DEPARTMENT OF AGRICULTURAL, FOOD AND ENVIRONMENTAL SCIENCES

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EVALUATION OF THE ENVIRONMENTAL SUSTAINABILITY OF FROZEN VEGETABLES:

CASE STUDY OF A SPINACH PRODUCING COMPANY

TYPE OF DISSERTATION: Research

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A te, il mio sole.

Perché questo era anche un tuo sogno.

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ACRONYMS AND ABBREVIATIONS

LCA Life Cycle Assessment

FAO Food and Agriculture Organization

GHG Greenhouse gasses

FLW Food Loss and Waste

CE Circular Economy

SETAC Society of Environmental Toxicology and Chemistry

ISO International Organization for Standardization

*UNE*P United Nations Environment Programme

EU European Union

CALCAS Co-ordination Action for innovation in Life Cycle Analysis for Sustainability

LCSA Life Cycle Sustainability Analysis

CFP Carbon Footprint of a Product

EPD Environmental Product Declaration

PCR Product Category Rules

LCI Inventory analysis phase

LCIA Impact assessment phase

IC Impact Category

GWP Global Warming Potential

CED Cumulative Energy Demand

PEF Product Environmental Footprint

JRC Joint Research Center

PEFCRs Product Environmental Footprint Category Rules

ILCD International Reference Life Cycle Data System

EFIA Environmental Footprint Impact Assessment

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

OP Organizzazione di Produttori

BRC British Retail Consortium

QM Qualità Garantita delle Marche

ERASM European Detergents and Surfactants Industries

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

BAT Best available technology

DB Dichlorobenzene

VC Variation coefficient

CHP heat and power units

DRI dietary reference intake

GRAS Generally recognized as safe

EFSA European Food Safety Authority

BSF Black Soldier Fly

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 spinach production through a Life Cycle Assessment (LCA) analysis, which allows finding solutions for improving the industrial chain efficiency.

All over the world, it is common to notice that human activities and the environment have a conflictual relationship. Indeed, humans adapted the environment to their needs, the population is constantly increasing for years, and technological advancement accelerated the environment decline.

Food industries are one of the main ones responsible for this decay. Wastes and emissions derived from food production negatively influence the environment, climate, water resources, land use, and biodiversity. Among all these aspects, the climate is the most affected. Indeed, climate change, due to greenhouse gasses emissions, is the most significant environmental challenge nowadays.

The total greenhouse gas emissions in the European Union, together with Iceland and the United Kingdom, amounted to 4067 million tonnes CO_2 eq. in 2019, including direct and indirect emissions (European Environment Agency, 2021).

The global food system, which comprises the production, and post-farm processes such as processing, and distribution is an important contributor to emissions. Food is responsible for 26% of global greenhouse gas emissions (Ritchie, 2019). The main four categories and their contributions, represented in graphic in *figure 1-1*, are:

- *Livestock and fisheries*

Livestock and fish farms contribute to 30% of food emissions, while wild fish catch 1%. Greenhouse gasses are mainly due to methane production from cattle's enteric digestion; to manure and pasture management, and fuel emissions (Ritchie, 2019).

- *Crop production*

Crop production accounts for 27% of food emissions, 21% for crops for human consumption and 6% for animal feeds. The release of greenhouse gasses is due to fertilizers, manure, and agricultural machinery emissions (Ritchie, 2019).

- *Land use*

Most of the land use is for livestock, and it contributes to 16% of food emissions, while only 8% of food emissions is for human consumption crops. The greenhouse gas emissions are due to the conversion of forests and grasslands into cropland or pasture (Ritchie, 2019).

- *Supply chain*

The supply chain accounts for 18% of food emissions, and it includes transport (6%), packaging (5%), food processing (4%), and retail (3%) (Ritchie, 2019).

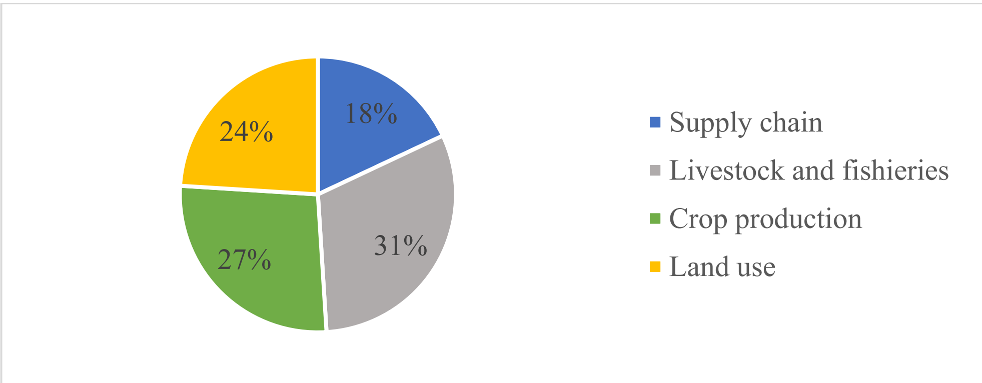

Figure 1-1: Categories contribution to greenhouse gas emissions

Since supply chain emissions may seem high, it is essential to reduce them by preventing food waste. Food waste emissions are large: one-quarter of emissions from food production end up as wastage either from supply chain losses or consumers (Ritchie, 2019).

In 2011, the Food and Agriculture Organization (FAO) estimated that 1/3 of the world's food produced for human consumption is lost or wasted every day, which amounts to 1.3 billion tonnes per year (FAO, 2011). Particularly, the fruit and vegetable sector accounts for 40-50%

of this (Yetunde Omolayo, 2021). Food is lost or wasted throughout the supply chain from initial agricultural production to final household consumption (FAO, 2011).

Food loss is the decrease in quantity and quality of food from post-harvest up to, but not including the retail level. In contrast, food waste refers to the reduction of food quantity and quality resulting from foodservice providers and consumers (FAO, 2011). Food wastes are more impactive than food losses because the product is completed, so more inputs have been implied for production.

Food losses and wastes have a negative environmental impact because of water, land, energy, and other natural resources used to produce food that no one consumes. Moreover, food losses represent a reduction in the economic value for a company. The value of food losses or wastes annually at the global level is estimated at US $1 trillion (FAO, 2014). Durable packaging, refrigeration, and food processing help prevent food waste (Ritchie, 2019).

1.1 **European policy initiatives**

The European Union proposes an economic and societal transformation to meet climate ambitions. In July 2021, the European Green Deal was adopted. It is a set of proposals for reducing greenhouse gasses (GHG) emissions by at least 55% by 2030, compared to 1990 levels (European Commission, 2021).

Since 1990, GHG emissions have been decreasing. In 2019 a reduction of 28% was identified. The graphic in *figure 1-2* indicates the quantity (expressed as million tonnes of CO_2 eq.) of direct and indirect emissions of the EU, Iceland, and United Kingdom; but it does not include the emissions from the international aviation and maritime transport (European Environment Agency, 2021).

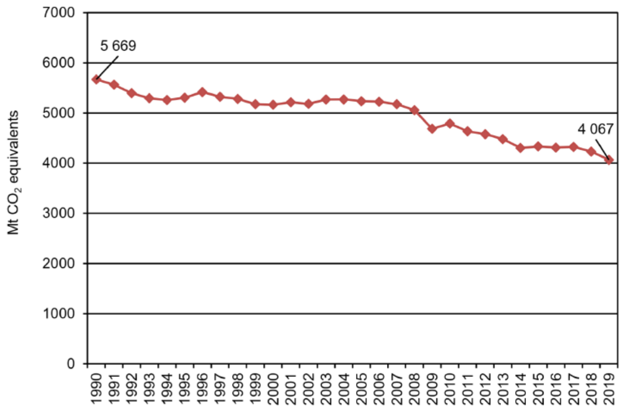

Figure 1-2: GHG emissions in 2019

The European Green Deal's final aim is the achievement of a climate-neutral continent by 2050. The new proposal regards many sectors such as transport, energy, construction, and renovation (European Commission, 2021).
Regarding the food sector, the European Union's goals are:

- Ensure food security in the face of climate change and biodiversity loss
- Reduce the environmental and climate footprint of the EU food system
- Strengthening the EU food system's resilience
- Lead a global transition towards competitive sustainability from farm to form

Two main strategies are proposed in the European Green Deal to favour a more sustainable, fair, and competitive system, and they are an opportunity for consumers and producers.

1. "*From Farm to Fork Strategy*"

It is the heart of the EU Green Deal, and it includes 27 objectives focusing on four areas:

- Sustainable food production
- Sustainable food processing and distribution
- Sustainable food consumption
- Food losses and wastes prevention

Some targets have been set for different areas. Among them, 50% pesticide reduction and 20% fertilizer reduction within 2030, an increase in the lands destined for organic production by 25%, and 50% sales reduction of livestock and aquaculture antimicrobials (European Commisison, 2021).

2. "*Biodiversity Strategy*"

It evaluates the causes of biodiversity loss and faces these problems thanks to 39 actions. Among them, 30% conversion of the European land surface and water into a protected area and the restoration of degraded zones.

Another main building block of the European Green Deal is the "*Circular Economy Action Plan*" (CEAP). It is an economical approach in line with sustainable environment and economic development. Indeed, it can reduce negative environmental impacts and stimulate new business opportunities (Jouni Korhonen, 2018). Focusing on the environmental impact reduction, there are many advantages:

- New inputs and energy are limited because they are mainly from other productive systems,
- Wastes and emissions are reduced;

- Resources in the production system are reused many times.

In the food system, a circular economy implies reducing wastes generated in the food system, the reuse of food, the utilization of by-products and food waste, and nutrient recycling. The measures must be implemented at the producer and consumer levels, and finally in the food waste and surplus management (Alexandra Jurgilevich, 2016).

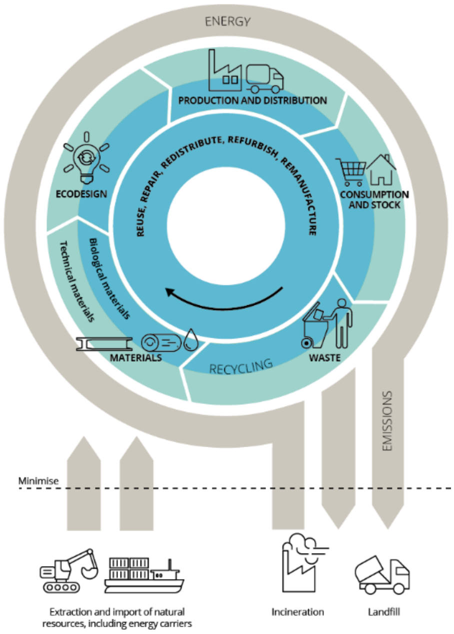

Figure 1-3: Circular economy scheme

In *figure 1-3*, the circular economy system diagram of the European Environment Agency is reported (European Environment Agency, 2020).

