DEPARTMENT OF AGRICULTURAL, FOOD AND ENVIRONMENTAL SCIENCES

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Environmental assessment of tomato cultivation.

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ACRONYMS AND ABBREVIATIONS

LCA Life Cycle Assessment

FAO Food and Agriculture Organization

GHG Greenhouse gasses

ISO International Organization for Standardization

EU European Union

EPD Environmental Product Declaration

PCR Product Category Rules

LCI Inventory analysis phase

LCIA Impact assessment phase

IC Impact Category

GWP Global Warming Potential

C.O.V.A.L.M Coltivatori Ortofrutticoli Valli delle Marche

ADP Abiotic Depletion Potential

GWP Global Warming Potential

ODP Ozone Layer Depletion Potential

HTP Human Toxicity Potential

FAETP Fresh Water Aquatic Ecotoxicity Potential

MAETP Marine Aquatic Ecotoxicity Potential

TETP Terrestrial Ecotoxicity Potential

POCP Photochemical Oxone Creation Potential

AP Acidification Potential

EP Eutrophication Potential

FU Functional unit

1. INTRODUCTION

This work is part of the activities carried out by the Department of Agricultural, Food and Environmental Science of Università Politecnica delle Marche for a Rural Development Program of Marche Region (PSR). The PSR refers to the bioconversion of agricultural and industrial-chain residues through the insect *Hermetia illucens*. Part of this project consists of the environmental sustainability evaluation of frozen tomatoes production through a LCA analysis, as one of the four vegetable residues selected, which allows finding solutions for improving the industrial chain efficiency.

This thesis project is aimed to assess the environmental sustainability of tomato cultivation carried mainly in Puglia region, Italy, where various local producers send the raw product to C.O.Val.M O.R.T.O. Verde – the Consortium base of this case study – where tomatoes are cleaned, cut, freezed and packed.

Once got cultivation data from the Consortium I prepared the Life Cycle Inventory and analysed it through the SimaPro software for LCA analysis.

1.1 Sustainability and Policies.

The UN estimated that the global population will increase up to closely 10 billion individuals by 2050, leading to an increased necessity of food worldwide (FAO, Food and Agriculture Organization., 2009).

In 2020 the EU Commission released a publication where was stated that the F&B sector is one of the largest manufacturing in Europe (European Commission, Directorate-General for Research and Innovation, Group of Chief Scientific Advisors. Independent expert report, Publications Office, 2020); that sector is the main natural resources demander, resources like water, soil and energy are highly-demanded by the agrifood system in EU, thus significantly contributing to GHG emissions and climate change.

Some authors assumed that the food production chain costs to the planet 26% of total GHG emissions (Ritchie, 2019). These authors analysed numerous studies about the food system environmental impact, assessing the average GHG emissions per kilogram of food product. results demonstrated how the **land use** for livestock and human nutrition contributes for 24% of the total food production emissions, together with losses of biodiversity and deforestation. 18% of food's emissions are related to all the steps of the **supply chain** such as transport, retail, packaging, transformation etc., even if the major contribution to supply chain's emission is caused by the food waste, due to losses along the supply chain and because of consumers.

Another 31% of total emissions is derived from the **livestock and fisheries** sector including GHG gases like methane, nitrous oxides and carbon dioxide, products of fuel consumption, manure from livestock etc.

Finally, a 27% of GHG emissions from **crop production**, derived from the application of fertilizers (N_2O mainly), and CO_2 from the use of agricultural machineries.

1.2 United Nations strategy.

Greenhouse Gases (GHGs) include CH_4, N_2O, and CO_2, even if many other substances can be counted, these three are the most important. The latter (CO_2), in fact, is used as a unit reference to measure the impact of food products, the so-called carbon footprint, based on the measure unit "kg CO_2eq", while CH_4 and N_2O bring high amount and great impact.

Basically, products derived from animals present much higher emissions than plant-based foods; that's because to sustain livestock is required much more land to feed them and much more water too, leading to a huge depletion of resources.

All these statements, together with the food waste and food loss phenomena must lead to a reversal of habits in the economic system – for example favoring a circular model of economy, where the inevitable production of wastes can find a new path and feed other systems – and an important adaptation by us, the consumers, last ring of the supply chain, choosing more sustainable products, having care to avoid waste even inside our own house.

The United Nations prepared and approved a plan to find out strategies to ensure food security to all populations of the world, to increase the well-being and the health of people, to improve the supply chains, to fight against climate change and to preserve life under water and on the mainland; all these concepts are included into one of the biggest policies made so far, the United Nation's Agenda 2030 that, with its 17 goals declare the world's intention to improve our production systems and behaviors in order to safeguard the environment and the public health.

Some of these 17 Sustainable Development Goals (SDGs) are perfectly in line with the main topic of this thesis or the assessment of the environmental impact derived from the cultivation of tomatoes in Italy; the SDGs touched by that topic are the n.2 "Zero Hunger", n.3 "Good Health and Well-being", n.12 "Responsible Consumption and Production", n.13 "Climate Action", n.14 "Life Below Water" and n.15 "Life on Land".

1.3 EU strategy.

The European Commission proposed new initiatives in order to support the sustainable transition; it is done mainly through the European Green Deal, a set of policies aimed at turning Europe into the first climate neutral continent by 2050. In order to reach this goal, in June 2021 entered into force the EU "Climate Law". From 1990 to 2018 the quantity of GHG was reduced of 23%, next step will be a further reduction of 22% within 2030 (European Commission. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the regions, 2019b). To achieve the environmental goals of the Green Deal, the Commission proposed two main strategies:

1) The "Farm to Fork" strategy.
   Is the core of the Green Deal, it sets out regulatory and non-regulatory initiatives about the common agricultural and fisheries policies as a crucial part to support the climate neutrality transition. The "FtF" strategy's objectives cover four main areas: sustainable food production, sustainable food processing and distribution, sustainable food consumption and food loss and waste prevention. Moreover, the EU Commission adopted, in 2020, the Circular Economy Action Plan (CEAP) with a list of 35 actions aimed to educate buyers and consumers, to enhance circularity within the production processes and to design more sustainable products.

2) The Biodiversity Strategy.

Aims to recover biodiversity by 2030 in order to protect the population by food insecurity, epidemics and climate change. Some measure adopted following these guidelines are the increasing of protected biodiversity-rich lands, the building of new structures aimed restore damaged marine ecosystems etc. (European Commission. Energy, Climate change, Environment, 2022a).

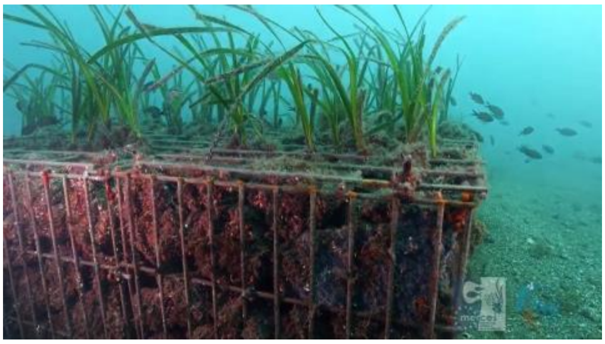

Figure 1.1: A structure made with organic materials placed underwater to restore biodiversity.

1.4 Frozen vegetables.

"Frozen vegetables are a range of products prepared by freezing fresh vegetables with the appropriate maturity for processing. They undergo operations such as washing, peeling, grading, cutting, and blanching/deactivating enzyme activity, depending on the type of product" (CBI, Centre for the Promotion of Imports from developing countries. The European market potential for frozen vegetables. , 2020).

"The freezing operation is carried out in such a way that the range of temperature of maximum crystallisation is passed quickly. The quick-freezing process is not regarded as complete unless and until the product temperature has reached −18°C at the thermal centre of the vegetable after thermal stabilisation.

"In the majority of cases, frozen vegetables are traded without any ingredients added. In some cases, such as in ready-to-cook mixtures, ingredients such as salt, sugars, aromatic herbs, stock or juices of vegetables and garnishes may be added" (CBI, Centre for the Promotion of Imports from developing countries. The European market potential for frozen vegetables. , 2020).

1.5 Frozen vegetables and tomato market data.

“Europe is by far the world’s largest importer of frozen vegetables, accounting for around half of global imports. European imports of frozen vegetables have increased annually by an average of 3% in volume in the period of 2014-2018. The largest share of imports is intra-European trade, while only 11% of imports come from developing countries” (CBI, Centre for the Promotion of Imports from developing countries. The European market potential for frozen vegetables. , 2020).

“In the next five years, the European market for frozen vegetables is likely to increase with an annual growth rate of 2-4%. The main reason for the expected market growth is the convenience in eating and increasing consumption of ready-to-eat frozen food. Also, consumption of vegetables (including frozen) is increasing due to the popularisation of vegan and vegetarian food across Europe (Istituto Italiano Alimenti Surgelati, 2020). Regular fluctuations in imports will continue to be influenced by harvested crop volumes and accessory price developments, rather than changes in demand” (CBI, Centre for the Promotion of Imports from developing countries. The European market potential for frozen vegetables. , 2020).

About tomatoes, Italy is placed in 6^{th} position as tomato producer on a global scale, while China holds the title of first producer with its annual production of about 56.424.000 tonnes of tomatoes, followed by India, USA, Turkey and Egypt (Atlasbig.com, s.d.).

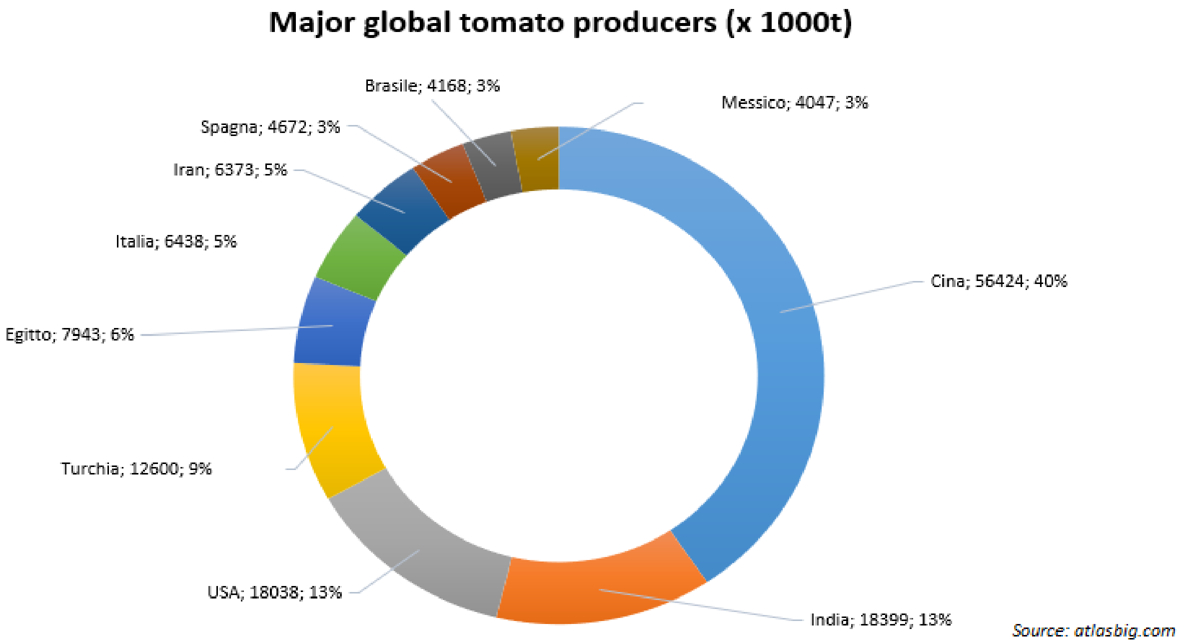

Figure 1.2: The graph reports major tomato producers worldwide.

