy in the open field, both for the conventional and organic system. Cultivating in open field is the most commonly used system in this area. Fresh tomatoes are then transported to the processing plant, which is about 50 km from the farm, this is where the entire production process takes place up to packaging in Tetra Pak®. From the processing plant, the packaged product is loaded onto trucks and transported to Sweden for about 3000 km. The functional unit selected is 400 grams of packed crushed tomato. Figure 2 represents the flow diagram and system boundaries considered of crushed tomatoes in Tetra Pak®.

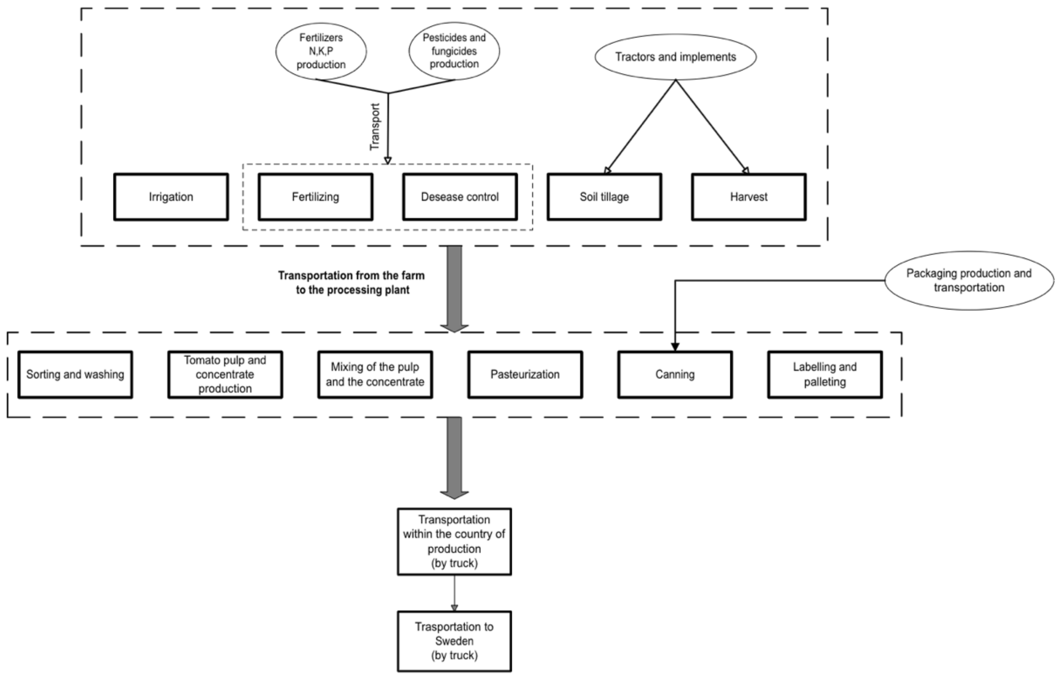

Figure 2 Flow diagram of the system boundaries considered for packaged crushed tomatoes transported to Sweden.

Agricultural phase

For the agricultural phase, data provided by Ronga *et al.* (2019) are used as a reference as they focus on the carbon footprint and energetic analysis of tomato production for both conventional and organic cropping systems. The area where this study is based, southern Italy, is commonly used for the cultivation of tomatoes intended for the production of tomato products. The activities considered are soil tillage, water irrigation, fertilizer and pesticide and fungicide application, with particular focus on data relating to mineral fertilizers production and transport. Values regarding yields (t), diesel used (kg) for soil tillage and pesticide/fungicide application, electricity for irrigation and fertilizer application (kWh), fertilizers used (kg), lubricant (kg) for soil tillage and pesticide/fungicide application is summarised in Table 4, divided by type of cultivation system. Data was collected in one year and referred to one hectare of cultivated land (Ronga *et al.*, 2019).