1.2 **Frozen vegetable context**

Frozen vegetables are prepared by freezing fresh vegetables, and they undergo many operations such as washing, peeling, grading, cutting, and blanching. Then, freezing is a quick process, and the whole product should reach -18°C at the core.

The European Union is the world's largest importer of frozen vegetables. Frozen vegetables have increased annually by an average of 3% in volume in 2014-2018 (Centre for the Promotion of Imports from developing countries, 2020). In the next five years (up to 2023), the European market will likely increase with an annual rate of 2-4%. In the graphic in *figure 1-4*, the origin of European imports is represented.

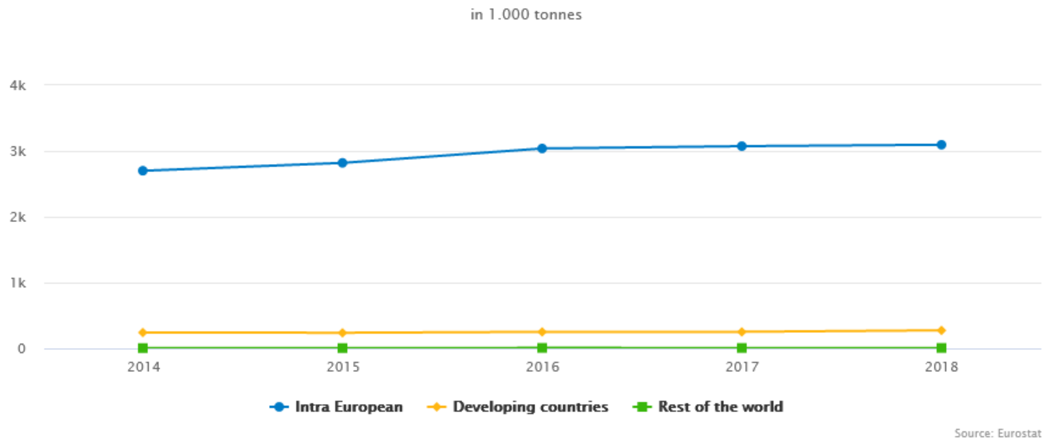

Figure 1-4: EU frozen vegetable imports

Europe is also the largest producer of frozen vegetables globally; 92% of all imports are intra-European, while 8% is from developing countries. In the graphic in *figure 1-5*, the production of frozen vegetables by country is reported (Centre for the Promotion of Imports from developing countries, 2020).

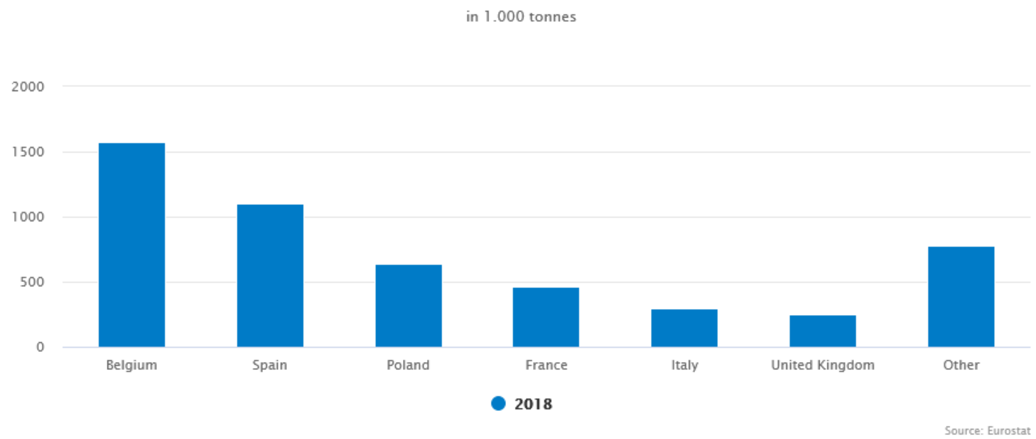

Figure 1-5: EU frozen vegetable production

In addition, consumption is increasing over the years because frozen vegetables are perceived as healthy and easy to prepare. France, Germany, Belgium, Spain, and Italy are the largest markets.

More precisely, Italy is the fifth-largest importer and the sixth-largest market for frozen vegetables in Europe (Centre for the Promotion of Imports from developing countries, 2020).

As well as the Italian consumption is constantly increasing. In *table 1-1*, the sales of frozen vegetables for the past three years are reported (Istituto Italiano Alimenti Surgelati, 2020). The best-selling vegetables are peas and spinach.

Table 1-1: Italian frozen vegetable sales

Year 2018 (tons)	***Year 2019 (tons)***	***Variation 2018-2019***	***Year 2020 (tons)***	***Variation 2019-2020***
226810	228000	+0,5%	251940	+10,5%

2. LIFE CYCLE ASSESSMENT – STANDARDS AND FRAMEWORK

Life Cycle Assessment (LCA) is an analytical tool for assessing and comparing the environmental impacts of products or services life cycle, and it dates to the 1960s – 1970s. In other words, the LCA is the "compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product system throughout its life cycle." In *figure 2-1*, it is possible to visualize the scheme describing all the steps of a food production chain taken into consideration during the LCA analysis.

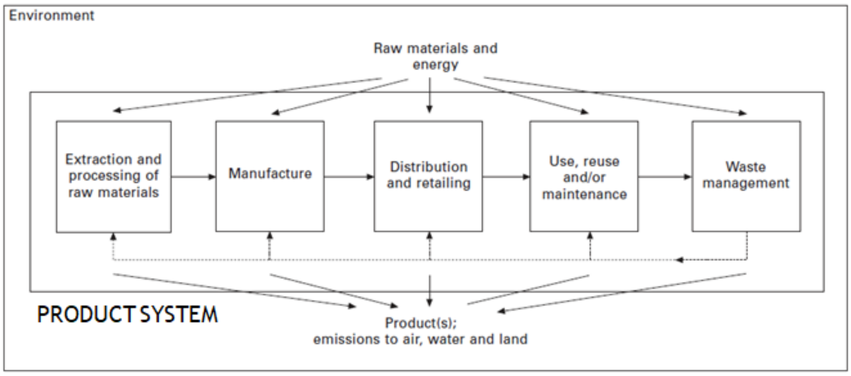

Figure 2-1: LCA framework

The LCA results allow the identification of the environmental critical points throughout the product life cycle, comparing between products, and knowing the contribution of a specific life cycle step to the overall environmental load.

In the context of a considerable amount of food losses and wastes (FLW), the LCA methodology can help manage them. LCA can be significant for comparing the environmental sustainability of waste management strategies, evaluating the environmental impacts of food waste management technologies and policies, and determining the combinations of technologies for maximizing environmental benefits (Yetunde Omolayo, 2021).

Moreover, the LCA supports the development and implementation of food losses and wastes policies. LCA studies combined with legislation and practices can be a helpful tool to understand how to reduce FLW. Interventions can regard food security, waste prevention, waste management, and waste valorisation (Yetunde Omolayo, 2021).

Focusing on the waste recycling into resources, LCA allows assessing if the claimed environmental benefits of circular economy (CE) solutions can be achieved and to what extent, and which aspects should be properly managed. In some situations, CE projects focus too much on the circularity of a specific resource, omitting that is not the best choice in a broader assessment. LCA is essential to compare CE strategies in terms of sustainable performance (Claudia Peña, 2021).

2.1 **Life Cycle Assessment history**

It is possible to consider the years between 1970 to 1990 as the *decade of conception*. The first studies were performed in the late 1960 and early 1970 (some have never been published). In that period, LCA studies mainly focused on energy analysis. Indeed, LCA was mainly applied by firms for the validation of market claims. From early 1980, the interest started to grow, but there were different approaches, terminologies, and results because there was no a common theoretical framework (Jeroen B. Guinée, 2011).

Starting from 1990 to 2000, the *decade of standardization* began. The Society of Environmental Toxicology and Chemistry (SETAC) coordinated workshops to produce LCA guides and handbooks during this period. Finally, in 1994, the International Organization for Standardization (ISO) introduced standardized and official methods and procedures. During this period of LCA growth, many scientific journal papers appeared and, LCA became part of documents and legislation (Jeroen B. Guinée, 2011).

The present decade of LCA is considered the *decade of elaboration*. In 2002, the Life Cycle Initiative was launched by SETAC and the United Nations Environment Programme (UNEP). It aimed to put LCA into practice and improve supporting tools (e.g., better data and indicators). In 2005, the European Union (EU) took the first steps by establishing the European Platform on Life Cycle Assessment to promote the exchange and use of quality data and methods for reliable decision support in EU public policy. In the same period, worldwide, there was the tendency to draft life cycle-based legislations. However, there is no a single method for conducting LCA, so divergences are still present due to different possible interpretations of some ISO requirements regarding, for example, the system boundaries and allocation methods (Jeroen B. Guinée, 2011).

Some developments in LCA studies recently occurred, determining the entrance in the *decade of Life Cycle Sustainability Analysis*. The European Commission commissioned the Coordination Action for innovation in Life Cycle Analysis for Sustainability (CALCAS) project. One of the results was the establishment of the Life Cycle Sustainability Analysis (LCSA) trans-disciplinary framework (Jeroen B. Guinée, 2011). LCSA evaluates the environmental, social, and economic negative impacts and benefits of decision-making processes towards more sustainable products throughout their life cycle (Claudia Peña, 2021).

2.2 **ISO standards on Life Cycle Assessment**

The International Organization for Standardization (ISO) is an independent, non-governmental international organization with a membership of 165 national standards bodies. The experts share knowledge and develop voluntary International Standards that support innovation and provide solutions to global challenges.

2.2.1 *Primary ISO standards*

Currently, the main two international standards on LCA are:

- **ISO 14040:2021** "Environmental management – Life cycle assessment – Principles and framework."

It describes the framework and the principles for LCA, including the steps that compose it, but it does not specify the methodology for the individual LCA phase.

- **ISO 14044:2021** "Environmental management – Life cycle assessment – Requirements and guidelines."

It is complementary to the previous one, and it specifies the requirements and provides guidelines for life cycle assessment (LCA).