In Europe the Italian production of tomatoes results much more represented, being Italy the first producer of tomatoes within the whole EU Community, followed by Spain, Portugal and Poland (Eurostat.eu, s.d.).

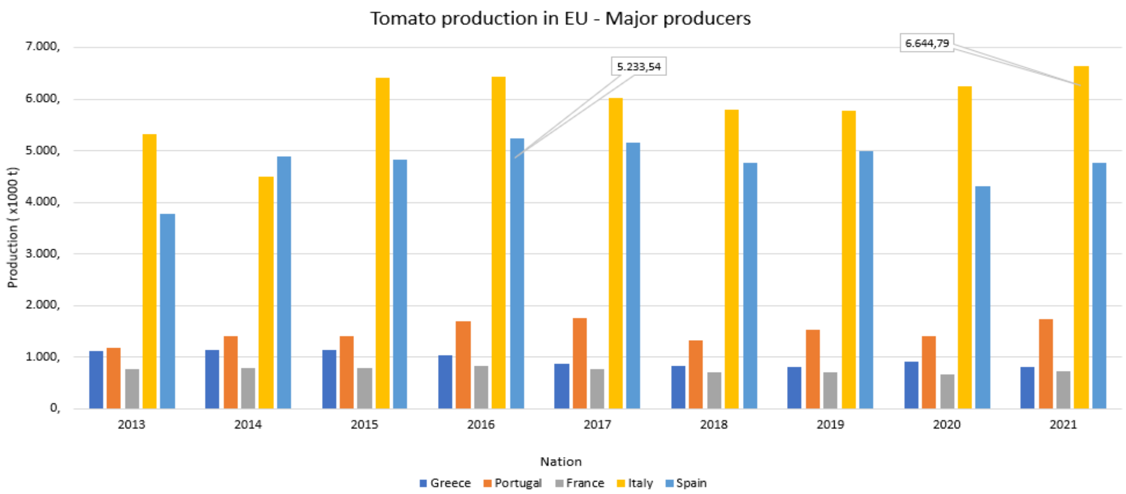

Figure 1.3: A graph reporting the major tomato producers within EU.

Even the area of occupied land for the tomato production can be red as an index of the importance that this culture represents for each nation; as the previous example, even for what regards the cultivated area, Italy stands on all the other EU nations with its 107.000 hectares dedicated to the tomato cultivations, followed by Spain (58.000 hectares), Romania (25.000 hectares) and Portugal (19.000 hectares) (Eurostat.eu, s.d.).

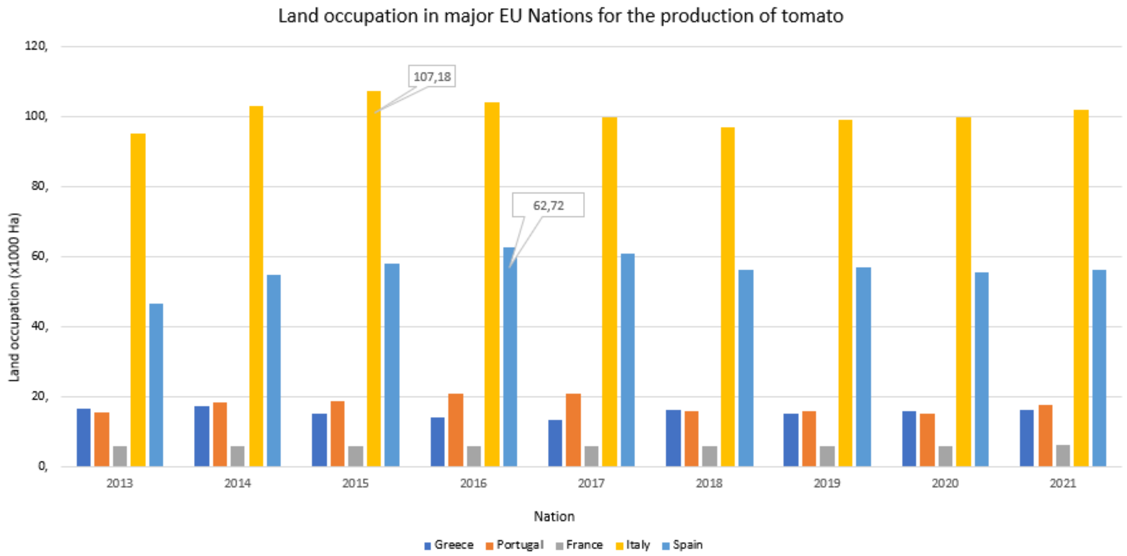

Figure 1.4: The graph reports the major EU nations showing the area for the tomato cultivation.

The tomato is the edible berry of the plant *Solanum lycopersicum L.1753*, commonly known as the tomato plant. The species originated in western South America, Mexico, and Central America.

The Aztecs used tomatoes in their cooking at the time of the Spanish conquest of the Aztec Empire, and after the Spanish encountered the tomato for the first time after their contact with the Aztecs, they brought the plant to Europe. From there, the tomato was introduced to other parts of the European-colonized world during the 16th century.

Tomatoes are a significant source of umami flavour and are consumed in many different ways: raw or cooked, and in many dishes, sauces, salads, and drinks. Tomatoes are fruits - botanically classified as berries - used culinarily as a vegetable ingredient or side dish.

Numerous varieties of the tomato plant are widely grown in temperate climates across the world, with greenhouses allowing for the production of tomatoes throughout all seasons of the year. Tomato plants typically grow to 1-3 meters in height. They are vines that have a weak stem that sprawls and typically needs support. Indeterminate tomato plants are perennials in their native habitat, but are cultivated as annual crops.

1.6 Tomato Consumption

In the marketing year 2020/2021 the quantity of tomato consumed worldwide was estimated around 37 million metric tonnes (mT, raw material equivalent), a quantity of about 10% higher than the average of the three marketing years that preceded the pandemic (2016/2017, 2017/2018, 2018/2019).

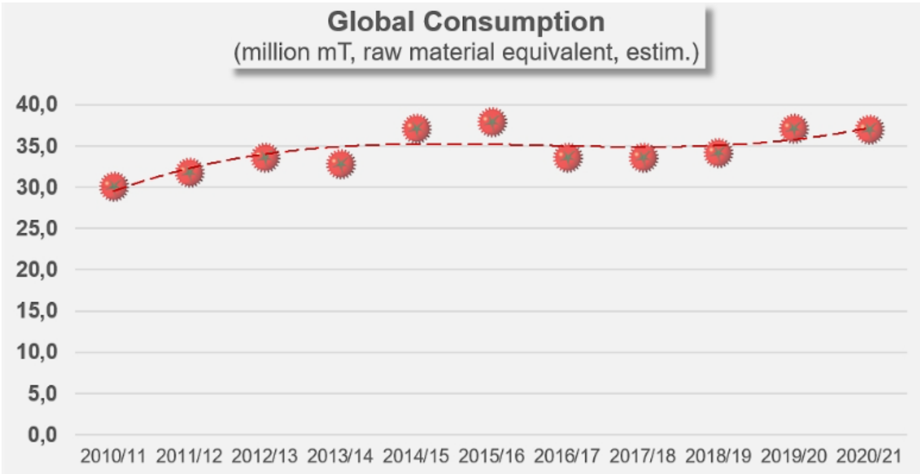

Figure 1.5: The graph reports an estimation of global tomato consumption. (tomatonews.com, s.d.)

1.7 Related studies

LCA analysis plays an increasingly important role for building a more responsible supply chain in various sectors. Recently have been published several studies regarding the environmental impact and mitigation strategies related to the production of frozen vegetables, for example, inside the research paper: (Ríos-Fuentes B. et al. "Life cycle assessment of frozen broccoli processing: Environmental mitigation scenarios" – Volume 32, July 2022) the researchers assessed that greenhouse gas emission for 1 t of frozen broccoli was estimated in 816.44 kgCO_2eq and when the broccoli stalk is treated to produce flour or applied as forage, the GHG emissions decrease to 640 and 689 kgCO2eq, respectively.

2. LIFE CYCLE ASSESSMENT – STANDARDS AND FRAMEWORK

Life Cycle Assessment (LCA) consists of an analytical method used for assessing the environmental impact derived from the production life cycle of products and services.

The relevance of LCA techniques lies mainly in their innovative approach, which consists in being able to assess all the stages of a productive process "from farm to fork"; among the methodologies created for the analysis of industrial systems, the LCA has therefore assumed in these years an important role and recently its use is growing in many different fields: from the automotive to the energy sector, up to the agri-food sector.

The LCA approach arose between the '60s and '70s, especially thanks to the contribution of Harold Smith, the man who ideated the first calculation of cumulative energy requirements for chemicals, proposed during the World Energy Conference in 1963.

This idea increased the interest of experts that started to calculate the energy used for inputs and outputs in industrial processes. During the following years, many studies were published with the idea to determine the costs of application of alternative sources of energy.

Since that moment many more predictions were made by experts, that tried to foresee world's changing trends and population, putting it in relation with the higher demands for energy and raw materials as time goes by (Jeroen B. Guinée, 2011).

In 1994, the International Organization for Standardization (ISO) set standardized procedures and methods for the application of LCA studies.

So, summing up, it's possible to affirm that the main goal of LCA is the determination of impacts of consumer products.