Table 4 Agricultural phase - inventory data per hectare of cultivated land (Ronga et al., 2019)

Cultivation system	**Yield (t/ha)**	**Diesel (kg/ha)**	**Lubricant (kg/ha)**	**Organic/Mineral fertilizers – N (kg/ha)**	**Energy use (kWh/ha)**	**Tot GHG Kg CO_2-eq/ha**	**Tot energy use MJ**
Organic	49	723	5.4	85	1500	3154	37092
Conventional	102	1240	9.2	150	1272	5291	59365

As shown in Table 4 one hectare of land in the organic system produces about 50 tons of marketable tomatoes. On the contrary, the conventional system, one hectare of land produces about 100. Table 5 shows the value of emissions referring to 1 ton of marketable fresh tomatoes, in which the organic cropping system has the greatest impact. (Ronga *et al.*, 2019).

Table 5 Energy demand and GHG emissions in organic and conventional cultivation systems expressed per ton of marketable fresh tomatoes according to Ronga et al. (2019)

Cultivation system	**GHG Kg CO_2-eq/t**	**Energy use MJ/t**	**Reference**
Organic system	67	793	Ronga *et al.*, 2019
Conventional system	55	618	Ronga *et al.*, 2019

Table 6 shows the contributions (%) to total GWP and CED impacts for each stage for both cropping systems according to Ronga *et al.* (2019). The highest impact level in the organic cropping system for GWP and CED resulted in pesticide/fungicides application and soil tillage activities. The latter, on the other hand, is the hot-spot for the conventional system for both impact categories (Ronga *et al*., 2019). Table 6 shows the pesticide and fungicide application stage as a hotspot in both conventional and organic systems. In this specific case, the values are justified due to a high level of disease on both cropping system, which requires more tractor used for pesticide and fungicide application.

Table 6 Contribution to total GWP and CED impacts (%) for each phase in organic and conventional system Ronga et al. (2019)

	Organic system		**Conventional system**	
	GWP %	CED %	GWP %	CED %
Pesticide/Fungicide application	28	31	28	32
Fertilizer application	6	9	3	4
Fertilizer production	4	12	5	13
Soil tillage	25	27	31	35
Irrigation	13	19	8	12
Diesel production	7	3	8	3
Field emission	17	0	18	0
Lubricant production	0.1	0.1	0.1	0.1

Furthermore, considering the functional unit selected in this study - 400 grams of packaged crushed tomatoes - 650 grams of incoming fresh tomatoes are required (Casalasco, pers. comm.). Total GHG emissions and energy used are then shown in Table 7.

Table 7 Energy demand and GHG emissions to produce 0,65 kg of marketable fresh tomatoes (400 g of packaged crushed tomatoes) related to cultivation phase

Cultivation system	**GHG Kg CO_2-eq**	**Energy use MJ**
Organic system	0.044	0.52
Conventional system	0.035	0.4

Processing and packaging

As concern the process phase, data from Manfredi & Vignali (2013) are used as a reference, which considers both GWP and CED in the process phases of tomato puree. The process is similar to that used for crushed tomato products, and the same machines are often used to produce different types of tomato products. Energy consumption and emissions to water used in the process are considered in unloading, sorting, washing, blenching, cutting, filtration, concentration, pasteurization steps. According to Manfredi & Vignali, 1.79 MJ and 0.108 kg CO2 -eq in GWP are used to produce 700 grams of tomato puree. In this context, where the FU is 400 grams of packaged crushed tomato, the data to be considered are 0.061 Kg CO_2-eq and 1.02 MJ as shown in Table 8.

Primary packaging solutions are mainly two, in tin cans or Tetra Pak®. More than 50% of the crushed tomatoes found in main grocery stores are packaged in Tetra Pak®, for both organic and conventional product. According to the data provided by Tidåker *et* al. (2021) referring to the packaging used for 1 kg of pulse, the GWP is 0.14 kg CO_2-eq, and the energy required is 4.5 MJ. These values include the production and the final waste management of the package (*Ibid*). Based on this data, approximately 0.05 kg CO_2-eq and 1.8 MJ would be required to package 400 g of crushed tomatoes (Table 8).