These two standards support the implementation of the Sustainable Development Goals (SDG), adopted in the United Nations 2030 Agenda framework. The 17 SDGs aim at ensuring sustainable development worldwide. Specifically, the ISO 14040:2021 and ISO 14044:2021 are linked to the SDG number 13 regarding climate action.

2.2.2 *Additional ISO standards*

Based on the previous two ISO standards, there are other standards on specific issues:

- **ISO 14067:2018** "Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification."

It specifies principles, requirements and guidelines for quantifying and reporting the Carbon Footprint of a Product (CFP). It's a technical specification focusing only on climate change impact category. Carbon offsetting and communication of CFP are outside the scope of this document. This document does not assess any social or economic aspects or impacts, or any other environmental aspects and related impacts potentially arising from the life cycle of a product.

- **ISO 14046:2016** "Environmental management – Water footprint – Principles, requirements and guidelines."

It specifies principles, requirements and guidelines related to water footprint assessment of products, processes and organizations based on LCA. Only air and soil emissions that impact water quality are included in the assessment, and not all air and soil emissions are included. The result of a water footprint assessment is a single value or a profile of impact indicator results. Whereas reporting is within the scope of this International Standard, communication of water footprint results, is outside the scope of this International Standard.

2.2.3 *ISO standards for results communication*

ISO standards currently available for communicating the results are:

- **ISO 14020:2000** "Environmental labels and declarations – General principles"

It establishes the fundamental principles for the development and use of environmental labels and declarations. This standard will be replaced soon by the ISO/CD 14020.2 that is under development. The title of this future standard is “Environmental Statements and Programmes for products – Principles and General Requirements”.

- **ISO 14024:2018** “Environmental labels and declarations – Type I environmental labelling – Principles and procedures”

It establishes the principles and the procedures for developing type I environmental labelling, also known as “ecolabelling schemes.” It also states the certification procedure for awarding the label.

These schemes grant a mark or logo to products or services upon fulfilling a set of criteria. Type I labelling is applied in many parts of the world. Specifically, the EU ecolabelling is in *figure 2-2*; it aims to promote the circular economy and encourage companies to develop durable, easy to repair, and recycle products (European Commission, 1992).

Figure 2-2: EU ecolabelling

- **ISO 14021:2016** “Environmental labels and declarations – Self-declared environmental claims (Type II environmental labelling)”

This standard has been amended in July 2021 and it identifies requirements for self-declared environmental claims, including statements, symbols, and graphics, regarding products. It further describes selected terms commonly used in environmental claims and gives qualifications for their use. This International Standard also describes evaluation and verification methodologies. In *figure 2-3* is represented an example of symbols that can be used.

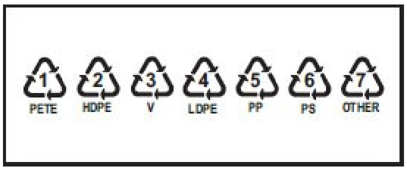

Figure 2-3: Example of type II environmental labelling

- **ISO 14025:2010** "Environmental labels and declarations – Type III environmental declarations – Principles and procedures."

It establishes the principles and specifies the procedures for developing Type III environmental declaration programmes and Type III environmental declarations. They are intended for use in business-to-business communication, but their use in business-to-consumer communication under certain conditions is not precluded.

The Environmental Product Declaration (EPD) is a Type III declaration that quantifies environmental information on the life cycle of a product to enable comparisons between products fulfilling the same function. This is possible thanks to Product Category Rules (PCR) that indicates the description of the product category, the LCA goal, functional units, system boundaries, cut-off criteria, allocation rules, impact categories, information of the use phase, units, calculation procedures, requirements for data quality and other information. Having all these details for most food categories allows fair comparability between products belonging to the same product category. The EPD is based on the LCA tool, and the results can be added to the product label because a third party verifies the reliability of the data provided.

2.3 Life Cycle Assessment steps

Depending on what the ultimate goal is, two different LCA analyses can be performed. The *attributional Life Cycle Assessment* estimates how the global environment burdens are affected by the product's production and the use. The other one is the *consequential Life Cycle Assessment* describes how relevant environment flows will change in response to some decisions.

Not considering the LCA type, the Life Cycle Assessment's framework includes four phases, according to the ISO standard 14040:2021 (ISO 14040, 2021) and 14044:2021 (ISO 14044, 2021).

1. *Goal and scope definition phase*

It includes the system boundary, the level of LCA detail analysis and the intended use of the study.

2. *Inventory analysis phase (LCI)*

It is a collection of the most relevant input/output data of a product system.

3. *Impact assessment phase (LCIA)*

In this step, the data from the inventory analysis phase are translated into environmental impacts.

4. *Interpretation phase*

Conclusions, recommendations, and decision-making are drawn from the LCI and LCIA results.

Since it is possible to acquire a large amount of information during the analysis, the scope can be redefined throughout the study. The LCA technique is iterative; it can be repeated several times. *Figure 2-4* represents the LCA steps graphically:

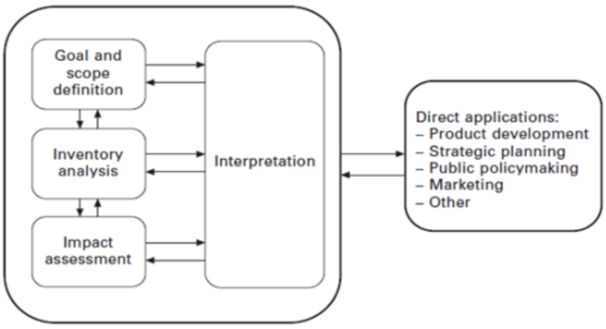

Figure 2-4: Iterative representation of LCA

2.3.1 *Goal and scope definition phase*

In this phase, the main choices may be justified, including the following information:
The *goal* states the study's objective, the intended use of the results, the commissioner, the practitioner, and the parties involved.

The *scope* comprises the temporal, geographical and technology coverage and describes the level of LCA sophistication. In addition, the product system to be studied should be defined, including all the unit processes within the system boundary.

The *functional unit* is extremely important because it is a reference to which all the inputs/outputs are related, allowing comparability.

The *system boundary* defines the unit process to be included in the study. There are four options to set it:
- in the "*cradle to gate*" approach, the system boundary includes all the unit processes from the raw material acquisition to the factory gate.
- "*cradle to consumers*" incorporates the unit processes of the "cradle to gate" and the distribution step.
- "*cradle to grave*" is a complete analysis because it considers all the unit processes from the raw material acquisition to the use and disposal step.
- "*gate to gate*" comprises all the unit processes that occur inside the factory.

Data quality is one of the essential requirements for study reliability. Data can be classified as primary data or foreground data (based on direct measurements), secondary data or background data (taken from secondary sources such as databases, other scientific papers) and tertiary data (estimations).

When an industrial process yields more than one product, there are two ways to proceed: system expansion or allocation. The *system expansion* considers co-products as alternatives to other products on the global market defined as marginal products. The substitution of this product with the co-product determines a credit of impact to subtract from the principal product's total impact. The *allocation* can be performed from an economic, energy and mass point of view. It divides the environmental impacts according to how much the products and co-products cost, weight, or power.

Assumptions that can influence the result and *limitations* should be stated to avoid misinterpretations of the outcomes.

2.3.2 *Life cycle inventory analysis*

The drafting of the LCI table is the most time consuming and working intensive section of the LCA study. Indeed, it includes the *data collection* and *calculations* for referring each input and output to the functional unit. It is essential to ensure mass and energy balance since each unit process pursues the lay of mass and energy conservation.

The data regard all inputs and outputs of the system, including materials, resources, energy and emissions throughout the process or product life cycle. At this step, it is fundamental to gather as much primary data as possible to get a reliable LCA.

2.3.3 *Impact assessment phase*

Finally, the effective evaluation of the potential environmental impact of the product system occurs. Various of LCIA methods can be used, such as CML 2011, ReCiPe, EDIP 2003, Eco Indicator 99.

The impact assessment phase consists of different elements: classification and characterization are obligatory, normalization, grouping (ranking or sorting), and weighting are optional (*figure 2-5*).

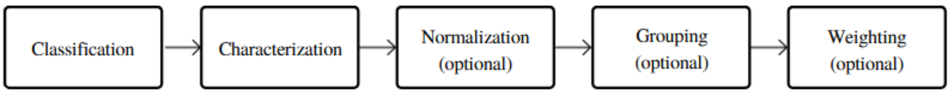

Figure 2-5: Impact assessment phases

- **Classification**

All substances listed in the inventory table are associated with an impact category (IC), indicating the environmental issues related to the production system to be studied. The most common impact categories that are usually examined are: global warming potential (GWP), cumulative energy demand (CED), eutrophication, acidification, ozone depletion, human toxicity potential, ecotoxicity potential, land use, and water use (Yetunde Omolayo, 2021).

Global warming potential is also known as climate change. It is a global effect caused by greenhouse gasses such as carbon dioxide and methane. They contribute to the “greenhouse effect” in controlled quantities, essential for maintaining the Earth’s atmosphere temperature stable. Currently, there is a large production of these gasses that modify the balance.

Consequently, sun heat is entrapped in the atmosphere determining an increase in Earth's temperature. This can, in turn, have adverse impacts on ecosystem health, human health, and material welfare.

The *cumulative energy demand* is the direct and indirect energy use throughout the life cycle.

Eutrophication is mainly linked to the hydrosphere. It is caused by high levels of macronutrients (mostly nitrogen and phosphorus) and organic matter from livestock and agriculture. Nutrient enrichment can cause an undesirable shift in species composition and elevated biomass production in aquatic and terrestrial ecosystems. In aquatic ecosystems, increased biomass production may lead to depressed oxygen levels because of the additional oxygen consumption in biomass decomposition.

Sulphur dioxide and nitrogen oxide emissions to the atmosphere trigger *acidification*. These compounds can be produced by human activities, power plant, trucks, and other sources. The acidification potential measures the molecule's capacity to increase the hydrogen ion (H^+) concentration in the presence of water, thus decreasing the pH value (e.g., acid rain). Acid rains are precipitations with a pH less than 5.7. This excess hydrogen ion can bring to the acidification of freshwater aquatic systems. The potential effects include fish mortality, forest decline and the deterioration of building materials.