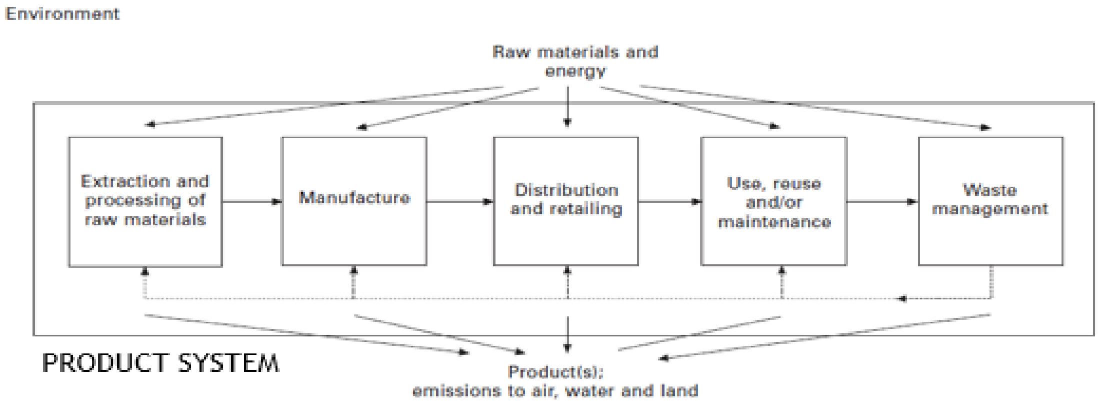

Figure 2.1: General scheme reporting the steps of food production chain, used as a model when performing LCA.

2.1 ISO standards on Life Cycle Assessment – Main Standards.

Nowadays, the two main international standards on LCA are the **ISO 14040:2021** called "*Environmental management – Life Cycle Assessment – Principles and framework*", and the **ISO 14044:2021** called "*Environmental management – Life Cycle Assessment – Requirements and guidelines*".

The ISO 14040:2021 is the main reference for the evaluation and interpretation of environmental impacts of any product and service during its life cycle; instead, the ISO 14044:2021, provides requirements and guidelines for Life Cycle Assessment.

While the first one is basically the definition for LCA, the second one is complementary and gives the practical approach, both are applied together when approaching an LCA study.

More specifically, the ISO 14040:2021 has entered into force the 18th February 2021, updating the previous ISO 14040:2006 and includes:

- Definition of the goal and the application fields of LCA;
- Guidelines to approach the Life Cycle Inventory (LCI) phase of LCA;
- Guidelines for the evaluation of impacts of Life Cycle (LCIA);
- Guidelines for the interpretation of the Life Cycle;
- Limitations and correlations among the different phases of a LCA study.

The ISO 14044:2021 has entered into force the 18^{th} February 2021 updating the previous ISO 14044:2006 and includes guidelines similar to those reported in the ISO 14040 but reporting also the conditions for the use of choices of values and facultative elements during the evaluation of the Life Cycle (LCA) and of the Life Cycle Inventory.

2.1.1 ISO standards on Life Cycle Assessment – Other Standards.

Other important Standards to be considered when approaching a LCA study are the ones specific for greenhouse gases and carbon footprint (**ISO 14067:2018**), and for the environmental management and water footprint (**ISO 14046:2016**).

The first one reports principles, requirements and guidelines for the quantification of the Carbon Footprint of a Product (CFP); constituting a technical guide focused only on climate change impact category.

The second one provides principles and requirements related to the Water Footprint quantification. In this case are considered just the emissions of air and soil that directly impact on water quality.

2.1.2 ISO standards on Life Cycle Assessment – LCA results communication.

The communication of results derived from any LCA study is regulated also by the ISO 14020 series of standards; it sets a series of globally recognized and credible international benchmarks to apply in the label in response to consumer’s demand.

It results useful also within the market because companies may be interested in investing money on the environmental improvement; surely, the main reason for that is the possibility to get recognized the company’s efforts through the use of labels and logos, increasing awareness on consumers.

The ISO Committee classified different types of labelling:

- Type I environmental labelling: the "classic" ecolabelling schemes are logos exposed when the fulfilment of a set of criteria has been accomplished.
- Type II self-declared environmental claims: are self-declared claims made by manufacturers and businesses.
- Type III environmental declaration: also called "Life Cycle data declaration", are a set of formalized information describing the environmental aspects of a product or service.

The Ecolabelling Schemes, covered by the **ISO 14024:2018** (ISO, International Standard Organization., 2018), are intended to educate and increase consumer awareness on the environmental impacts of a product; those schemes are voluntary labels, in compliance with other legislations, based on specific environmental criteria.

To get the Ecolabel, the whole product life cycle must be taken into account.

The following logos are some of the ones used as Ecolabels.

Figure 2.2: Some logos used as Ecolabels.

Self-declared environmental claims are covered by the **ISO 14021:2016** are based on three key elements:

1. Use of symbols;
2. Evaluation and claim verification requirements;
3. Specific requirements for selected claims.

Some examples of Self-declared environmental claims may be "free from HCFCs" or "lead free".

Some of the logos used to expose these claims is reported in the picture below.

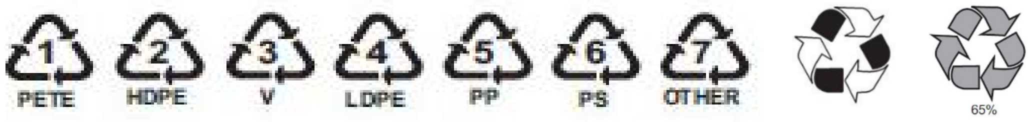

Figure 2.3: Examples of logos used to report a self-declared environmental claim.

Life-Cycle data declarations are ruled by the **ISO 14025:2010**, those are also called "Environmental Product Declarations" (EPD), and are not intended to be "green" certifications or claims of environmental superiority, but there are third parties that verify the authenticity of information on the product.

An EPD contains the descriptions of manufacturers and product, information on the composition and on the LCA, including energy sources employed, use of water, waste management, and so on.

2.2 Life Cycle Assessment steps.

Life Cycle Assessment studies are performed following a scheme of four steps, appliable to any LCA study, those steps are reported below:

- Goal and scope definition: defined in relation to the intended applications.
- Inventory analysis: involves the collection of data for each process, including the calculation procedures. That phase results into a table where are reported and quantified all the relevant inputs and outputs of the production system.
- Impact assessment: consists in the translation of the inventory analysis results into environmental impacts.
- Interpretation: in which conclusions and recommendations are drawn.

In the picture below is reported the general scheme used when approaching a LCA study.

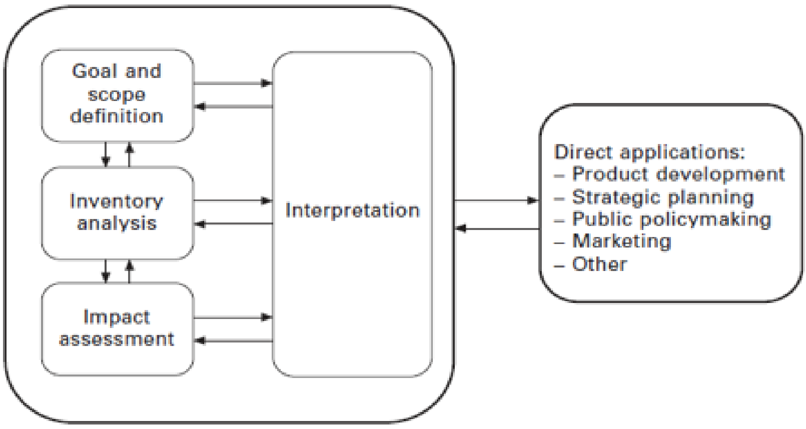

Figure 2.4: General scheme summarizing the LCA approach.

2.2.1 LCA steps – Goal and scope definition.

In this phase must be stated and justified the goal of the LCA pointing out the objective of the study (unambiguous and transparent), the name of the operator who performs the LCA, the name of the commissioner of the study, the involved stakeholders and the target audience. It is also suggested to determine possibilities and limitations of the study during this phase.

Two very important definitions are:

- *Functional unit*: or "comparison basis", provides the reference to which all the other data in the product system are normalized, often allowing comparisons between products.
- *System boundary*: are schemes used to determine which process unit must be included into the LCA.

The choice of system boundary usually takes care of many aspects such as the 1) *geographical area*, because transport system, infrastructure and waste management may vary depending on the region; 2) *time horizon*, because LCA analysis are used to predict future scenarios analysing present impacts.

The *system boundaries* determine which unit processes are included in the product system and which not. Depending on which unit processes are inside the system boundaries they can be classified as follow:

- *"cradle to grave"* allows a complete LCA since the system boundaries include all the phases of the product life cycle, starting from the extraction of raw materials to the use and disposal phase.
- *"cradle to gate"* includes the unit processes from the raw material extraction to the exit of the factory gate.
- *"cradle to consumers"* include the same unit processes of the "cradle to gate" approach along with the distribution phase.
- *"gate to gate"* is a very limited LCA because within the system boundaries are included only the unit processes from the entrance to the exit of the factory.

Data used during the LCA analysis must be reliable, accessible and relevant; it means data are more valuable when the source is credible and provides numerical accuracy.

Based on the source of date it is possible to make a distinction between:

- *Primary data*: are taken from measurement reports like field notebooks and patents;
- *Secondary data*: come from secondary sources that, preferentially, should be well documented; for example, they are taken from LCA databases;
- *Tertiary data*: are represented by estimations, those date must be limited in use as much as possible.

2.2.2 LCA steps – Inventory analysis.

During the Life Cycle Inventory (LCI) phase products are defined quantitatively, collecting all data taken during the goal and scope phase, resulting into an inventory table listing all the quantified inputs and outputs. In this phase the data must also be harmonized between the different process units of the supply chain and finally mathematically referred to the functional unit

The data are often classified as "foreground data" that are generally primary data, and "background data" that may be not specifically related to the product system and may consist of average and range values, generally taken from LCA databases and literature.

While foreground data are collected from questionnaires or annual reports and company brochures, background data can be collected from the existing literature or from the dedicated databases such as the "Input-Output" database.

2.2.3 LCA steps – Impact assessment.

The Life Cycle Impact Assessment (LCIA) is the third phase of any LCA study; here results from the Inventory analysis are further processed and interpreted in terms of environmental impacts.

The **ISO 14040/14044** provides the guidelines to perform the LCIA phase, that is carried out listing impact categories such as Climate change, Acidification and Eutrophication, those are characterized using factors that express how much a single unit of mass of a certain substance contributes to an impact category, that is useful for the impact quantification. Different LCIA methods can be used such as ReCiPe and CML.

When performing the impact assessment there are mandatory elements that must be done in order to obtain reliable results:

- *Method selection*: consists in selecting the impact assessment methods, which are used to calculate impact assessment results; among the global methods, there are the ReCiPe 2016 Endpoint (E, H, I) and Midpoint (E, H, I) while, among the European methods, there are CML-IA baseline and non-baseline, the EF Method ecc.
- *Classification*: consists in classifying the inputs and outputs into impact categories according depending on their expected impact.
- *Characterization*: this action is done when has to be performed a contribution analysis; it consists in multiplying the inventory data for the characterization factors, resulting in a quantification of the impact for every impact category.