Transport

As far as transport is concerned, both the route from the farm to the processing plant for fresh tomatoes and the route from Italy to Sweden are considered. Regarding the transportation from field to the processing plant, data provided by Garofalo *et al.* (2017) are considered as a reference as in the study is conducted in Italy and similar distance between the farm and the processing plant is taking into account. The average distance between the fields and the processing plant considered is 50 km and about 650 g per functional unit is trucked, without considering losses. Transportation is carried out by 27-ton articulated lorry. According to this, carbon footprint is approximately 0.07 kg CO_2-eq per functional unit (Table 7).

Sundin (2020) calculated the average transport distances and related impacts for the transport of legumes from Italy to Sweden. Assuming that 30–34-ton articulated lorry is used for transport for a route of approximately 2940 km, 0.29 kg CO_2-eq are emitted and 4.25 MJ of energy are used for every 1 kg of canned pulse in Tetra Pak® (*Ibid*). Based on this, approximately 0.1 kg CO_2-eq is the carbon footprint and 1.70 MJ is the energy used to transport 400g of canned crushed tomato in Tetra Pak® (Table 8).

Table 8 Energy demand and GHG emissions to produce 400 g of packaged crushed tomato related to processing, packaging and transport stages

Activity	GHG Kg CO_2-eq	Energy use MJ
Processing	0.061	1.02
Packaging	0.05	1.8
Transport (farm to processing plant + processing plant to Stockholm)	0.17 (0.07 + 0.1)	1.70

This basic LCA shows that the transport phase has the greatest impact in terms of carbon footprint emissions compared to the FU considered, followed by the processing, packaging and cultivation phase (Table 9). On the contrary, the packaging stage is the hot-spot in terms of energy use (Table 8). Table 9 also shows relatively high values in the packaging and transportation stages in terms of energy consumption, but low values in terms of GWP in the same stages. This could be justified by the type of energy used. A mix of renewable and non-renewable energy - such as a mix of hydro/solar and nuclear power - could account for very high energy consumption associated with lower CO_2 emissions to the environment, resulting in low values in terms of climate impact. To determine the gap between the two systems are the values obtained in the cultivation phase, where the organic farming system has a greater impact in terms of GWP than the conventional one, as the quantity of marketable fresh tomatoes is taken into account (Table 4 and Table 7).

Table 9 LCA-results related to 400 g of packaged crushed tomato. (OS=organic system; CS=conventional system)

	Cultivation		Processing	Packaging	Transport	Tot	
	OS	**CS**				**OS**	**CS**
Kg CO_2-eq	0.044	0.035	0.061	0.05	0.17	0.32	0.31
MJ	0.5	0.4	1.02	1.8	1.7	5.02	4.9

5. Discussion

5.1. Origin of canned crushed tomato products

The method for identifying the country of origin used was based on the collection of the information reported on the packaging of the products sold in the main grocery stores in Stockholm, as shown in Table 3, and it is not based on statistics. The main country of origin of crushed tomatoes for the 16 products considered in this study is Italy, followed equally by Spain, Portugal and Greece. This confirms what is declared by Eurostat (2020) and Ismea (2021) which identify Italy as the main producers of tomato products in general. Only Italy covers about 50% and 13% of European and global production respectively, exporting more than 60% of its total production (*Ibid*). The results show that the consumption of packaged crushed tomatoes is highly dependent on long supply chains from southern Europe. None of the products selected were produced in Sweden or contain tomatoes with Swedish origin. Most of the crushed tomatoes found are produced by third-party companies that supply the product with Private Label. In addition, six out of sixteen are certified organic products through the European organic logo. Some of these also show the KRAV certification, an exclusively Swedish certification for organic products.

5.1.1. Information about country of origin on packaging

An important aspect to consider is the information on the packaging regarding the origin of the raw material. Among the 16 products considered, only one shows unclear information regarding the origin of the raw material, defining only the origin of the chopped tomatoes but not the origin of the tomato juice used. It can be assumed that the origin is the same as the cut tomatoes, but not being specified this can mislead the consumer. The regulation (EU) n.1169/2011 (European Parliament, 2011) establishes the mandatory specification on the label regarding the country of origin or place of provenance in the event that failure to specify could mislead the consumer. Furthermore, the EU regulation 2018/775 (European Commission, 2018) indicates the obligation to declare on the label the information about the origin of the primary ingredient with regard to processed foods, when the ingredient is present in quantities equal to or greater than 50%.