Ozone depletion is a global effect. Ozone is found in the stratosphere, and it contributes to protect lives on Earth from sun ultraviolet (UV) rays. Hydrochlorofluorocarbons, foaming agents, fire extinguishers, solvents, pesticides, and aerosol propellants are thinning this layer leading to a higher level of UV radiation reaching the Earth's surface with detrimental effects on humans (e.g., skin cancer and impaired immune systems) and plants (e.g., crop yield reduction).

IC can be grouped as:

- Midpoint impact categories (or problem-oriented approach) → focus on one single environmental problem. Among them there are climate change, acidification, and human toxicity.
- Endpoint impact categories (or damage-oriented approach) → show the effect of environmental impact on human health, biodiversity, and resource scarcity.

For example, carbon dioxide (CO_2) is linked to the impact category called GWP. The measurement unit for this impact category is $kgCO_2eq$. In *table 2-1*, there are other examples.

Table 2-1: Correlation between elements and the affected impact category

Elements	*Impact category*
Carbon dioxide (CO_2) Methane (CH_4) Nitrogen protoxide (N_2O)	Global Warming Potential $kgCO_2eq/kg$
Sulphur dioxide (S_2O) Hydrochloric acid (HCl) Ammonia (NH_3)	Acidification Potential $kgSO_2eq/kg$
Phosphate (PO_4) Ammonia (NH_3)	Eutrophication Potential $kgPO_4eq/kg$

- **Characterization**

This element of LCIA is essential because it is the effective quantification of the impact. The LCIA methods provide the characterization factors that express how much a single unit of mass of a substance contributes to a typical impact category. Multiplying the characterization factor by the substance quantity indicated in the LCI table, it is possible to get the impact specific for an impact category.

For example, the characterization factor of CO_2 for the global warming potential is 1 kg CO_2 eq. Assuming that the quantity of CO_2 is 1386 kg, the impact of CO_2 for the global warming potential impact category is 1386 kg CO_2 eq.

- **Normalization**

Since each impact category has its measurement units, normalization involves calculations for converting the potential into scores per impact category, allowing the comparison between different impact categories. These scores can express an average person's annual impact or a country's resource use per year.

- **Grouping**

Two possible procedures are available: ranking the category indicators on an ordinary scale (e.g., low, medium, and high priority) or sorting the category indicators on a nominal base (e.g., resources, emissions). It does not need calculations.

- **Weighting**

Weighting factors can be assigned to normalized values according to the importance of each impact category relative to the others. Multiplying each normalized value by the weighting factors and summing all the points, it is possible to obtain a weighting result. This final score can be used to compare different production chains.

2.3.4 *Interpretation phase*

The interpretation phase includes two simultaneous steps: identifying significant issues and evaluating the results. These steps result in conclusions and recommendations, or they can result in a reiteration of the life cycle assessment phases.

When the results do not align with the goal and scope section's requirements, the analysis should start again, improving some parameters. As previously mentioned, the LCA analysis is an iterative process. Each additional iteration phase causes an increase in efforts, costs, and time to increase the accuracy and precision of the LCA results.

To facilitate the interpretation of the results, it is possible to set cut-off criteria that point out the amount of material, energy, or environmental impact associated with the product system or life cycle steps to be excluded from the study.

Results shall be reported without biases to the intended audience and in a detailed manner, ensuring transparency.

- **Identification of significant issues**

Depending on the goal and scope of the study and the level of detail required, there are different methods for identifying issues:

- Contribution analysis → based on the assignment of a contribution of each life cycle step to the total result. The results are expressed as a percentage of the total.
- Dominance analysis → significant results are determined by statistical tools (e.g., ABC analysis).
- Influence analysis → identifies how a parameter can influence an environmental impact.

- Anomaly assessment→ based on the analyst experience: an expert should be able to identify critical outcomes or deviations.

- **Evaluation**

Similarly to the identification of significant issues, for the evaluation, there are different methods to take into consideration:

- Completeness check → the aim is the data gaps identification. If these data are necessary for satisfying the goal and scope, further data should be acquired (even during a second iteration), or the goal and scope need and adjustment.
- Sensitivity check → evaluate the reliability of the result and conclusions by determining the influence of data uncertainties, allocation method, calculations, etc., on the outcome.
- Consistency check → establish if the assumptions, methods, and data are consistent with the goal and scope section.

2.4 **Product Environmental Footprint (PEF)**

Product Environmental Footprint has been developed as an initiative of the European 2020 Strategy to "establish a common methodological approach to enable the Member States and the private sector to assess, display and benchmark the environmental performance of products, services and companies based on a comprehensive assessment of environmental impacts over the life-cycle (environmental footprint)."

At the European level, PEF can have many applications. First, PEF studies can be useful for environmental management, hotspot identification, and environmental performance tracking (*in-house applications*). Secondly, they can be the foundation for sustainable EU policies and play an important role in marketing for possible environmental labelling development (*external applications*).

PEF is an official methodology based on the LCA promoted by the European Commission's Joint Research Centre (JRC). PEF is like a standardized LCA study; in fact, its main goal is to provide a common way to measure companies' environmental performances at the European level.

A specific PEF Guide was draft. It is a multi-criteria measure of the environmental performance of a good or service throughout its life cycle. It provides a method for modelling the environmental impacts of the material and energy flows and the emissions and waste streams associated with a product throughout its life cycle. The guide requirements were chosen considering similar methods and guidance documents, such as the ISO 14044:2006, ILCD (International Reference Life Cycle Data System) Handbook, Greenhouse Gas Protocol, Ecological Ecofootprint, and others (European Commission, 2012).

2.4.1 *Phases of a PEF study*

PEF studies follow a specific framework (*figure 2-6*) that is equivalent to an LCA study. The first two steps define the goals and the scope. Then, the resource use and emissions profile phase and Environmental Footprint Impact Assessment (EFIA) correspond to the LCI and LCIA, respectively. The last part includes the results interpretation and the reporting.

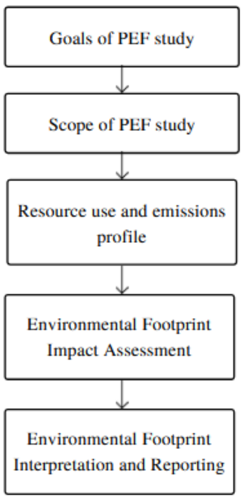

Figure 2-6: PEF framework

2.4.2 *Product Environmental Footprint Category Rules*

There are some rules to follow for each product category (e.g., dairy products, bakery, meat…) to avoid ignoring a PEF study's key aspects and improve results comparability within each product category. These categories are called Product Environmental Footprint Category Rules (PEFCRs). They increase the reproducibility, consistency, and relevance of PEF studies, helping PEF experts to focus on the most important parameters, thus also possibly reducing the time, effort, and costs involved in conducting a PEF study. PEFCRs provide specifications regarding:

- Goal and scope definition;
- Identification of the relevant impact categories;
- Identification of system boundaries;
- Identification of key parameters and life-cycle stages;
- Possible data sources;
- Resource Use and Emissions Profile phase;
- Specification for multi-functionality problems (allocation methods)

2.4.3 *Product Environmental Footprint's history*

The PEF development was gradual, and its evolution can be divided into four stages.
From 2008 to 2013, there was the *preparatory phase* during which all the Product Environmental Footprint Category Rules (PEFCRs) were defined. Then, with the *pilot phase* (2013-2019), the first practical tests of PEFCRs were carried on. These preliminary studies helped find adjustments and improvements. Starting from 2019, PEFCRs were applied on a larger scale. This period was called the *transition phase*. The *implementation phase* began in 2021. Nowadays, it is time to decide when and where PEF is required by law and how to communicate the results (e.g., uniform labelling).

2.4.4 *Differences between PEF and LCA*

LCA and PEF are both methods for evaluating environmental sustainability, but they differ in some aspects. PEF provides more specifications for each product category, allowing better comparability of the results. Regarding the system boundaries, PEF covers the "*cradle to grave*" life cycle of a product, while in LCA studies, it is possible to choose the unit processes to consider. Additionally, in the PEF approach can be employed standardized LCIA methods and concrete formulas for the end-of-life process.

3. CASE STUDY DESCRIPTION

3.1 **Objective of the study**

The study aims to evaluate the environmental sustainability of frozen spinach to identify hotspots along the production chain and improve them. Moreover, solutions for reducing the environmental impact will be proposed from a circularity perspective, starting from spinach wastes.

Thanks to the collaboration with Coltivatori Ortofrutticoli Valli delle Marche (C.O.V.A.L.M.) and ORTO Verde, it was possible to carry on the study in a very precise way. Indeed, because of this project with Università Politecnica delle Marche, it was possible to get accurate data and perfectly know the production chain of frozen spinaches.

3.2 **Coltivatori Ortofrutticoli Valli delle Marche and ORTO Verde**

Coltivatori Ortofrutticoli Valli delle Marche is an agricultural cooperative society (C.o.val.mSca) that produces and transforms vegetables destined to be sold as fresh (small part) or frozen.

C.o.val.mSca born in 2004 as an association called Organizzazione di Produttori (OP) with 130 members. The presence of this association revealed to be fundamental for farmers when the Marche Region was subjected to a strong crisis due to the discontinuation of beet cultivation after the European decision about sugar. In 2007, the OP acquired the plant in Cesano di Senigallia (AN). From 2014 to nowadays, C.o.val.mSca is continuously growing in associates' numbers. Currently, C.o.val.mSca includes about 600 farmers from different italian regions, primarily from Marche, Umbria, Abruzzo, Lazio, Emilia Romagna, and Puglia.

C.o.val.mSca members produce vegetables and legumes. The main products are peas, garlic, basil, chard, broccoli, cauliflower, chicory, turnip greens, onion, beans, green beans, carrots, potatoes, peas, tomato, leek, celery, shallot, spinach, snow peas, cabbage, pumpkin, and zucchini. To get an idea of the production quantity, in *figure 3-1*, 100 kg per year of the main crops are reported. Due to the high quantity of peas produced annually, it is the first in Italy to cultivate, transform, and commercialize peas.

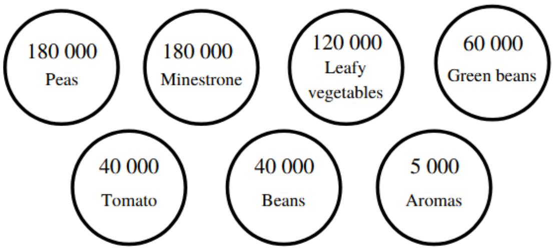

Figure 3-1: Production quantity

Associates are followed from the sowing to the harvesting by the technical experts of Agroteam S.P.A. Most of the production follows an integrated farming approach, but for some years, C.o.val.mSca stimulates the growers to cultivate under the organic guidelines.