There are also optional elements that may be included in the analysis to give to the study a more specific direction

- *Normalization*: is applied to compare the various impact categories, it consists in dividing the total impact for a certain impact category by the normalization factor.
- *Grouping*: in which impact categories are aggregate into bigger sets, sorted on nominal basis or ranked (indicators are listed on an ordinal scale) as explained by ISO:

- *Weighting*: in which normalized results for each impact category are assigned numerical factors according to their importance; this step is based on "value choices" given by, for example, monetary values, standards or expert panels.

2.2.4 LCA steps – Interpretation.

Is the last phase, during which the results of Inventory analysis and Impact assessment are combined with Goal and scope and elaborated to reach conclusions and recommendations or to define the starting point for a next iteration of the LCA method (needed to refine the study).

The **ISO 14044:2021** describes how to test the conclusions in order to ensure they are adequately supported by the data. This evaluation of LCA conclusions includes checks for the completeness, sensitivity and consistency; The first analyse data gaps to ensure that all the data required for the analysis has been used and are available for interpretation; the second is applied mostly to the major issues, trying to determine the influence of assumption variations; the third one determine if methods, assumptions, models and data are consistent and coherent with the Goal and scope.

Conclusions and recommendations should include environmental-related aspects of the product, possible areas for improvement along the supply chain or any other key information to be communicated to the consumer (CTI, 2004).

3.TOMATO RECOVERY STRATEGIES

LCA studies are a powerful tool to improve the supply chain, the production of goods and the related necessity to reduce the environmental impact as much as possible within every step of a product life cycle; its application may lead companies' actions to a new direction, oriented in terms of efficiency and environmental care, which leads to improving (their reputation and) the way they are perceived by customers.

Considering the potentiality of LCA studies, companies may improve different phases of their production chain, from the agricultural management to the way wastes and by-products are disposed of. By-products from cultivation and products at their life end (wastes) may be used to produce biogas or bioethanol, compost or feeds.

3.1 Another end for tomatoes

Tomatoes are fruits that are commonly used as vegetables in culinary contexts. They belong to the Solanaceae family and are scientifically known as Solanum lycopersicum. Tomatoes are rich in essential nutrients including vitamins, minerals, and antioxidants. They are a good source of potassium, folate, and vitamin K.

One of the key compounds found in tomatoes is lycopene. Lycopene is a carotenoid, which is a type of pigment that gives tomatoes their red colour. It is also present in other red and pink fruits such as watermelon, pink grapefruit and guava. Lycopene is known for its antioxidant properties, which may help protect human? cells from damage caused by free radicals. Some studies suggest that a diet rich in lycopene may be associated with certain health benefits, including a reduced risk of certain types of cancer and cardiovascular diseases.

In addition to lycopene, tomatoes also contain other antioxidants like beta-carotene, quercetin, and vitamin C. These compounds contribute to the overall health-enhancing properties of tomatoes. Moreover, tomatoes are versatile fruits and can be consumed in various forms, including raw, cooked, or processed into products such as tomato sauce, canned tomatoes and ketchup sauce.

3.1.1 Tomato waste generation in industries

In the tomato processing industry, tomatoes are often peeled, diced, or crushed. The parts of the tomato that are not used for the final product, such as its skins, seeds, and sometimes a portion of its flesh, do contribute to waste; even tomatoes that do not meet quality standards in terms size, colour, or shape may be discarded.

The residual material after extracting juice or pulp, often containing skins and seeds, is known as pomace and, while some of this is used for byproducts like animal feed, some may be used for the extraction of compounds of interest such as lycopene.

Other ways to generate tomato waste is when they are canned, leaving peel and seeds, as well as some liquid that may not be used in the final product, as well as the presence of damaged or overripe tomatoes (this damage is caused by transportation and storage, leading to an unsalable product).

Figure 3.1: Example of fresh tomato waste after harvest.

3.2 Lycopene: health-related reasons to save tomato by-products

Lycopene has been the subject of numerous studies exploring its potential health benefits. While more research is needed, several studies suggest that lycopene may have positive effects on various health aspects. Here are some potential health benefits associated with lycopene:

Antioxidant Properties:

Lycopene is a powerful antioxidant that helps neutralize free radicals in the body. Free radicals are unstable molecules that can cause oxidative stress, potentially leading to cell damage. Antioxidants like lycopene may contribute to reducing oxidative stress and protecting human? cells from damage.

Cardiovascular Health:

Some studies have suggested a link between lycopene consumption and cardiovascular health. Lycopene may help lower blood pressure, reduce LDL cholesterol levels, and improve the flexibility of blood vessels. These factors contribute to a healthier cardiovascular system.

Cancer Prevention:

Research has explored the potential role of lycopene in reducing the risk of certain types of cancer, particularly prostate cancer. Some studies have indicated that diets rich in lycopene may be associated with a lower risk of developing prostate cancer. However, more research is needed to establish a definitive link.

Eye Health:

Lycopene, along with other antioxidants present in tomatoes, may contribute to eye health. It has been suggested that a diet rich in lycopene may help reduce the risk of age-related macular degeneration (AMD) and other eye-related conditions.

Skin Protection:

Lycopene has been investigated for its potential to protect the skin from damage caused by UV radiation. Some studies suggest that lycopene may help reduce the risk of sunburn and protect against skin aging.

Anti-Inflammatory Effects:

Lycopene may have anti-inflammatory properties, which can be beneficial in reducing inflammation in the body. Chronic inflammation is associated with various health conditions.

It's important to note that while these potential health benefits are intriguing, more research is necessary to fully understand the mechanisms and to establish definitive conclusions. Moreover, individual responses to lycopene may vary, and a balanced and varied diet, along with a healthy lifestyle, is essential for overall well-being. If you have specific health concerns, it's advisable to consult with a healthcare professional for personalized advice. (S., 2019)

3.2.1 Lycopene extraction

Lycopene extraction from tomato waste can be an environmentally friendly as well as an economically viable approach to utilize leftover or discarded tomatoes. Here's a simplified process for lycopene extraction: discarded or unsuitable tomatoes from food processing or distribution centres are collected and put aside, commonly solvents are used for lycopene extraction including hexane, ethanol or a combination of both; to break down the tomato material into smaller pieces they are ground – increasing the surface area for extraction - and so separating the solvent extract from the solid residue through a centrifuge or a separatory funnel.

Figure 3.2: example of separatory funnel (precisionlabware).

Solvent is removed with a rotary evaporator in order to concentrate the lycopene extract, it applies vacuum and gentle heat to evaporate the solvent, leaving behind a concentrated lycopene extract.

Finally, can be applied analytical equipment to determine lycopene concentration and purity, it must be stored in a fresh and dark place in order to prevent heat and light degradation. (Madia, et al., 2021)

3.2.2 Possible claims for lycopene

In the first decade of the 21st century, some products containing lycopene were patented; a Spanish company submitted study data for a "*product for use in the prevention and treatment of CVDs, cancer and chronic inflammatory diseases*" (*European patent application EP 1997487 A1 - 21.06.2007*). Another patent, submitted by an English company, describes "*lycopene formulations for the treatment of atherosclerotic conditions*".

Even if in the past some products were successfully patented, in 2011 the European Food Safety Authority released a scientific opinion on lycopene and its health claims:

"*On the basis of the data presented, the Panel concludes that a cause and effect relationship has not been established between the consumption of lycopene and* *protection of DNA, proteins and lipids from oxidative damage; protection of the skin from UV-induced damage; contribution to the normal cardiac function; maintenance of normal vision*" (EFSA Journal 2011; 9(4):2031).

3.2.3 Practical application of lycopene

Lycopene is a liposoluble molecule, so it must be joined with a fat molecule (oil, butter or any other fatty acid source) in order to enhance its bioavailability and absorbability. It can be used as an ingredient for the production of biscuits and other bakery products such as bread or crackers; lycopene is an optimal addition also in tomato sauces and canned tomatoes in order to increase their antioxidant power. Ideally, it could also be used for the creation of supplements, but keeping in mind the necessity to add some fats in their formulation.

4. CASE STUDY DESCRIPTION.

4.1 Objective of the study.

The study is proposed to give an evaluation of the environmental impact related to the cultivation of tomatoes intended for industrial purposes, in order to find out hotspots along the process with, as last instance, its improvement.

4.2 Coltivatori Ortofrutticoli Valli delle Marche and Orto Verde

The study is made with the collaboration of the Cooperative "Coltivatori Ortofrutticoli Valli delle Marche" (C.O.VAL.M Sca.).

C.O.VAL.M. was born in 2004 as an association, joining together 130 members. In 2007, the association acquired the plant in Cesano di Senigallia (AN) and the numbers of associated continued growing year by year including, nowadays, more than 600 farmers from various Italian regions, but mostly from Marche, Umbria, Abruzzo, Lazio, Emilia Romagna and Puglia.

C.O.VAL.M. and A.C.O.M. (Associazione Coltivatori Ortofrutticoli Marchigiani) create together the O.R.T.O. Verde S.c.a.p.a., an agricultural consortium that produces, stores and sells frozen vegetables for industries and catering companies, within both national and international market.

The cooperative produces mostly peas (13 ktons) and leaf vegetables (6,5 ktons) but other productions are tomatoes (3 ktons) and beans (2,1 ktons).

Figure 4.1: The industrial plant of C.O.VAL.M. - Ortoverde sited in Senigallia, IT.

They cover about 8.000 hectares of cultivated soil each year, producing about 50.000 tonnes of frozen vegetables processed in the two plants of Rotella (AP) and Cesano di Senigallia (AN).

Thanks to the precise controls and analysis the company performs on its products, it earned the trust of the most important Italian companies, like Orogel and Findus. For the same reason C.O.VAL.M. - O.R.T.O. Verde bears important certifications such as the UNI CEI EN 17065: 2012 standard that provides technical indications for agricultural producers and stakeholders about the production and transformation of vegetables for industrial purposes.

C.O.VAL.M. controls the whole supply chain including the production of raw materials, their processing, packaging and retail; as well as, their whole production can be divided into three main categories of cultivation: organic, sustainable and integrated.

A part of the wastes is destined to the biogas plant sited in Osimo (AN), where production wastes are converted, through anaerobic fermentation, into biogas and digestate, the latter is sent back to farmers and used as soil fertilizer. The biogas plant is also equipped with a generator that burns methane to produce electricity and heat.

4.3 Methods.

The evaluation of environmental sustainability on the cultivation of tomatoes intended for third parties involved the application of the SimaPro software (version 9.1).

SimaPro is one of the most used software for LCA analysis and allows to study and model the product life cycle stages according to the fixed goals.

As reported in the previous paragraphs, the LCA is based on libraries that must be selected, containing the LCI databases that provide data about inputs, outputs and emissions spacing in many different production fields, such as agricultural, transport, industrial etc.