As already mentioned, in the last decade the quantity of tomatoes from China in Europe has increased significantly (European Commission, 2019). Consumers have highlighted concerns about fraud and the provenance of the raw material in tomato-based products, thus requiring a more transparent label (European Parliament, 2022). In 2017, two parliamentary questions were presented to the European Commission denouncing concerns about extra-European tomatoes, and in which the commission was asked to regulate and limit imports from the extra-European market, especially those that do not comply with European phytosanitary standards. A report dedicated to the composition of the tomato concentrate sold in the European market and the mandatory indication on the label of the origin and place of production of the tomato products were also requested in order to protect the "Made in Italy" (European Parliament, 2017). The commission replies that it has not been informed either by the Member States' competent authorities or by the companies in the food sector about fraud and violations, and with no evidence it is therefore not possible to take any action. In the absence of EU rules covering different categories of food, some EU states have enacted provisional legislation requiring mandatory origin labelling of certain products. In the case of tomato products, Italy has declared mandatory the introduction of specific information on the label such as the origin of the raw material (place of cultivation) and the place where the tomato products are processed. It has been proposed to introduce the same regulation at European level and the commission is expected to implement the proposal at the end of 2022 (European Parliament, 2022).

Having all the information regarding the origin of the products is not only necessary for food safety and fairness towards the consumer. Consumers want to be increasingly aware of what they buy not only to preserve their health, but also to be aware of the environmental impact of the product and draw their own conclusions (Solomon *et al.*, 2019). From the process sustainability point of view, in terms of emissions and energy use, the values obtained from an LCA analysis would change substantially as many variables would change, for example cultivation techniques, types and quantities of inputs, process energy, transportation.

5.2. Analysis of the LCA results

The lack of a large part of primary inventory data does not allow to calculate specifically what the impacts of the products exported to Sweden may be. However, through previous studies it is possible to make an approximation of what the results could be considering both the few basic information obtained as primary data and data deriving from contexts very similar to what it is considered in this study. The results of the simplified LCA resulting from the LCA review (Table 9) show slightly higher values for both impact categories in the open-field organic system compared to the conventional one, with 0.48 kg CO_2-eq and 7.81 MJ, and 0.47 kg CO_2-eq and 7.69 MJ respectively. The stages with the greatest impact for both impact categories are the transport and the process. However, there are some aspects to consider for each phase:

Agricultural phase

Data used as a reference for this phase were chosen as they compare conventional and organic cultivation systems in open field in the same geographical area (Ronga *et al.,* 2019). The geographical area considered, Apulia, is among the production areas from which some of the products considered in this study come from. GWP and CED are calculated for both systems and the results show that the organic system has higher values in both impact categories (Table 6) when one ton of marketable product is considered. The main difference is the yield with about the double yield per hectare in the conventional system. This means that in order to have the same quantity of marketable tomatoes per hectare, the organic system would have to produce at least twice as much under the same conditions. Ronga *et al.* (2019) proposes to use cultivars that require a low level of input, more resistant to pests and grown in systems where innovative organic fertilizers are used. What made the difference in terms of GWP and CED in both systems were mainly the application of fungicides/pesticides and soil tillage (Figure 3). Trying to reduce pesticide and fungicide applications without compromising crops could be among the solutions. As specified by previous studies cited, a potential improvement in this phase would also be given by better soil tillage and better management of fertilization and irrigation systems, associated with the use of renewable energy sources to reduce the environmental burdens deriving from the consumption of electricity.