Part of the wastes is intended for the *biogas plant* in Osimo (AN). Agricultural by-products are subjected to anaerobic fermentation, and they are converted into methane and digestate that is sent back to farmers for soil fertilization. Thanks to a cogenerator, methane is transformed into electric energy.

C.o.val.mSca pays great attention to traceability. Laboratory analyses are carried out in the facility placed in Rotella (AP), which, ACCREDIA, the Italian accreditation body, accredited. In addition, it focuses on the short food supply chain, ensuring the product transformation quickly upon the arrival at company's gates. For these features, C.o.val.mSca products are chosen and sold by the biggest brands, such as Findus and Orogel.

C.o.val.mSca together with Acom OP S.c.a.p.a society gave birth to *ORTO Verde S.c.a.p.a*. that is an agricultural consortium company. From 2007, ORTO Verde produces, stores, and sells frozen vegetables intended for industries, retails, and catering customers into the national and international market. It has its brand called "*I Freschi di Campo*", but it also produces for third parties.

It involves 500 members, 6.000 hectares of soil cultivated each year, 50.000 tonnes of frozen vegetables processed in 2 plants: one in Rotella (AP) and one in Cesano di Senigallia (AN).

ORTO Verde boasts various certifications. It is certified according to the international standard BRC (British Retail Consortium), and it has two other certifications regarding integrated and organic productions. Moreover, Marche Region gave to ORTO Verde the certification QM (Qualità Garantita delle Marche) for peas, spinaches, and green beans. These certifications reveal that the company has high-quality products, pay attention to traceability, and it's able to operate in line with many disciplinaries.

3.3 **Frozen spinach supply chain**

Spinach (*Spinacia oleracea L.*) is a green leafy vegetable belonging to the Chenopodiaceous family. It is an annual plant that can be grown in spring and autumn, giving high yields in a short time. The edible parts are the young leaves that can be eaten raw or cooked and are tasteful and easy-to-digest. It has great content in water (about 91%) and a low percentage of proteins (2.9%), carbohydrates (3.6%), and lipids (0.4%). However, spinach is considered very nutritious since it is rich in vitamins (vitamin A, C, and folic acid), minerals (such as calcium, magnesium, potassium, and iron), and carotenoids (lutein) compared to other vegetables.

Spinach is a perishable vegetable, and it can be store for about two weeks as fresh. To have a high-quality product all over the year, freezing is suggested.

At ORTO Verde, the supply chain was organized as the following:

3.3.1 *Cultivation*

In 2018/2019, farmers had 78 fields for a total of 480.7 hectares. Since spinach grows in spring and autumn, autumnal spinaches were sowed in the end of 2018. In *table 3-1* there are details about the fields and hectares according to the product typology.

Table 3-1: Fields number and dimension

Product typology	***Fields numbers***	***Hectares***
Organic (sowed in 2018)	1	6.6
Organic (sowed in 2019)	1	10
Integrated (sowed in 2018)	22	133.9
Integrated (sowed in 2019)	54	330.2
Total	*78*	*480.7*

From the table, it is easy to deduce that in 2019 the organic production of associates was a minimal part. For this reason, it is not possible to have a representative result for comparing the environmental impact of organic frozen spinach and frozen spinach from integrated cultivation.

During the cultivation, many operations have been carried out. First, *ploughing* was performed at 30 or 20 cm deep. After that, *harrowing* was done at 10, 15, or 20 cm. Then, to produce frozen spinach in 2019, the *sowing* was accomplished in three different periods:

- September - December 2018
- January - February 2019
- August - September 2019

The main varieties cultivated were Crow, Tahiti, Bufflehead, Falcon, Night hawk, Kangaroo, Zanzibar, Gnu, Savrun, Eland, Sparrow, Meerkat, SV 3749, RS 1549 and RS 3549.

Next to the sowing, *rolling* was carried out. During the spinach growth, *irrigation* was necessary for some parcels, and one to five interventions were done. Each intervention was about 20 or 30 m^3/ha of water. According to the sowing period, the *harvesting* was from January to April 2019 and between October and November 2019.

3.3.2 *Integrated approach*

Generally, all the fields under the integrated approach were subjected to similar pesticides and fertilizers treatments. Even if the commercial name was often different, the active principle was the same.

Pesticide is a substance that prevents, destroys, or controls a harmful organism ("pest") or disease or protects plants or plant products during production, storage, and transport. The term includes, amongst others: herbicides, fungicides, insecticides, acaricides, nematicides, molluscicides, rodenticides, growth regulators, repellents, rodenticides, and biocides (European Commission). They can be applied to the soil in solid form or diluted in water. In *table 3-2*, the active principles of fungicides and insecticides are listed, and they are associated with the pest or disease they control. While, in *table 3-3*, the active principles of herbicides applied are reported.

Table 3-2: Insecticides and fungicides active principle

Insecticides	***Pest/disease***	***Fungicides***	***Pest/disease***
Bacillus thuringiensis	Noctuid	Boscalid	Powdery mildew
Chlorantraniliprole	Lepidopteran larvae	Cymoxanil	Downy mildew
Ethofenprox	Aphid and bugs	Cymoxanil + copper	Downy mildew
Indoxacarb	Noctuid	Pyraclostrobin + Dimetomorf	Downy mildew
Lambda-cyhalothrin	Aphid and bedbug	Propamocarb	Downy mildew

Table 3-3: Herbicides active principle

Herbicides	
Cycloxydin	Fenmedifam
Lenacil	Metamitron
Propaquizafop	Quizalofop-p-ethyl
S-metolachlor	

Slugs represent another common pest. For controlling and destroying them, farmers usually use iron phosphate.

Fertilizers are substances that supply plant nutrients, and they can be applied to the soil before and after the sowing. The three main macronutrients are nitrogen (N), phosphorous (P), and potassium (K). The NPK content represents their proportion, and it is generally indicated as three percentages. In *table 3-4*, the fertilizers used by farmers are listed.

Table 3-4: Fertilizers composition

Fertilizers	*NPK content*	*Fertilizers*	*NPK content*
Ammonium nitrate	27:0:0	Ammonium nitrate	34:0:0
Ammonium sulphate	27:0:0	Booster	3:12:0
Booster	03:16:0	Calcium nitrate	15:0:0
Calcium nitrate	15:0:0	Diammonium phosphate	18:46:0
Entec	25:15:0	Entec	26:0:0
Entec	46:0:0	Golden Fertil Premium	10:10:15
Gran NPK	11:22:16	Monoammonium phosphate	12:52:0
Megafol	3:0:8	Nitrophoska	12:12:17
Urea	46:0:0	YaraMila Bulstar/NPK	12:12:17
Simple superphosphate	0:19:0		

In addition to the mentioned fertilizers, others were applied, providing micronutrients to the soil, such as Kendal TE and Block 5 containing copper and YaraVita Stopit containing calcium.

Moreover, bio stimulants were practical for boosting plant activity, stress resistance, and production yield. Digestate was also used for the cultivation, and it was from the biogas plant.

3.3.3 *Organic approach*

The organic production is much lower than the integrated one, and only two fields performed this agricultural method. Under the organic system, the cultivation is based on natural substances (not synthesis) and processes (such as crop rotation).

The only treatments carried out in the two parcels were:

- Use of Spinosad (insecticide) against noctuid
- Use of copper oxychloride (fungicide) against downy mildew
- Use of sulphur (fungicide) against powdery mildew

3.3.4 *Transport*

Third-party companies oversee the transport process. Generally, a truck with a payload of 11 tons is used for spinach cultivated in Marche. Spinaches from all the other regions are transported by articulated trucks of 23 tons of load. These transport means are opened at the top to avoid spinach fermentation. They are powered by diesel and loaded at 50% because spinaches have a low density, and also helps to prevent compressing the spinach in the truck. Since the transport involves food products, trucks are empty for the return journey because they are solely dedicated to these transports.

Table 3-5 can help understand the geographical origin of the product and the specific transport means used.

Table 3-5: Transport typology

Truck typology	***Region***	***Fields numbers***	***Hectares***
11 tons of load	*Marche*		
	Ancona	6	26.3
	Fermo	7	33
	Macerata	30	170.3
23 tons of load	*Basilicata*		
	Potenza	1	5
	Emilia Romagna		
	Ravenna	1	2
	Lazio		
	Latina	1	6
	Molise		
	Campobasso	1	8
	Puglia		
	Foggia	26 + 2 (organic)	163 + 16.6 (organic)
	Umbria		
	Perugia	3	50.5

3.3.5 *Processing*

In *table 3-6,* the quantities of spinach that associates provided to ORTO Verde in 2019 are reported.

It is important to mention that once the trucks arrive at the company's gate, a percentage of the total quantity (generally between 5% and 20%) is not paid to the farmer because a visual analysis estimates the amount of the waste.

Table 3-6: Fields production

Product typology	***Quantities at the gate***
Organic (sowed in 2018)	163 770 kg
Organic (sowed in 2019)	126 110 kg
Integrated (sowed in 2018)	1 062 460 kg
Integrated (sowed in 2019)	3 096 830 kg
Total	*4 449 170 kg*

Once harvested, spinaches are immediately transported to the company's gate, and the processing starts soon. In *table 3-7*, there is a detailed description of weeks spent processing spinaches over the year 2019.

Table 3-7: Months of spinach processing

January			***February***			***March***			***April***			***May***			***June***			***July***		
1°	2°	3°	1°	2°	3°	1°	2°	3°	1°	2°	3°	1°	2°	3°	1°	2°	3°	1°	2°	3°
		x	*x*	*x*	*x*	*x*	*x*	*x*	*x*											

August			***September***			***October***			***November***			***December***		
1°	2°	3°	1°	2°	3°	1°	2°	3°	1°	2°	3°	1°	2°	3°
								x	*x*	*x*	*x*	*x*	*x*	*x*

From the transport means, spinaches are directly introduced into the *bucker*.

The first three-unit processes are separators, and they work depending on different discriminatory agents. The *sand trap* generates the first waste, generally composed of sand, destined to the biogas plant. The *helium separator* creates a flow that drops heavy particles, such as stones, stems, and ground (second waste). Then, the *laser separator* discriminates according to the colour. All the wastes produced from this step are, in fact, brown, and they can be insects or dried leaves. Also, this third waste is destined for the biogas plant.