SimaPro software includes many different databases and is not necessary to use them all; for this work the ones selected were:

- Ecoinvent 3

It can be applied in many projects such as water and carbon footprint assessment; it includes numerous datasets (>15.000) throughout different groups like transport, agriculture, processing, energy supply and waste treatment. Ecoinvent 3 is one of the most used databases when performing a Life Cycle Assessment being the most complete among all.

- Agri-footprint

Is a database centred on agriculture, suited for sensitivity analysis, it is used also to perform comparations between different product life cycle assessments. This database contains datasets (>5.000) strictly belonging to the agricultural field, reporting data about crops, products and background processes such as transport, energy, processing, pesticides and fertilizers.

Among the numerous impact categories that can be studied through a LCA study, the following are the ones this study focuses on:

- Eutrophication

Consists in an increased eutrophication potential (EP) at ground level, in water and in air, it is expressed as kg PO_4^{3-} equivalents and is caused – in agriculture – by the application of fertilizers or manure. The increased concentration of nutrients and minerals in the ecosystem causes a loss of biodiversity due to a strong induction in growth of algae present in water, those release oxygen during the day but consume it during the night making its concentration vary considerably, damaging the whole ecosystem.

- Acidification

Caused by the reaction of ammonia (NH_3), sulphur oxides (SOx) and nitrogen oxides (NOx) with atmospheric water forming acid rain that, falling in the ground induces a decrease of soil and water pH damaging vegetal, bacterial and animal species and, as last instance, a simplification of the population damaging the ecosystem. The acidification is measured through the acidification potential expressed as kg SO_2 equivalents.

- Climate change

"This term refers to long-term shifts in temperatures and weather patterns" (*UN*). These variations can be caused by both natural phenomena like the changes in the solar cycle, and human-related, mainly because of the combustion of fossil fuels; this behaviour leads to the release, in the atmosphere, of greenhouse gases (GHGs) with, as last instance, the raise of global temperature. The UN's Intergovernmental Panel on Climate Change (IPCC) defined models for the characterization of environmental profiles expressed as Global Warming Potential (GWP). This index may be referred to different time horizons such as 20 or 100 years, even if the most common unit used is the GWP100. GWP takes into account many parameters and substances which contribute to the absorption and storage of heat in air, substances such as methane, sulphur hexafluoride, dinitrogen monoxide and carbon dioxide offer the major contribute to that phenomenon; carbon dioxide, in particular is used as reference unit to measure the Global Warming Potential, expressed as kg CO_2 equivalent.

4.4 Primary data.

Crop registry or "treatment registers" are mandatory registers for all farms that use plant protection products for the protection of agricultural crops. the Notebook must tell the story of everything that happens on the farm from sowing to the harvest. All the operations that take place, the protocols followed and the techniques used must be noted inside the register and it can be useful as a control and programming tool.

The treatments carried out with all the plant protection products used on the farm must be noted in the register. This information must be noted within the collection period and in any case at the latest within thirty days of the execution of the treatment itself.

ITINERARIO TECNICO

Parcella :
Coltura : Pomodorino
Supeficie : 4,0000 ha

Interventi : Realizzati
Campagna 2020

Varietà	WILSON	**Superficie**	4,00 ha	**Preced.**		**Comune**	San Severo
Sem./Imp.	19/04/2020	**SPS Letame**	4,00 ha	**Obb. resa**	280,00 q	**Tipo di suolo**	
Codice EDI	12	**SPS Liquame**	4,00 ha	**Raccolta**	23/09/2020	**Analisi del**	
Codice tracc.	POM.012/20	**SPS Altro**	4,00 ha	**Resa reale**		**Appezzam.**	PR.INTEGR.

Lavoro del

	Data	Operazione	Sup. lav. (ha)	Dettagli
✓	14/03/2020	Aratura	4,00	Motivazione : Inferiore a 30 cm
✓	18/03/2020	Estirpatura	4,00	
✓	10/04/2020	Erpicatura	4,00	

Irrigazione

	Data	Dettagli	Prodotto	Dose (mm)	Quantità	Unità
✓	24/04/2020	4,00	Acqua	15,00	600,00	m^3

Figure 4.2: Example of a Treatment register.

All the primary data used during the writing of the thesis has been provided by C.O.Val.M. - ORTO Verde through the treatments book, belonging to different producers and all referred to the production year 2020. From the total number of producers, (as many as the crop registries) 116, only 49 of those (42,24%) declared the effective harvest of tomatoes.

Some farmers (50 out of 116) have not reported any data inside the crop registry, lacking of information such as the use of water, fertilizers and pesticides, these farmers only declared the hectares and the absence of harvesting suggesting that the fields were not cultivated; for this I decided to exclude these farmers from the dataset.

Another document applied to give more consistency to the research is the transport report, an Excel file reporting distances and quantity of product transported from the farms to the industrial plant of C.O.Val.M. ORTO Verde sited in Senigallia where tomatoes are sorted, cleaned, frozen and packed. Unfortunately, this report is incomplete and data were available only for 28 farmers out of 116.

C.O.Val.M. Ortoverde collects tomatoes from 116 different fields placed in the Italian territory, whose majority is sited in Puglia (112 fields), other 3 fields are placed in Tuscany and just one field in Emilia Romagna.

The type of cultivation approach can be summarized with 116 fields cultivated with an **integrated** approach.

Assessing the impact derived from the production of a certain product may lead in facing many difficulties, but there are guidelines and standards that turn the work easier; the Product Category Rules are documents reporting many instructions for a better approach to LCA.

Since the methodology can be used for the analysis of impacts in agriculture through the study of inputs and outputs, the PCR provide the emission factors used to calculate the impact for a specific input/output, various formulas to calculate erosion, run-off and leaching, not as last reporting information about the interpretation of results and the allocation for cultivation.

The PCR adopted during the impact assessment phase of this study is the (Product Category Rules according to ISO 14025, 2018).

4.5 Integrated approach.

Includes the use of organic and synthetic fertilizers, insecticides, herbicides and fungicides; their usage is allowed to allow the farmer to get a higher yield of product.

Fertilizers are applied to the soil or on the plant to provide Nitrogen, Potassium and Phosphorous for supporting the plant growth; each fertilizer present different concentration of those three elements and may be used different fertilizers to obtain the optimal fertilization for the cultivar. Formulations of fertilizers may be liquid or in granules and require specific patents for their usage. The most used fertilizers were Calcium nitrate, Sulphur nitrate, Ammonium nitrate, Urea and NPK formulations like the MAP monoammonium phosphate and other formulations (ex. NPK 12-12-17 or NPK 11-22-16).

Herbicides are used to avoid the growth of infesting grass species (commonly called weeds) that may compete with the cultivar for the nutrients; **fungicides** and **insecticides** are applied to prevent or cure the plant infections caused by fungi – such as Phytophthora infestans, Alternaria solani, *Leveilulla Taurica* and powdery mildew – and insects like *Spodoptera littoralis*, *Tuta absoluta* and *Heliothis armigera*.

4.6 Inputs descriptive summary.

In 2020, tomatoes were cultivated in 116 farms of different size; the total cultivated area is about 509 hectares and the total estimated production is about 9.083,51 tons of fresh tomatoes. The total water usage corresponds to 1.224.817 m^3 of which 1.217.816 m^3 for irrigation (about the 99,4%) and 7.372 m^3 for fertigation.

Regarding the plant protection phytochemicals has been used a total of 70,327 tons of fertilizers, 0,196 tons of herbicides, 3,304 tons of fungicides and 2,888 tons of insecticides.

4.7 Output description.

Emissions derived from the application of pesticides (herbicides, fungicides and insecticides) were calculated following the guidelines of (M. Margni, Life cycle impact assesment of pesticides on human health and ecosystems, 2002), considering that 85% of the total active product is emitted to soil, 10% in air and 5% in water. It may happen that a pesticide may contain more than just one active compound, in this case the emission is calculated proportionally to the concentration of each compound multiplied by the quantity of pesticide (ex. the insecticide "Cabrio Duo", used against *Phytophthora infestans*, contains Dimetomorf and Pyraclostrobin with 72g/L and 40g/L of concentration, respectively).

The emissions derived from the use of fertilizers containing nitrogen and/or phosphorous have been calculated applying the guidelines contained in the (Product Category Rules according to ISO 14025, 2018).

The emissions which **directly emit to air** - caused by nitrogen fertilizers - were calculated applying the emission factors: 0,037-0,293 for ammonia (NH_3), 0,007-0,022 for dinitrogen oxide (N_2O) and 0,006-0,029 for nitrogen monoxide (NO). The emission that **indirectly emit to groundwaters** were assessed applying the emission factor 0,0075 to ion nitrate (NO_3^-). Furthermore, N_2O is **indirectly emitted to air** from NH_3 and NO_3^-, applying emission factor 0,01.

Nitrogen was the most abundant nutrient applied in crop management, but also Phosphorous and some Potassium were added, even if Potassium was present in negligible quantities.

Considering Phosphorus emissions concern the soil and water sectors. The emission factor for **leaching** considered was 0,07 kgP/ha; for **run-off** 0,175 kgP/ha and for the **erosion potential** 0,53 kgP/ha.

5.LCA OF CASE STUDY

5.1 Goal and scope phase

The goal of this attributional LCA study is to evaluate the environmental sustainability of the cultivation of tomatoes for industrial purposes (frozen tomatoes) in Italy.

The study involves ORTO Verde and C.O.Val.M and the researchers of Università Politecnica delle Marche; other interested parties are those companies who use the ORTO Verde frozen products in their recipes.

The defined functional unit (FU) is 1 kg of fresh tomatoes (that may be harvested or just declared as primary data by the grower); it is the reference to which all the inputs/outputs of LCI are normalized.

All the data directly belong to C.O.Val.M ORTO Verde and their farmers' direct measurement and documents – including treatment registers and transport reports – contributing to the credibility of the study.

The harvest of tomatoes is referred to the year 2020, but cultivation started from September 2019 to March 2020.

About the system boundary, it has been provided from C.O.Val.M ORTO Verde and includes all the processing steps from the receiving of fresh tomatoes inside the industrial plant, here tomatoes are firstly cleaned from big contaminants such as leaves, mud and stones that could be present from the field; after they are moved to different vibrating plates and a drum washing machine to remove the small particles of soil.

Clean tomatoes are so sanitized passing through a chlorination tank and sorted using an optical sorter in order to detect and remove the defective tomatoes.

Finally clean ad sorted tomatoes pass through a system of conveyors to the "Urschel" cutter and to the freezer.

A last control is performed using a metal detector in order to prevent the presence of unwanted metallic materials inside the final product.

C.O.Val.M ORTO Verde does not sell tomatoes with its own brand but straight to third companies, to do that, tomatoes are packed in containers called “octabins” made up of wooden pallet, cardboard and plastic, whose capacity is around 500-800 kg each.