As mentioned in the description of the production process, tomato cultivation takes place mainly in May-June directly in the field, and this is possible thanks to the favourable climatic conditions. When system boundaries and production systems are different, a comparison can give an idea of what the impacts of production are under different conditions. It can therefore be assumed to consider the cultivation of tomatoes in Sweden, which takes place mainly in Skåne (Karlsson, 2011) in heated greenhouse condition, heated by renewable energy sources. This system generally requires high total energy due to the greenhouse heating, useful for extending the growing season (Manfredi & Vignali, 2014), but the environmental impact is also affected by the greenhouse construction material (Bosona & Gebresenbet, 2018). Considering a yield in greenhouse ranging from 7.8 kg/m^2 to

35 kg/m^2 in the organic system, the yield in a heated greenhouse for each hectare cultivated would hypothetically be between 78 and 350 tons (*Ibid*). The yield of the organic system in the greenhouse is greater than that considered in this study (Table 4) despite the fact that the energy use to produce the same quantity of tomato would hypothetically result in 45000 MJ and 548 kg CO2-eq against 37000 MJ and 3154 kg CO2- eq. In this case the comparison shows, with the same performance, a significantly higher CED and GWP for the greenhouse cultivation system. The study conducted by Ntinas *et al.* (2016) confirms the same criticality in the comparison between the open-field and greenhouse systems, underlining how much the major impacts of heated greenhouse cultivation are given by the quantity of fuel and electricity used for heating.

Processing phase

Processing phase is the second hot-spot, after transport. Based on most of the published studies considered in this study (Del Borghi *et al.,* 2014; De Marco *et al.,* 2017: Farahani *et al.,* 2019; Garofalo *et al.,* 2016; Ingrao *et al.,* 2019; Manfredi & Vignali 2014), the process phase is not usually among the main hot-spots of the value chain. However, this depends on several factors. In this case, the activities included in the process are unloading, sorting, washing, blenching, cutting, filtration, concentration, pasteurization and filling of the packaging and the energy source were electricity and natural gas. Most of these activities have high energy requirement, especially the pasteurization and concentration phases. Furthermore, it must be considered that the water used in the process must be initially collected and purified, and this requires a high energy intake (Manfredi & Vignali, 2014).

The food waste management generated along the cultivation and process phases is not considered in this study, but the quantity of tomato waste generated above all during the process phase are huge, representing approximately 70% of the total waste generated throughout the value chain (Boccia *et al.,* 2019). Therefore, exploiting by-products could be one of the solutions to mitigate the impacts in this phase. One of the solutions identified by Bacenetti *et al.* (2015) consists of the use of by-products in biogas plants for energy production. Furthermore, to mitigate the impacts of this phase, alternative renewable energy sources could be considered, such as solar energy (Ghnimi *et al.,* 2021) that can be used in process structures.

Packaging

Among the phases analysed, packaging is the phase that consumes the most energy. The packaging used as a reference is the Tetra Recart®, one of the most used in packaged crushed tomatoes found in the main grocery stores. The production impacts for this type of packaging show decidedly lower values when compared to other types such as glass bottles and tin steel can (Del Borghi *et al.*, 2014). As far as crushed tomatoes are concerned, tin can package is still in common use. In this simplified LCA, the GWP and CED values in this phase are 0.05 kg CO_2-eq and 1.8 MJ for a Tetra Pak® packaging containing 400 g of crushed tomato. These values include both packaging production and final waste management. Considering instead a tin steel can packaging, the impact would be substantially greater. For example, Del Borghi *et al.* (2014) calculated that to contain 400 g of crushed tomato, the GWP and CED values would be 0.22 kg CO2-eq and 3.7MJ respectively. In the main grocery stores in Stockholm, no packages of crushed tomatoes in glass bottles were found, much more commonly used instead for tomato puree. The environmental impact of packaging such as glass bottles is among the highest (Manfredi & Vignali, 2014). This shows how the selection of the material used for packaging is of fundamental importance for mitigating the environmental impact. As in the previous phase, to further reduce the environmental performance for this stage, the use of by-products for the production of biogas could be one of the solutions associated with reducing the transport distances of packaging to the transformation plant. This would further reduce the amount of diesel fuel needed.