After the separators, there are two-unit processes aimed at *washing* spinach leaves. The first is *by fluctuation* and the second one *by decantation*. In both washing unit processes, water is from wells, and it is subjected to a purification process because only potable water is used. Sludges (fourth and the fifth wastes) are formed and poured on the ground near the company's plant.

Subsequently, the spinaches are cooked using a *multiphase cooker* composed of four steps, having different temperatures. The section temperatures are 75°C (pre-heating), 90°C (heating), 80°C (pre-cooling), and 23°C (cooling of the product).

Afterwards, the *visual inspection* is performed by humans. All the unwanted parts (sixth waste) that are not in line with the requisites are destined to the biogas plant. They should be listed in a specific paper because farmers are informed in case of particular elements.

Later, the product is *pressed into cubes* of 30 or 50 grams, depending on the stipulations they have with the other brand) and *frozen* at -35°C. Ammonia is the refrigerator agent, and it works in a closed system, so its dispersion can be considered irrelevant.

A *metal detector* verifies if metallic parts are inside the product.

As the last step, the *glazing* is performed. It consists of wetting the external surface of the spinach cubes with water to have a smooth and homogenous product (useful from an aesthetic point of view). Glazing is not mandatory; some brands do not want it and some consumers do not appreciate it.

At this moment, frozen spinach can be *stored in freezing cells,* placing the cubes into big cardboard boxes (load: 850 kg) lined with a plastic bag, or follow the line for the packaging steps. The first option is required by the biggest companies such as Orogel and Findus because they will pack the product on their own, while Esselunga and Eurospin involve producing frozen spinach in plastic bags.

The packaging steps alternate with various inspections to make sure there are no unwanted parts. Indeed, first, there is a *visual inspection* (eighth waste), then the *primary packaging* is added, which is in direct contact with the product itself. After that, the other two controls are performed using a *metal detector* and *x rays* (ninth and tenth waste). At the end, the *secondary* and *tertiary packaging* are adjunct and *stored*. The three packaging are made of plastic.

All the processing line is powered by methane and electric energy from three different sources: photovoltaic panels, co-generator, and power line (as a general average, 1 million 100 kilowatt-month is consumed). This allows the production of 20 quintals of spinach per hour.

As previously mentioned, they are subjected to many controls along the whole production process since they work under many certification disciplines. Some analyses are carried out on the raw material before the processing. Every anomaly is always reported during the processing, and the critical control points (CCP) are carefully checked. For example, the freezer and cooker temperatures are controlled each hour, while the metal detectors every two and laboratory analyses are performed after each hour's sorting and freezing steps. Also, the visual inspection has specific rules, and the working shifts do not last too long to avoid losing the operator's attention. Other analyses are performed on the final product to verify if it has the requirements imposed by the brands.

Last but not least, there is a strict succession of codes to allow traceability. ORTO Verde works under a management system called "Filo di Arianna." It gives the possibility to reconstruct, follow, and communicate the food product path through harvesting, production, transformation, packaging, and distribution phases.

In *figure 3-2*, the whole processing flow is represented schematically.

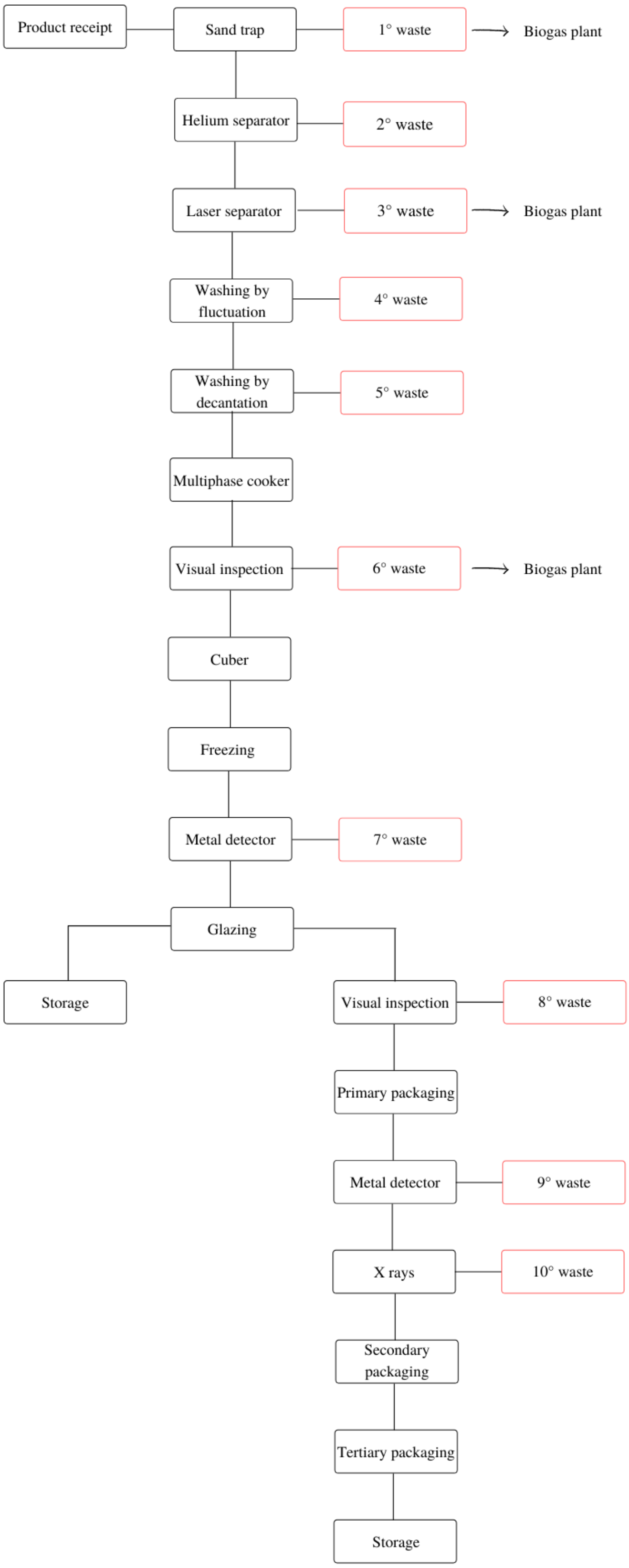

Figure 3-2: Processing flow

3.4 **Materials and methods**

The environmental sustainability study was assessed using the Life Cycle Assessment methodology. This was possible thanks to the use of SimaPro (version 8.3) software, based on the ISO 14040 and 14044 standards.

SimaPro is a tool for collecting, analysing, and monitoring the sustainability performance data of a product or service. With SimaPro is possible to model the life cycle of the product or service you are studying. Indeed, to make use of SimaPro is necessary to search for the processes inside the software. These processes should be the most specific as possible for the supply chain in analysis. In addition, primary, secondary, or tertiary data are added, paying attention to the measurement units. The same process can be present more times, and they are very different among them, so it is necessary to read the descriptions carefully. Some of them can already include, for example, emissions or operations. After this first step, which is the formulation of an LCI, SimaPro automatically measures the environmental impact of the products and services across all the life cycle stages. The LCIA is carried out by selecting the functional unit and the method. At the end, thanks to SimaPro, you can identify the hotspots of your supply chain.

SimaPro includes many LCI databases that are called “libraries” in SimaPro. Currently, SimaPro comprises the following libraries, but additional databases are available for download in SimaPro format.

- Agri-footprint

It was developed by Blonk Consultants that is a sustainability consulting firm specialized in agricultural LCA. It is an LCI database about agricultural products: feed, food, and biomass. Indeed, it contains about 5000 products and processes; there are crops, products and intermediate products, feed compounds, food products, animal production systems and background processes (transport, energy, fertiliser, pesticide). In addition, it includes a range of specific impact categories such as the water and land use, the land-use change, fertilisers, pesticides, and soil carbon content.

- Ecoinvent

Ecoinvent can be used for life cycle assessment, life cycle management, carbon footprint assessment, water footprint assessment, environmental performance monitoring, product design and eco-design or Environmental Footprint Declarations (EDP). It is the largest and the most consistent LCI database on the market. Indeed, it contains more than 15000 datasets in the areas of energy supply, agriculture, transport, biofuels and biomaterials, chemicals, construction materials, packaging materials, textiles, metals, electronics, dairy, wood, and waste treatment.

- EU and Danish Input Output

It is based on economic and environmental statistics. Contrarily to process databases, it covers the entire economy eliminating the need for making cut-offs in the LCA.

- Industry data 2.0

It contains data collected by industry associations: processes are provided by PlasticsEurope, worldsteel and ERASM (European Detergents and Surfactants Industries). It includes over 300 datasets at the system level, meaning that only the LCI is available rather than unit processes.

- US Life Cycle Inventory Database

It provides individual gate-to-gate, cradle-to-gate, and cradle-to-grave accounting of the energy and material flows into and out of the environment that are associated with producing a material, component, or assembly in the U.S.

Furthermore, SimaPro comprises several impact assessment methods, which are used to calculate impact assessment results. Among the global methods, there are the IMPACT World+ Endpoint and Midpoint, and ReCiPe 2016 Endpoint (E, H, I) and Midpoint (E, H, I). While, among the European methods, there are CML-IA baseline and non-baseline, Ecological Scarcity 2013, EF Method, Environmental Prices, EPD (2018) and EPS 2015d and dx.

For this study, the CML_IA impact assessment method was used. CML (proposed by the Center of Environmental Science of Leiden University) is a database containing a set of impact categories and characterizations method defined for the midpoint approach (SimaPro Database Manual, 2020). The midpoint methods look at the impact earlier along the cause-effect chain before the endpoint is reached. Normalization is provided, but there is neither weighting nor addition. The version of CML_IA employed is the “baseline” with eleven impact categories:

- Abiotic Depletion Potential (ADP) elements

This impact category is concerned with the protection of human welfare, human health, and ecosystem health. It is the availability decrease of material resources, such as minerals, because of their unsustainable use.

(Measurement unit: kg antimony equivalent)

- Abiotic Depletion Potential (fossil fuel)

Also this impact category is concerned with the protection of human welfare, human health and ecosystem health. It is the availability decrease of non-biological and non-renewable resources, such as because of their unsustainable use.

(Measurement unit: MJ of fossil fuel)

- Global Warming Potential (GWP 100 year)

It is also called climate change, and it can result in adverse effects upon ecosystem health, human health, and material welfare. It is the global temperature alteration caused by greenhouse gases (gas that absorbs and emits radiation within the thermal infrared range) emissions to air. Greenhouse gases are methane (CH_4) and sulphur hexafluoride. The rise in global temperature causes disturbances in climatic phenomena, desertification, rising sea levels and spread of disease. It is expressed over a time horizon of 100 years.