Octabins are not only used to transport the product but also to preserve it for the moment it must be ulteriorly processed; this happens because some companies want tomatoes to be also cut in a certain way and it requires a partial thawing prior to be processed and frozen again. When it occurs, tomatoes are further sorted in order to avoid the presence of external contaminants.

This system boundary is defined as *“cradle to gate”* because it includes all the steps of processing from the raw material extraction to the exit of the factory gate, even if it lacks of the packaging step that has not been considered in this study.

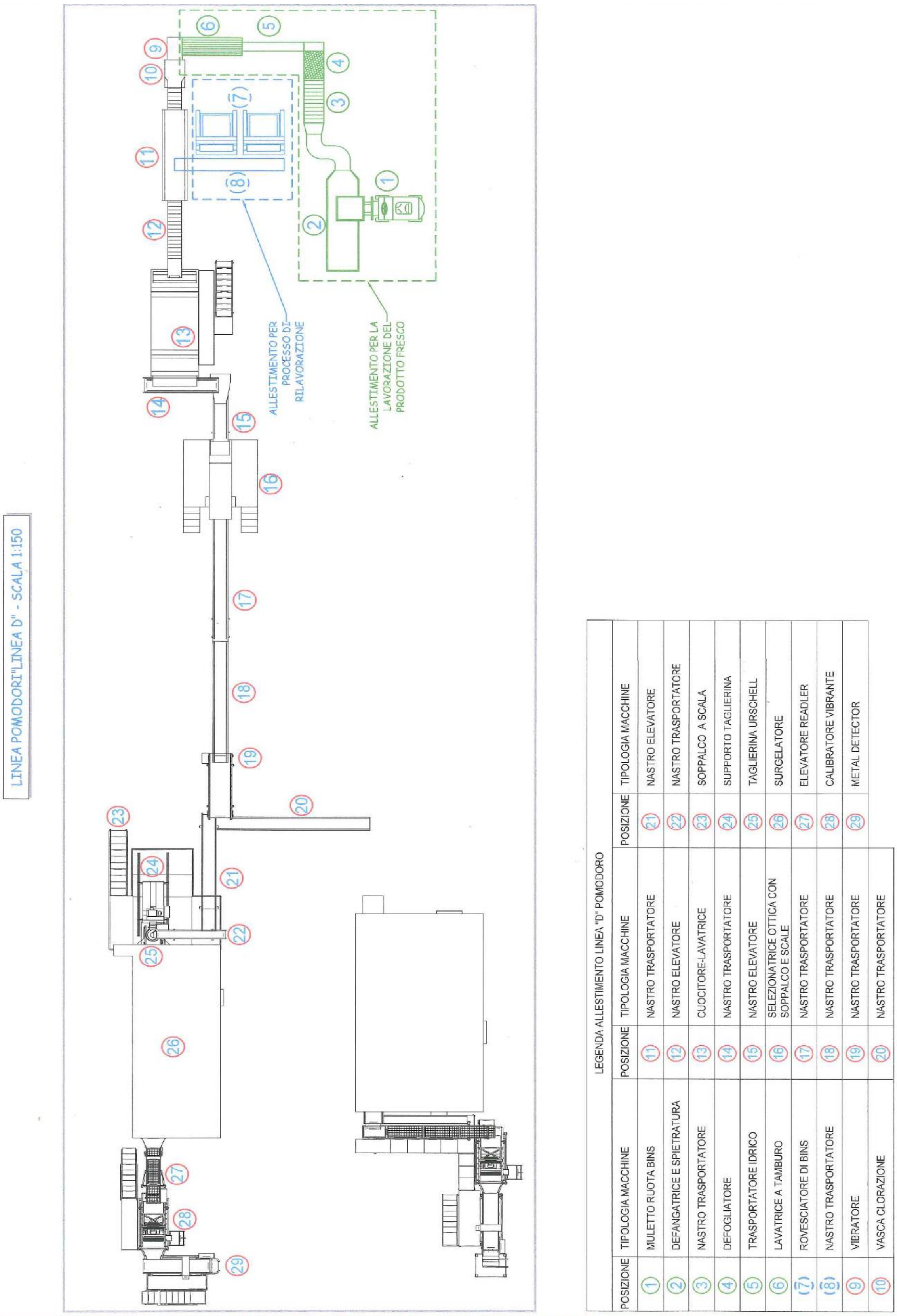

Figure 5.1: System boundary reporting the step-by-step processing of fresh tomatoes

5.2 Inventory analysis phase (LCI)

During the LCI phase all the data are collected and normalized to the functional unit of 1 kg of fresh tomatoes. A complete LCI includes data regarding land surface, water used for irrigation, treatments and fertilizers, pesticide quantity and fertilizer quantity, over the field operations.

For the land surface, the hectares of the 116 crops are summed; the water used for irrigation, as well as the quantity of fertilizers and other chemicals, is the sum of all the quantities declared in the treatment registers, while the water used for the application of fertilizers, fungicides, insecticides and herbicides has been calculated summing the water required for each chemical depending on the guidelines reported in the chemicals' label.

5.2.1 Cultivation inputs

Table 5.1:Total cultivation inputs (raw LCI)

Process/material	***Unit***	***Value***
Total land surface	ha	509,23
Water for irrigation	m^3	1,22E+06
Water for fertilizers	m^3	7,37E+03
Water for herbicides	m^3	1,33E+02
Water for fungicides	m^3	1,56E+03
Water for insecticides	m^3	1,06E+03
Total applied water	**m^3**	**1,23E+06**
Operations		
Tillage, ploughing	ha	509,23
Tillage, currying, by weeder	ha	485,03
Tillage, rotary cultivator	ha	15,64
Tillage, harrowing, by spring tine harrow	ha	223,23
Tillage, harrowing, by rotary harrow	ha	323,39
Total of field interventions	**ha**	**1556,52**
Fertilizers		
18:46	kg	8,27E+03
Urea	kg	9,60E+02
Ammonium nitrate 34%	kg	2,74E+03
Calcium nitrate	kg	5,47E+03
Diammonium phosphate	kg	2,50E+04

Ammonium sulphate 8%	kg	1,36E+03
Org.-Min. Npk 11-22-16	kg	1,72E+03
Nitram 34	kg	1,65E+03
Ammonium sulphate 21%	kg	6,13E+03
Agrisol NP	kg	1,38E+03
Palio 100 L	kg	1,76E+01
Organomag	kg	1,65E+03
MAP monoammonium phosphate	kg	2,42E+03
Top NP 7-14	kg	1,20E+03
Haifa P / orthophosphoric acid	kg	4,95E+02
Timasprint	kg	1,15E+03
Regenor	kg	3,92E+03
Herbicides		
S-metolachlor	l	2,09E+01
Glyphosate	l	3,18E+01
Pendimethalin	l	7,77E+01
Rimsulfuron	kg	3,48E+00
Propaquizafop	l	1,18E+01
Rapeseed oil	l	1,03E+01
Metribuzin	l	4,70E+01
Cicloxidim	l	4,14E+00
Insecticides		
Tefluthrin	l	1,47E+03
Spirotetramat	l	4,53E+01
Indoxacarb	kg	1,07E+01
Abamectin	l	8,75E+01
Lambda cyhalothrin	l	5,75E+02
Cypermethrin	kg	2,53E+01
Methoxyfenozide	l	6,83E+00
Deltamethrin	l	2,58E+01
B. Thur.Kurstaki Abts351	kg	5,06E+01
Formethanate	kg	3,19E+01
Spinetoram	l	2,11E+02
Emamectin Benzoate	kg	1,28E+02
Chlorantraniliprole	kg	8,96E+00
Alpha-cypermethrin	l	2,00E+00
Etoxazole	l	5,48E+00
Acetamiprid	l	7,69E+01
1,2-Benzisothiazolin-3-One	l	5,97E+00*
Spinosad	l	5,97E+00*
B. Thur.Aizawai Abts1857	kg	2,14E+01
Metaflumizone	l	1,84E+01
Sulfur	l	4,16E+01
Pyrethrins	l	1,82E+01
Methoxyfenozide	l	5,75E+00
Sulfoxaflor	l	6,34E-01
B. Thur.Kurstaki Eg2348	kg	4,51E+00

Fungicides		
Cymoxanil	kg	1,08E+02
Copper oxychloride	kg	1,05E+03
Metiram	kg	1,30E+01
Pyraclostrobin	kg	3,73E+01
Copper sulphate	kg	8,13E+02
Dimetomorf	l	5,66E+01
Zoxamide	l	3,70E+01
Sulfur	kg	5,06E+02
Metraphenone	l	3,34E+00
Bordeaux mixture (copper sulphate + lime)	kg	4,69E+02
B. subtilis Qst713	l	1,87E+02
Difenoconazole	kg	1,97E+01
Metalaxil-M	l	4,87E+02
Tetraconazole	l	2,59E+01
Azoxystrobin	kg	3,42E+01
Penconazole	kg	1,00E+00
Acibenzolar-S-Methyl	l	9,00E-01
Oxathiapiprolin	l	5,51E+00
Amisulbrom	kg	2,03E+01
Mandipropamid	l	1,20E+02
Propamocarb Hydrochloride	l	1,30E+01
Fluxapyroxad	kg	3,69E+00
Fosetyl aluminium	l	1,00E+01

**Active compounds belonging to the same formulation.*

5.2.2 Fertilizers

After listing the inputs inside the database, the emissions of fertilizers, pesticides and the operations' emissions were calculated through the SimaPro software.

Nitrogen is emitted as dinitrogen monoxide (N_2O), ammonia (NH_3), nitrogen monoxide (NO) and nitrates (NO^{3-}); while N_2O, NH_3 and NO are released in the air, NO^{3-} is released in groundwater. In table 4.2 and 4.3 are listed the nitrogen emissions derived from the use of fertilizers as total N emissions and as N emissions referred to the functional unit of 1 kg of fresh tomatoes.

Table 5.2: total N fertilizers emissions from cultivation

Emission type	***Unit***	***Value***	***Sub compartment***
Direct emissions			
N_2O	kg	3,38E+02	Air
NH_3	kg	3,00E+03	Air
NO	kg	3,69E+02	Air
Indirect emissions			
N_2O	kg	3,82E+02	Air
NO^{3-}	kg	4,01E+02	Groundwater

Table 5.3: N fertilizers emissions from cultivation per kg of tomatoes

Emission type	***Unit***	***Value***	***Sub compartment***
Direct emissions			
N_2O	kg	8,5635E-06	Air
NH_3	kg	7,60243E-05	Air
NO	kg	9,34421E-06	Air
Indirect emissions			
N_2O	kg	9,69372E-06	Air
NO^{3-}	kg	1,01642E-05	Groundwater

Phosphorous is emitted from fertilizers as phosphorous pentoxide (P_2O_5) that *leaches* in the ground depending on its permeability reaching groundwaters (P_{gw}), or flows down throw the current of the rivers as run-off (P_{ro}) and causing erosion of the soil ($P_{erosion}$). The following tables 4.4 and 4.5 summarise the total emissions derived from the release of P due to the application of fertilizers, as well as the P emitted in relation to the functional unit of 1 kg of tomatoes produced.