Transport

The transport phase appears to be the main environmental burden among the phases considered both in terms of GWP and CED (0.1 kg CO2-eq, 1.7 MJ for 400 grams of canned crushed tomato). The vehicle considered was an articulated lorry that travels the entire route from Italy to Sweden for about 2900 km. An alternative is a multimodal mode of transport via lorry, trains and roll-on/roll-off ship, when products are from Italy. The transport system considered is the same used for the transport of canned and dry pulses (Sundin, 2020). In comparing distance travelled, the type of vehicle used affects the total emissions. Choosing to adopt the train for a large part of the route, in the case of multimodal transport, would further reduce emissions at this stage. Furthermore, the choice of using a retortable cardboard packaging is also the most convenient from the point of view of transport because it allows to use all the available space in an optimal manner. Transporting steel cans requires 30% more volume due to its cylindrical shape (Sundin, 2020).

5.3. Considerations

Sweden currently lacks facilities for the production of tomato products and therefore is totally dependent on long-distance supplies, mainly from Italy. Assuming the availability of processing plants in Sweden, emissions would not be reduced, as it would still be necessary to export tomatoes suitable for processing and in the quantities required by the domestic market for tomato products production. This would be even more inconvenient from emissions and energy consumption point of view since, by transporting the same weight, the volume of fresh tomatoes to be transported would be considerably greater than the volume occupied by tomatoes already processed and packaged. Furthermore, it must be considered that the transport of fresh products for such a long route is not recommended and there would be a risk of having large quantities of food loss. In this sense, processed tomato products are considered as a way to extend the shelf life of tomatoes. Referring to the study conducted by Payen *et al.* (2014), the tomato production in open field or unheated greenhouses carried out abroad is much more convenient from an energy point of view when compared to on-site and off-season production in heated greenhouses, as the energy used for the production of the material useful for the greenhouse and that used for heating require much more energy. By choosing the most suitable vehicles for transport, the impact would be lower despite the long distance.

There are other impact categories that it would be interesting to include in this LCA for the comparison of these two different systems. The agricultural sector in Europe consumes up to 80% of the total water in the Mediterranean area (Evangelou *et al.,* 2016). In some areas, water consumption has reached levels that can no longer be considered sustainable. To this is added the water used in the subsequent production steps (*Ibid*). With regard to tomato products, in addition to the water used in the cultivation phase, the water used in the processing phase must also be considered. Including in the assessment the volume of freshwater needed to produce the functional unit along the supply chain would give a more complete view. This is identified through the water footprint (WF) impact category. The WF is a multimodal indicator as it includes the assessment of the green water footprint (consumption of rainwater that is stored in the soil), blue water footprint (consumption of subsurface and surface water solutions along the production chain) and gray water footprint (assessment of freshwater necessary to assimilate the polluting load, helps to evaluate the quality of the water). Another impact category to be included in the LCA in addition to CED and GWP, would be the eutrophication potential - EP. The use of fertilizers has led to an increase in nutrients in the land, contributing more and more to soil and water pollution (Martínez-Blanco *et al.,* 2010). This indicator measures the amount of nutrients added to the environment, such as nitrogen and phosphorus, which are induced by human activity. Values are usually expressed in units of PO_4-eq. This evaluation would be interesting in the comparison between both organic and conventional crop systems.

6. Conclusion

Most of the crushed tomatoes found in the main grocery stores are produced by third-party companies that supply the product with Private Label, which means that the packaging shows the retailer's brand name and not the manufacturer's brand name. The main countries of origin for canned crushed tomatoes imported to Sweden are mainly Italy, followed by Portugal, Spain and Greece. Considering Italy as the main place of production of tomato products destined for the Swedish market, the places of production are divided mainly between the north and south of the peninsula. The place of production of the tomatoes coincides with the place where they are processed and packaged. A simplified LCA deriving from an LCA review identified the transport phase as the phase with the greatest climate impact and cumulative energy demand. The organic product seems to have a slightly higher climate impact and cumulative energy demand than the conventional product.