(Measurement unit: kg CO_2 equivalent)

- Ozone Layer Depletion Potential (ODP)

It is the diminution of the stratospheric ozone layer due to anthropogenic emissions of ozone-depleting substances. This increases the ultraviolet UV-B radiation (that are carcinogenic) reaching the earth's surface, causing harmful effects on human health, animal health, terrestrial and aquatic ecosystems, biochemical cycles, and materials. Chlorofluorocarbons (CFCs), halons and hydrofluorocarbons (HFCs) are the main responsible for ozone depletion.

(Measurement unit: kg CFC-11 equivalent).

- Human Toxicity Potential (HTP)

This category concerns effects of toxic substances on the human environment, leading to cancer and respiratory diseases. These compounds are mainly arsenic, sodium dichromate and hydrogen fluoride.

(Measurement unit: kg 1,4-dichlorobenzene equivalents).

- Fresh Water Aquatic Ecotoxicity Potential (FAETP)
- Marine Aquatic Ecotoxicity Potential (MAETP)

- Terrestrial Ecotoxicity Potential (TETP)

These three impact categories are linked to the toxic effects of chemicals on the three different ecosystems: fresh-water aquatic ecosystem, marine ecosystem, and terrestrial ecosystem. Ecotoxicity can lead to biodiversity loss and species extinction. Emissions of heavy metals are examples of compounds that can contribute to these impact categories.

(Measurement unit: kg 1,4-dichlorobenzene equivalents).

- Photochemical Oxone Creation Potential (POCP)

It is also called summer smog. It is caused by the reaction of non-methane volatile organic compounds and nitrogen oxides in the presence of heat and sunlight. These reactive substances decrease the ecosystem quality, affect human health, and may damage crops.

(Measurement unit: kg ethylene equivalent).

- Acidification Potential (AP)

It is the pH reduction in water and soil due to acidifying effects of anthropogenic emissions. It is caused by acidic gasses such as sulphur oxides (SO_x), ammonia (NH_3), and nitrogen oxides (NO_x). Acidification damages the ecosystem quality and decreases biodiversity.

(Measurement unit: kg SO_2 equivalent).

- Eutrophication Potential (EP)

It is the accumulation of macronutrients in aquatic systems, soil, and air. It is caused by emissions of ammonia, nitrates, nitrogen oxides and phosphorous to air or water. Its consequence is damage to the ecosystem.

(Measurement unit: kg PO_4^{3-} equivalents).

4. LCA OF CASE STUDY

4.1 **Goal and scope phase**

The *goal* of this attributional LCA study aims to evaluate the environmental sustainability of frozen spinach production and identify options for improving the environmental performance, using a circular economy approach. The following study involves the researchers of Università Politecnica delle Marche, ORTO Verde and C.o.val.mSca. Other interested parties can be companies producing frozen spinach, companies developing a circular economy, legislators, and LCA researchers.

Regarding the *system boundary*, the methodology chosen is the "cradle to gate," so all the relevant input/outputs and energy related to spinach cultivation, transportation, processing, and packaging are included (*figure 4-1*).

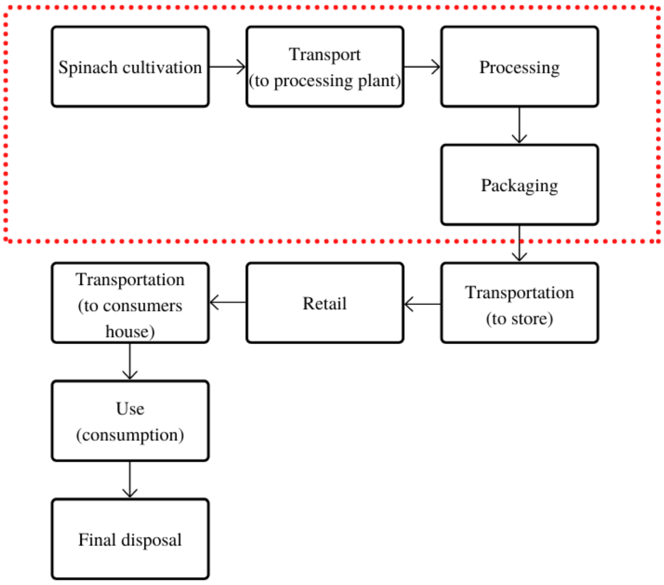

Figure 4-1: System boundary

The defined *functional unit* (FU) is 1 kg of frozen packaged spinach; it is the reference to which all the inputs/outputs of LCI are normalized.

All the *data* are primary because they directly come from ORTO Verde and farmers' direct measurements and documents. This contributes to the high reliability and credibility of the study.

The production of frozen spinach includes all the *year 2019*, but the spinach cultivation dates back September - December 2018, January - February 2019 and August - September 2019. The processing plant is placed in Cesano di Senigallia (AN), while the fields are distributed in the *Italian territory* (mainly from Puglia and Marche regions).

Unfortunately, the *technology* used to produce frozen spinach is not the best available technology (BAT), but it can be considered an average technology.

The *allocation* or the system expansion management is not performed. If spinach wastes will be considered coproduct and will be applied in other supply chains, a further LCA can be developed including the allocation. This can contribute reducing the environmental impact of frozen spinach production.

4.2 **Inventory analysis phase (LCI)**

LCI involves the collection of data and the normalization of inputs to the functional unit (1 kg of frozen packaged spinach).

4.2.1 *Cultivation*

To compose a complete LCI, the necessary information for the cultivation step include:

- Land surface
- Seed quantity
- Water for irrigation, treatments, and fertilizers
- Operations
- Fertilizer quantity
- Pesticide (herbicides, insecticides, and fungicides) quantity

4.2.2 *Integrated approach*

The inputs of the 76 producers who followed an integrated cultivation approach are reported in *table 4-1*. All data are expressed per functional unit of 1 kg of frozen packaged spinach.

Table 4-1: Integrated farming inputs

Process/material	*Unit*	*Value*
Land surface	ha	1.87E-04
Seed quantity	kg	2.80E-03
Water for irrigation	m^3	1.83E-03
Water for fertilizers	l	2.61E-01
Water for pesticides	l	8.51E-01
Operations		
Field interventions	ha	1.24E-03
Distribution of fertilizers and pesticides	ha	1.28E-03
Fertilizers		
Golden Fertil Premium (10:10:15)	kg	1.43E-03
Gran NPK (11:22:16)	kg	3.41E-04
NPK and YaraMila Bulstar (12:12:17)	kg	3.67E-03
Monoammonium phosphate (12:52)	kg	3.41E-04
Calcium nitrate	kg	1.10E-03
Diammonium phosphate (18:46)	kg	2.33E-02
Simple superphosphate (0:19)	kg	7.16E-04
Entec (25:15)	kg	1.02E-03
Entec (26)	kg	5.11E-04
Ammonium sulphate (27)	kg	5.11E-04
Ammonium nitrate (34)	kg	2.73E-04
Urea/Entec (46)	kg	2.52E-02
Bio stimulants	l	6.19E-04
Herbicides		
S-metolachlor	l	3.60E-05
Metamitron	l	2.97E-04
Lenacil	l	5.34E-05
Quizalofop-p-ethyl	l	8.87E-06
Propaquizafop	l	5.41E-05
Cycloxydin	l	1.19E-06
Fenmedifam	l	2.98E-05
Insecticides		
Bacillus thuringiensis	kg	1.64E-06
Etofenprox	kg	3.83E-05
Indoxacarb	kg	8.52E-07
Chlorantraniliprole	kg	1.62E-05
Lambda cyhalothrin	kg	4.53E-05
Iron phosphate	kg	5.34E-04
Fungicides		
Cymoxanil	kg	2.77E-05
Cymoxanil + copper	kg	2.86E-05
Dimetomorph + Pyraclostrobin	kg	2.86E-05
Propamocarb	kg	1.09E-05
Boscalid	kg	2.38E-05

For the land surface, the hectares of the 76 producers are summed. On average, 15 kg of seeds per hectare is considered for the sowing. In SimaPro software, the process of spinach seeds production is not present, so it has been considered the production of rapeseed which is very similar to the spinach one. The water for irrigation results from the sum of all the quantities of each irrigation intervention. While the water implied for fertilizers, herbicides, fungicides, and insecticides are deduced by reading the products' labels. The amount of chemicals applied to the soil is directly deemed from what the producers declared. Other farm operations performed by farmers, in addition to the distribution of pesticides and fertilizers, were ploughing, harrowing, sowing, rolling, irrigation, and harvesting.

After listing the inputs, the emissions of fertilizers and pesticides were calculated, while the operations' emissions were included in inputs chosen in SimaPro.

Pesticide emissions have been calculated considering that the 85% of the total active ingredient applied enters the soil, the 10% in air, and 5% in water (M. Margni, 2002). In *tables 4-2*, *4-3*, *4-4*, the emissions are listed, and they are referred to as the functional unit.

Table 4-2: Pesticide emissions from integrated farming

Herbicide	***Unit***	***Value***
S-metolachlor		
Soil	kg	3.06E-05
Air	kg	3.60E-06
Water	kg	1.80E-06
Metamitron		
Soil	kg	2.52E-04
Air	kg	2.97E-05
Water	kg	1.49E-05
Lenacil		
Soil	kg	4.54E-05
Air	kg	5.35E-06
Water	kg	2.67E-06
Quizalofop-p-ethyl		
Soil	kg	7.54E-06
Air	kg	8.87E-07
Water	kg	4.47E-07
Propaquizafop		
Soil	kg	4.60E-05
Air	kg	5.41E-06
Water	kg	2.71E-06
Cycloxydin		
Soil	kg	1.16E-05
Air	kg	1.36E-06
Water	kg	6.82E-07
Fenmedifam		
Soil	kg	2.54E-05
Air	kg	2.98E-06
Water	kg	1.49E-06

As it is possible to observe from *table 4-3*, the emissions of the insecticide *Bacillus thuringiensis* are not present. Its emissions can be omitted since it is a bacterium, naturally living in soil, with little known effects on humans and the environment. Moreover, there are no available studies in literature describing the LCA of *Bacillus thuringiensis* currently.