Table 5.4: Total P fertilizers emissions from cultivation

Emission type	***Unit***	***Value***	***Sub compartment***
Direct emissions			
P_2O_5 from P_{gw}	kg	8,15E+00	Groundwater
P_2O_5 from P_{ro}	kg	2,01E+01	River
P_2O_5 from $P_{erosion}$	kg	1,34E+02	River

Table 5.5: Total P fertilizers emissions from cultivation per kg of tomatoes

Emission type	***Unit***	***Value***	***Sub compartment***
Direct emissions			
P_2O_5 from P_{gw}	kg	2,06519E-07	Groundwater
P_2O_5 from P_{ro}	kg	5,09784E-07	River
P_2O_5 from $P_{erosion}$	kg	3,38544E-06	River

The emissions derived by the transportation of the product are mainly influenced by the loading factor, the fuel type and the distance covered by the truck.

5.3 Impact Assessment phase (LCIA)

5.3.1 Classification

In the Classification step inputs and outputs, which cause a certain impact are sorted according to the effect they have on the environment, which corresponds to a certain impact category. The impact categories taken into consideration depend on the LCIA method chosen. The LCIA method CML_IA baseline has eleven environmental impacts (followed by their acronyms and measurement unit):

- Abiotic Depletion Potential (ADP – *kg Sb eq*)
- Abiotic Deplation (fossil fuels – *MJ*)
- Acidification potential (AP – *kg* SO_2 *eq*)
- Eutrophication Potential (EP – *kg* PO_4^{3-} *eq*)
- Fresh Water Aquatic Ecotoxicity Potential (FAETP - *kg 1,4-DB eq*)
- Global Warming Potential (GWP 100 year - *kg* CO_2 *eq*)
- Human Toxicity Potential (HTP - *kg 1,4-DB eq*)
- Marine Aquatic Ecotoxicity Potential (MAETP - *kg 1,4-DB eq*)
- Ozone Layer Depletion Potential (ODP - *kg CFC-11 eq*)
- Photochemical Oxone Creation Potential (POCP - *kg* C_2H_4 *eq*)
- Terrestrial Ecotoxicity Potential (TETP - *kg 1,4-DB eq*)

5.3.2 Characterization

Once the impact categories have been classified, the potential impacts derived from the LCI are converted by the SimaPro software into actual impacts. This is the result of a multiplication of the quantity of inputs applied in the field with the characterisation factors present in the CML_IA baseline database.

The result is a list of impact scores for the mid-point environmental impact categories related to the Functional Unit (FU) of 1 kg of fresh tomatoes (Table 5.6). This table shows data considering all the plots whose harvesting have declared as effectively performed as well as not harvested, plus the plots where the production is assumed to be estimated.

Table 5.6: Environmental impact of fresh tomatoes production for each impact category.

Impact category	*Unit*	*Value*
Abiotic Depletion Potential (ADP)	kg Sb eq.	7,76E-07
Abiotic Depletion Potential (ADP - fossil fuel)	MJ	1,29E-01
Acidification potential (AP)	kg SO_2 eq	1,04E-04
Eutrophication Potential (EP)	kg $PO_4{}^{3-}$ eq	3,86E-05
Fresh Water Aquatic Ecotoxicity Potential (FAETP)	kg 1,4-DB eq	6,82E-01
Global Warming Potential (GWP 100 years)	kg CO_2 eq	1,40E-02
Human Toxicity Potential (HTP)	kg 1,4-DB eq	1,09E-02
Marine Aquatic Ecotoxicity Potential (MAETP)	kg 1,4-DB eq	9,54E+00
Ozone Layer Depletion Potential (ODP)	kg CFC-11 eq	4,34E-09
Photochemical Oxone Creation Potential (POCP)	kg C_2H_4 eq	-1,35E-05
Terrestrial Ecotoxicity Potential (TETP)	kg 1,4-DB eq	4,31E-02

In the next table (Table 5.7) are listed the impact scores for the mid-point environmental impact categories related to the Functional Unit (FU) of 1 kg of fresh tomatoes related to the plots where the actual harvest was declared.

Table 5.7: Environmental impact of fresh tomatoes production for each impact category.

Impact category	***Unit***	***Value***
Abiotic Depletion Potential (ADP)	kg Sb eq.	4,63E-07
Abiotic Depletion Potential (ADP - fossil fuel)	MJ	7,79E-02
Acidification Potential (AP)	kg SO_2 eq	5,31E-05
Eutrophication Potential (EP)	kg PO_4^{3-} eq	2,09E-05
Fresh Water Aquatic Ecotoxicity Potential (FAETP)	kg 1,4-DB eq	3,78E-01
Global Warming Potential (GWP 100 years)	kg CO_2 eq	9,16E-03
Human Toxicity Potential (HTP)	kg 1,4-DB eq	6,95E-03
Marine Aquatic Ecotoxicity Potential (MAETP)	kg 1,4-DB eq	5,30E+00
Ozone Layer Depletion Potential (ODP)	kg CFC-11 eq	2,43E-09
Photochemical Oxone Creation Potential (POCP)	kg C_2H_4 eq	-2,91E-06
Terrestrial Ecotoxicity Potential (TETP)	kg 1,4-DB eq	2,45E-02

The average emissions per FU released by plots and related to single impact category are reported in the following table (Table 5.8).

Table 5.8: Environmental impact related to the cultivation of 1 kg of fresh tomatoes (FU) for the impact categories Global Warming Potential, Acidification Potential and Eutrophication Potential for harvested plots.

Impact category	*Unit*	*Value*
Acidification potential (AP)	kg SO_2 eq	6,08E-05
Eutrophication Potential (EP)	kg PO_4^{3-} eq	2,40E-05
Global Warming Potential (GWP 100 years)	kg CO_2 eq	1,05E-02

5.4 Interpretation phase

The Life Cycle Interpretation serves to find out key issues, identifying elements that significantly contribute to each impact category, and assesses the completeness and consistency of LCI and LCIA results. In this phase, it's crucial to check the assumptions made during goal and scope definition. If the results do not meet these criteria, the analysis must be improved, maybe repeating the 4 phases of LCA.

Interpretation begins by gauging result accuracy and ensuring alignment with the study's objectives. Within the interpretation phase, significant issues are identified concurrently with the evaluation step. The completeness check is a valuable technique for assessment, aiming to determine if information from various LCA phases is adequate for drawing conclusions. Notably, most pesticides in the processing flow are undefined or neither associable to a generic chemical group; the lack of information inside the SimaPro is notable, even for other products applied in field - among the plurality of products - *Bacillus thuringiensis* (a bacteria applied in cultivation as a biological pest control method) is not present in the database and has not been included in the emissions count.

To address these gaps and align with the goal and scope, employing alternative analysis methods becomes a viable option.

5.4.1 Evaluation

To ensure the completeness of data acquired for the LCA analysis, a completeness check needs to be performed.

Due to the fact that the CML_IA baseline database completely lacks on biostimulant data, most pesticides applied and lots of fertilizers used in the various plots were included in the analysis as general processes (Ex. *"Pesticide, unspecified {RoW}| production | APOS, U"*). Surely, if this data was present inside the SimaPro software the research would have been more precise and complete. Taking into consideration these gaps may also be useful in the future for improvement purposes of the LCA studies.

5.4.2 Case study contribution analysis.

A contribution analysis allows to point and identify the measures of contribution of Life Cycle steps or groups of process to the total result, expressed as percentage of the total contribution.

The following graph (Figure 5.2) outlines the contribution analysis regarding data of emissions per FU released by crops, considering GWP, AP and EP and grouping the processes by *direct emissions from fertilizers*, *field operations*, *fertilizers*, *pesticides* and *harvesting*.

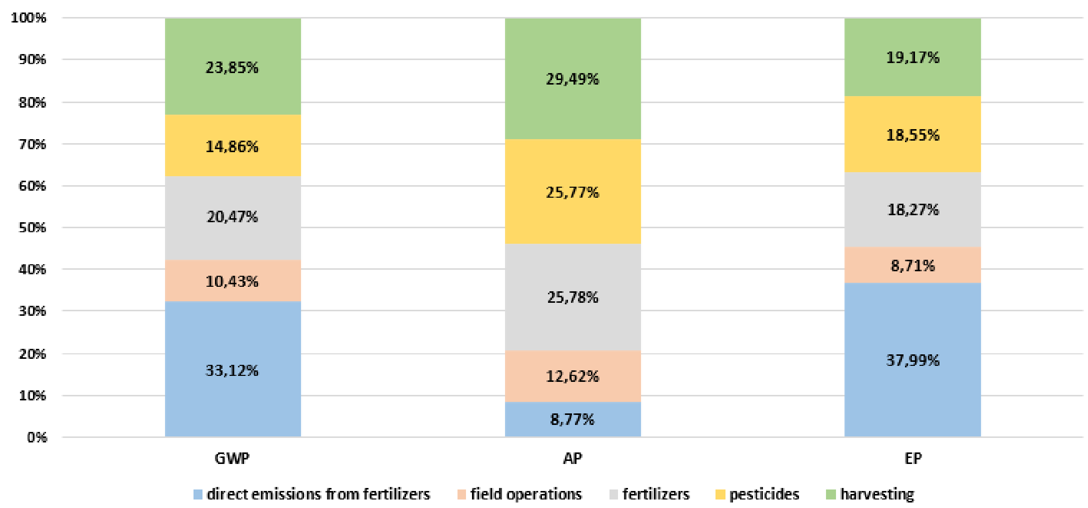

Figure 5.2: contribution analysis for GWP, AP and EP.

A contribution analysis has been performed considering the impacts related to the 49 field registers where the application of field operations for soil preparation was declared and the use of chemicals and water too; belonging to these 70 plots presenting declared data in the registry, only 49 were effectively harvested, the remaining 21 plots were supposed to declare an estimation of production in order to keep the data as much reliable as possible, also these plots were excluded from the contribution analysis.

5.4.3 Direct emissions from fertilizers.

Direct emissions from fertilizers impact through different mechanisms depending on the impact category: for GWP the impact is mainly caused by the emission of Nitrous oxide (N_2O), for AP the direct emission of Ammonia (NH_3) from fertilizers, for EP the contribution is given by Nitrogen in nitric form (NO) and Phosphorous as phosphates (PO_4^{3-}). While N_2O and NH_3 are emitted in the air, NO and PO_4^{3-} are emitted firstly in soil and so they move to groundwaters etc.