Under current conditions, Sweden is unable to produce the quantity of tomatoes necessary for the production of tomato products. The carbon footprint and energy use used in the production of tomatoes in a heated greenhouse is still too high compared to the production in Southern Europe. Furthermore, even the import of fresh tomatoes for the production of tomato products would not be convenient in terms of volumes during transport, and therefore in terms of GWP and CED. The drawback is also given by the lack of facilities for the process. The result is total dependence on the import of this product. As mentioned, along the supply chain it must be considered that some changes can significantly lower the impact in terms of energy consumption and greenhouse gas emissions. From the point of view of energy consumption, the choice of packaging is fundamental. It is therefore preferable to package with solutions such as Tetra Pak rather than tin cans or glass bottles. This allows to mitigate energy use along the supply chain. Regarding transport, it was noted that it is not only the distance travelled that determines the increase in emissions, but also the type of transport used. Replacing part of the route with electric trains would have a greater effect on the impact.

A relevant result to consider in this study is the lack of primary data resulting from a limited response from the production companies contacted. Greater collaboration could allow a much more in-depth analysis of the carbon footprint and energy use targeted on the real impacts of the packed crushed tomato imported to Sweden.

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Appendix

*Table 10 List of companies contacted during this study**

Company name	*Date*	*Information*
Casalasco Società Agricola S.p.a.	April 21st, 2022	Information about the origin of the tomatoes, places of cultivation, cultivation system, distance between the farm and the production plant, required quantity of tomatoes for a package. Description of the production process.
La Doria Group	April 21st, 2022	Information about the origin of the tomatoes, places of cultivation, cultivation system, distance between the farm and the production plant, required quantity of tomatoes for a package. Description of the cultivation process.
Coop, ICA, Willys, Hemköp – customer service	March/April 2022	Information regarding mode of transport and transportation route.

* *Companies contacted that did not respond were not included in this table.*

Table 11 List of crushed tomatoes in Tetra Pak® or metal can, found in main grocery stores in Stockholm.

Brand	Type of production	Origin	Container size	Packaging	Supermarket	Producer	Produced for
Coop (Naturella)	Conventional	Portugal	390	Tetra Pak	Coop	Sugal Alimentos S.A.	Coop trading A/S. Taastrup, Danmark
Coop (Naturella)	Conventional	Italy	400	Tetra Pak	Coop	La Doria S.p.a. (Salerno)	Coop trading A/S. Taastrup, Danmark
Änglamark	Organic	Italy	390	Tetra Pak	Coop	Consorzio Casalasco del Pomodoro (Cremona)	Coop trading A/S. Taastrup, Danmark
ICA Basic	Conventional	Italy	500	Tetra Pak	ICA	/	ICA AB
ICA - I Love eco	Organic	Italy	390	Tetra Pak	ICA	Rispoli Luigi & C. Srl (Salerno)	ICA AB
ICA	Conventional	Spain	500	Tetra Pak	ICA	/	ICA AB
GARANT	Conventional	Greece	390	Tetra Pak	Willys, Hemköp	/	Axfood AB
GARANT	Organic	Italy	390	Tetra Pak	Willys, Hemköp	/	Axfood AB
Mutti	Conventional	Italy	500	Tetra Pak	In all the grocery stores considered	Mutti S.p.a. (Parma) Stabilimento di Strada dei Notari - Collecchio	/
Kung Markatta	Organic	Italy	400	Can	ICA, Coop	/	Midsona Sverige AB
Mutti	Coventional	Italy	400	Can	Willys, Coop, Hemköp	Mutti S.p.a. (Parma - Montechiarugolo)	/
Mutti	Organic	Italy	400	Can	Willys, Hemköp	Mutti S.p.a. (Parma - Montechiarugolo)	/
Baresa	Conventional	Italy	400	Can	Lidl	/	Lidl Stiftung & Co
Solania	Organic	Italy	400	Can	Coop	Solania s.c.r.l (Salerno)	/
Eldorado	Conventional	Italy	400	Can	Willys	/	Axfood AB
Cirio	Conventional	Italy	400	Can	Coop	CONSERVE ITALIA Soc. Coop. agricola Via P.Poggi - Bologna	/

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