The weighted average impacts per FU and impact category, derived from direct emissions from fertilizers are: 3,02E-03 kg CO2 eq belonging to GWP, 4,78E-06 kg SO2 eq for the AP and 7,73E-06 kg PO4 3- eq belonging to EP.

5.4.4 Field operations.

The emissions derived from field operations – such as ploughing, currying, harrowing and harvesting – are mostly caused by the consumption of fossil fuels to make the farm machine move; their usage causes the release of various pollutants and greenhouse gases in the atmosphere; the release of sulfur dioxide (SO_2) and nitrogen oxides (NO_X) in the air may induce the developing of acid rain that falling on the ground and in water bodies can cause Acidification; the release of nitrogen oxides, ammonia (NH_3) and often Phosphorous (depending on the used fuel) contribute to Eutrophication; Global Warming Potential increases because of the production of by-products of the fuel combustion such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O).

The SimaPro software automatically considers – among the impacts generated by the application of operation fields – also the impact caused by the construction of the machines and their periodical manteinance (those are considered as background processes and related to the surface of application).

The weighted average impacts per FU and impact category, derived from field operations are: 9,16E-04 kg CO2 eq belonging to GWP, 6,37E-06 kg SO2 eq for the AP and 1,67E-06 kg PO4 3- eq belonging to EP.

5.4.5 Fertilizers.

Their impact must be considered as indirect because the software takes into account their production process as impacting (background processes), that's because the production of fertilizers is highly costly regarding the consumption of electricity and fossil fuels such as methane (CH_4).

Fertilizers are one of the most applied chemicals in the field and their presence can have various environmental impacts, thus contributing to Global Warming, Eutrophication and Acidification. The manufacturing of fertilizers often involves energy-intensive processes such as the production of ammonia, which results in a release of Green House Gases (GHGs) including carbon dioxide (CO_2) and nitrous oxide (N_2O), where the latter has a much higher **Global Warming Potential** than CO_2.

An excessive use of fertilizers, containing nitrogen and phosphorous, can lead to runoff into water bodies causing an enrichment in lakes, coastal areas and rivers leading to a phenomenon known as **Eutrophication** (high levels of nutrients stimulate the growth of algae that, when they die and decompose, oxygen is depleted and much less available for the rest of the biodiversity).

When ammonium-based fertilizers are applied to the soil, they can undergo to nitrification processes leading to the release of hydrogen ions (H^+) affecting nutrient availability, soil structure and health, thus lowering the pH - this phenomenon is known as soil **Acidification**.

The weighted average impacts per FU and impact category, derived from fertilizers are: 1,83E-03 kg CO2 eq belonging to GWP, 1,33E-05 kg SO2 eq for the AP and 3,76E-06 kg PO4 3- eq belonging to EP.

5.4.6 Pesticides.

The use of pesticides in cultivation, especially synthetic pesticides, contributes to the release of GHGs during manufacturing, transportation and application. Some of them are still derived from fossil resources, leading to an intrinsic impact from its source extraction (Global Warming and resource depletion).

Pesticides may break down once applied to releasing acidic byproducts, resulting in a pH lowering in soil (Acidification), inducing a cascading effect on ecosystems and affecting plant diversity and soil health; these chemicals may also contain Phosphorous and Nitrogen that, once degraded and released in soil and water may lead to the formation of "dead zones" because of the Oxygen depletion (Eutrophication).

The weighted average impacts per FU and impact category, derived from field operations are: 1,28E-03 kg CO2 eq belonging to GWP, 1,33E-05 kg SO2 eq for the AP and 3,76E-06 kg PO4 3- eq belonging to EP.

5.4.7 Harvesting.

Like field operations, harvesting also has an impact due to high consumption of fossil fuels. The machine used by the Cooperative is a complex machine called "combine harvester" that carries out different operations simultaneously, such as lifting up the plant from the soil, the cut of roots from the plant body, a first cleaning and sorting through a vibrant surface etc.

The weighted average impacts per FU and impact category, derived from field operations are: 2,11E-03 kg CO2 eq belonging to GWP, 1,54E-05kg SO2 eq for the AP and 3,97E-06 kg PO4 3- eq belonging to EP.

The following table (Table 5.9) shows the weighted average per impact category, grouping impact in direct emissions from fertilizers, field operations, fertilizers, pesticides and harvesting.

Table 5.9: Grouped impacts related to the cultivation of 1 kg of fresh tomatoes (FU) for the impact categories GWP, AP and EP.

impact category	direct emissions from fertilizers	field operations	fertilizers	pesticides	harvesting
GWP	3.02E-03	9.16E-04	1.83E-03	1.28E-03	2.11E-03
AP	4.78E-06	6.37E-06	1.33E-05	1.33E-05	1.54E-05
EP	7.73E-06	1.67E-06	3.76E-06	3.76E-06	3.97E-06

6. DISCUSSIONS

Standing on the Figure 5.2 (p.49) results clear how the direct emissions from fertilizers are the major contribution to GWP and EP, while for AP the major impact is given by the harvesting and its emission of SO_2 and NO_X due by the consumption of fossil fuels; following we find out the Acidification potential is strongly caused by the use of fertilizers and pesticides in the crops (51,55% of total AP).

The second most representative contribution to the various impact categories is given by harvesting operations for GWP (23,85%) and EP (19,17%).

Regarding field operations, their impact to the different impact categories is the lowest in absolute having a 10,43% of contribution for GWP, a 12,62% for AP and a 8,71% of contribution for EP; this low share may be explained because the impact is spread over the entire production

One of the most relevant issues related to this study is the abundant presence of unharvested crops, their presence can be explained in many ways; for example, it may be due to environmental issues that affected the production of tomatoes: very low temperatures may affect tomato plants that are very sensitive to frosting, impacting the cultivation. Even long periods of high temperatures can lead to blossom drop, where flowers are ruined and do not produce any fruit, affecting the overall yield.

The insufficient water supply may be another environmental cause, even more plausible, considering the region where tomatoes are mostly produced for O.R.T.O. Verde is Puglia, located in Southern Italy and characterised by low rainfalls during the year.

Another consideration needs to be done: C.O.Val.M O.R.T.O. Verde is a Consortium made up of numerous farmers that produce raw products such as tomatoes, peas, spinaches etc. and there is a single processor corresponding to the plant in Cesano di Senigallia (AN). This kind of relation producer-processor may present different dynamics: one example is the possibility that a portion of the tomatoes produced has been sold to other companies, even if the fields were managed by farmers under a contract with C.O.Val.M O.R.T.O. Verde; it may also be caused by a communication gap between farmers and C.O.Val.M, resulting in a misunderstandings regarding quality standards, delivery schedules and other important details (only for 28 out of 116 crops a transport register have been filled out).

For the impact categories at the focus of this study, the **Global Warming Potential** is the most represented with an emission equal to 1,40E-02 kg CO_2 eq per FU, as opposed to the **Acidification Potential** equal to 1,04E-04 kg SO_2 eq per FU and the **Eutrophication Potential** per FU equal to 3,86E-05 kg PO4--- eq.

The GWP is mainly caused by the consumption of fossil fuel during the operation fields (1,47E-02 kg CO2 eq), secondly it is caused by the use of pesticides (6,46E-03 kg CO2 eq) and finally there is the emission caused by fertilizers (4,53E-03 kg CO2 eq).

The efforts to mitigate these environmental impacts often involve reducing fossil fuel consumption, improving energy efficiency and transitioning to cleaner and more sustainable energy sources. This can include the adoption of renewable energy technologies and the implementation of more environmentally friendly practices; in this practical case, it would be functional to swich to farm machineries that use biogas or biofuel, being less impactful than those powered with fossil fuels.

The emissions caused by pesticides can be mitigated implementing various strategies, such as adopting an integrated pest management practice (IPM). These practices aim to manage pest populations while reducing the use of chemical pesticides: some examples of IPMs are the application in field of biological controls such as Bacillus spp., Pseudomonas spp. and Streptomyces spp. (Le KD, 2020); the use of cultural controls using beneficial plant associations and creating habitats for natural enemies of pests. Another way to minimize the negative effects of pesticide use on the environment is to put into use proper application techniques and respect the recommended dosage and timing of application (which are provided in the product label) or, a simpler strategy could be the use of environmentally friendly pesticides.

7. CONCLUSIONS

The aim of this LCA study is to give an evaluation of the environmental impact related to the cultivation of tomatoes intended for industrial purposes – fixing the Functional Unit at 1 kg of fresh tomatoes, in order to find out hotspots along the process with, as last instance, its improvement throughout the proposal of mitigation strategies with the focus on reducing the impacts; the study was carried on with a particular attention to the differences – in terms of impact – between the various groups of inputs (direct emissions from fertilisers, *field operations*, *fertilisers*, *pesticides* and *harvesting*).

The contribution analysis demonstrates how the majority of impacts is given by the direct emissions of fertilizers, followed by the consumption of fossil fuel for the harvesting and the indirect emissions from fertilizers (justified by their large use and the energy cost for their production).

Reducing emissions in agriculture is crucial for promoting sustainable development and for addressing the United Nations' Sustainable Development Goals (related to Climate action, Zero hunger, and Responsible consumption and production) and promoting a more resilient global food system. With the key concepts to "*reduce, reuse and recycle*" materials and products, the European Commission puts the focus on its Green Deal.

While there is limited comparable research in the scientific literature, this examination can be regarded as indicative of fresh tomatoes cultivation. This is attributable to the primary data supplied by the company, coupled with the important position of O.R.T.O. Verde as a key supplier of frozen tomatoes to several of the major Italian brands in the frozen sector.

However, it is advisable to conduct additional Life Cycle Assessment (LCA) studies to enhance the consistency and comprehensiveness of the results.

The results of LCA analysis demonstrate how the major contribution of cultivation is related to the impact category Global Warming Potential with an impact per FU of 1,40E-02 kg CO2 eq., and this impact is mostly related to the field operations (4,29E-03 kg CO2 eq.) carried out by each farmer in order to prepare the soil and to harvest the final product. (M. Margni, Life cycle impact assesment of pesticides on human health and ecosystems, 2022)

In conclusion, this study sheds light on how much impact is generated by the consumption of fossil fuel and the use of fertilizers in crops managed by the C.O.Val.M

O.R.T.O. Verde Consortium; single farmers could use these information to improve their behaviour applying strategies and decisions focused on preserving their production without exceeding in the introduction of fertilizers.

Surely, it must be considered to improve this study and go deeper to clarify the effective role of farmers along the production; moreover, from the limitations of this study, to gather inspiration and reference materials in order to implement with transformation and retail data, it would be important to give a more complete and exhaustive overview of which are the impacts generated by the whole supply chain of frozen tomatoes produced by C.O.Val.M O.R.T.O. Verde.

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