Table 4-3: Insecticide emissions from integrated farming

Insecticide	***Unit***	***Value***
Etofenprox		
Soil	kg	3.25E-05
Air	kg	3.83E-06
Water	kg	1.91E-06
Indoxacarb		
Soil	kg	7.26E-07
Air	kg	8.52E-08
Water	kg	4.43E-08
Chlorantraniliprole		
Soil	kg	1.38E-05
Air	kg	1.62E-06
Water	kg	8.11E-07
Lambda cyhalothrin		
Soil	kg	3.85E-05
Air	kg	4.52E-06
Water	kg	2.26E-06
Iron phosphate		
Soil	kg	4.54E-04

To calculate the emissions of "Cymoxanil + copper" fungicide, the proportion between the two components has been considered. Cymoxanil counts for 4,3% and copper oxychloride for 39,75%. Once the mass has been calculated, the emissions have been computed (Cymoxanil's emissions, from "Cymoxanil + copper", have been summed with the emissions of the fungicide composed by pure Cymoxanil). The same occurs for the fungicide "Pyraclostrobin + Dimetormorph." Pyraclostrobin represents 3,8% of the total, while Dimetomorph the 6,9% (*table 4-4*).

Table 4-4: Fungicide emissions from integrated farming

Fungicide	***Unit***	***Value***
Cymoxanil		
Soil	kg	2.45E-05
Air	kg	2.88E-06
Water	kg	1.44E-06
Copper		
Soil	kg	8.47E-06
Air	kg	9.96E-07
Water	kg	4.98E-07
Dimetomorph		
Soil	kg	1.68E-06
Air	kg	1.98E-07
Water	kg	9.89E-08
Pyraclostrobin		
Soil	kg	9.24E-07
Air	kg	1.09E-07
Water	kg	5.46E-08
Propamocarb		
Soil	kg	9.27E-06
Air	kg	1.09E-06
Water	kg	5.46E-07
Boscalid		
Soil	kg	2.02E-05
Air	kg	2.38E-06
Water	kg	1.19E-06

The *emissions of fertilizers* have been calculated based on information from the Product Category Rules (PCR) for arable and vegetable crops (Product Category Rules, 2020). All the fertilizers containing nitrogen and/or phosphorous emits.

- From *nitrogen*, dinitrogen monoxide (N_2O), ammonia (NH_3), and nitrogen monoxide (NO) are released in the air, while nitrates (NO^{3-}) in groundwater. In addition, fertilizers containing nitrogen can produce indirect emissions of N_2O, starting from ammonia and nitrates. In *table 4-5* the emissions are listed, and they are referred to the functional unit.

Table 4-5: N fertilizers emissions from integrated farming

Emission type	***Unit***	***Value***	***Sub compartment***
Direct emissions			
N_2O	kg	5.62E-04	Air
NH_3	kg	5.11E-03	Air
NO	kg	2.57E-04	Air
NO^{3-}	kg	2.29E-02	Groundwater
Indirect emissions			
N_2O from NH_3	kg	1.32E-04	Air
N_2O from NO^{3-}	kg	1.22E-04	Air

- From *phosphorous*, phosphorus pentoxide (P_2O_5) can circulate in rivers or in groundwaters due to leaching (P_{gw}), run-off (P_{ro}), and erosion ($P_{erosion}$). All values of *table 4-6* are normalised to the functional unit.

Table 4-6: P fertilizers emissions from integrated farming

Emission type	***Unit***	***Value***	***Sub compartment***
Direct emissions			
P_2O_5 from P_{gw}	kg	4.03E-04	Groundwater
P_2O_5 from P_{ro}	kg	1.01E-03	River
P_2O_5 from $P_{erosion}$	kg	1.24E-04	River

In SimaPro, some fertilizers are present in plastic bags of 25 kg. This is the case of diammonium sulphate, simple superphosphate, YaraMila Bulstar, Golden Fertil Premium, Gran N.P.K., Entec (25:15) and monoammonium phosphate for a total of 298,4 kg of plastic.

According to *PlasticsEurope* (PlasticsEurope, 2018):

- 40,8% of packaging plastic is recycled
- 20,4% is directed to the landfill
- 38,8% is destined to energy recovery

Following these specifications, the masses of plastic for each destination have been calculated (*table 4-7*).

Table 4-7: Plastic destination

Plastic destination	***Unit***	***Value***
Recycling	kg	92.79
Landfill	kg	81.45
Energy recovery	kg	124.11
Total	*kg*	*298.35*

4.2.3 *Organic approach*

Similarly to the integrated production, the organic agriculture inputs are reported, referring to the functional unit of 1 kg of frozen spinach (*table 4-8*). The inputs describe the three fields following this cultivation approach.

Table 4-8: Organic farming inputs

Process/material	***Unit***	***Value***
Land surface	ha	8.12E-05
Seed quantity	kg	1.22E-03
Water for irrigation	m^3	7.34E-05
Water for insecticide	l	1.16E-01
Operations		
Field interventions	ha	4.11E-04
Distribution of pesticides	ha	3.52E-04
Insecticides		
Spinosad	l	1.04E-04
Fungicides		
Copper oxychloride	kg	1.11E-04
Sulphur	kg	2.94E-04

As for integrated agriculture, the land surface corresponds to the sum of the two fields areas, and the seed quantity is, also in this case, 15kg/ha (instead of spinach seeds, rapeseed production has been used). The water quantity for the insecticide Spinosad is evaluated from the product's label. Field interventions include the hectares of both fields subjected to ploughing, harrowing, sowing, irrigation, and harvesting. The quantity of pesticides is directly obtained from farmers' documents.

In addition to the inputs, the emissions (referred to the functional unit) were estimated for the three pesticides employed in organic production. As for the integrated approach, pesticide emissions have been calculated considering that the 85% of the total active ingredient applied enters the soil, the 10% in air, and 5% in water (M. Margni, 2002). In *table 4-9*, there are the emissions of the insecticide, and in *table 4-10*, the emissions of fungicides.

Table 4-9: Insecticide emissions from organic farming

Insecticide	***Unit***	***Value***
Spinosad		
Soil	kg	8.85E-05
Air	kg	1.04E-05
Water	kg	5.21E-06

Table 4-10: Fungicide emissions from organic farming

Fungicide	***Unit***	***Value***
Copper oxychloride		
Soil	kg	9.40E-05
Air	kg	1.11E-05
Water	kg	5.53E-06
Sulphur		
Soil	kg	2.50E-04
Air	kg	2.94E-05
Water	kg	1.47E-05

The overall spinach production from the cultivation step is reported in *table 4-11*.

Table 4-11: Fresh spinach production

Product typology	***Fresh spinach quantity (tons)***
Organic production	2.90E+02
Integrated production	4.16E+03
Total	*4.45E+03*

4.2.4 *Transport*

For the transports, the main information required in an LCI phase are:

- Loading factor
- Fuel type
- Empty backhaul
- Distance covered by the truck
- The spinach quantity

As previously stated, two different transport means are used for moving spinach from the fields to the company's gate. For the fields located in the Marche region, a truck with 11 tons of payload is generally employed. For the fields in other regions, articulated trucks with a payload of 23 tons are often used.

For the study, it is assumed the absence of transport losses (100% efficiency), even if it is very difficult, and a 50% of truckload due to the low spinach density. Moreover, the transport means considered belong to the EURO 3 category.

The *emissions* of this step are included in the inputs chosen in SimaPro. Among them, there are carbon dioxide (CO_2), methane (CH_4), and dinitrogen monoxide (N_2O).

4.2.5 *Integrated approach*

The fields are diffused in many Italian regions, so they have different distances to the company's gate. For this reason, the minimum and maximum distance and the minimum and maximum mass of transported spinach have been calculated. Consequently, the minimum and the maximum tkm have been determined. This distribution is also registered in the SimaPro software.

The transport means considered have a payload of 17 tons, the average between the two truck typologies.

The details of the transport are reported in *table 4-12*.

Table 4-12: Spinach from integrated farming transport

Integrated production		
Process/material	***Unit***	***Value***
Transport mean	type	truck (payload 17 tons)
Fuel	diesel	
Minimum distance	km	51
Maximum distance	km	411
Transported spinach	tons	4.16E+03
Minimum transported spinach	tons	1.7
Maximum transported spinach	tons	28.09
	tkm min	8.67E+01
	tkm max	1.15E+04

4.2.6 *Organic approach*

Organic spinaches are produced in three fields placed in Cerignola (FG), so the farms' distance from the company is well defined (411 km). However, the spinach production of one of these fields is unknown, so it is not considered in the transportation step. Details are reported in *table 4-13*.

Table 4-13: Spinach from organic farming transport

Organic production		
Process/material	***Unit***	***Value***
Transport mean	type	truck (payload 23 tons)
Fuel	diesel	
Distance	km	411
Transported spinach	tons	2,90E+02
	tkm	1,19E+05

4.2.7 *Processing*

Starting from two different cultivation typologies, spinach from the integrated cultivation and organic spinach undergo the same processing. The company decides when to process one or the other to avoid their mixture.

The necessary processing knowledge for the LCI are:

- Raw material quantity
- Final product quantity
- Processing steps
- Plant powering
- Water quantity
- Packaging

In 2019, from 4449.17 tons of fresh spinach entering the processing line, 3137.26 tons of frozen spinach had been produced, having an efficiency of 71%. The remaining 29% is spinach waste, for a total of 1312.04 tons. The details are in *table 4-14*.

Table 4-14: Fresh/frozen spinach and waste quantities

Product typology	***Fresh spinach quantity (tons)***	***Frozen spinach quantity (tons)***	***Efficiency (%)***	***Spinach wastes (tons)***
Organic production	2.90E+02	2.01E+02	69.31	8.90E+01
Integrated production	4.16E+03	2.94E+03	70.60	1.22E+03
Total	*4.45E+03*	*3.14E+03*	*70.51*	*1.31E+03*

Also in this case, the company provided all data of the processing step. In *table 4-15*, all the inputs to produce packaged frozen spinach bags are listed, and they are normalized to the functional unit.

Table 4-15: Inputs of frozen spinach processing

Process/material	*Unit*	*Value*
Spinach	kg	1.42E+00
Electricity	kWh	5.19E-01
Methane	m3	6.14E-02
Water	m3	1.77E-02
Packaging		
Bags (plastic)	kg	1.55E-03
Stretch film (plastic)	kg	2.50E-04
Box covering (plastic)	kg	4.86E-05
Labels (paper)	kg	1.86E-06
Sheets (paper)	kg	1.71E-04
Boxes (cardboard)	kg	1.78E-02
Dividers (cardboard)	kg	3.48E-04
Pallets (wood)	kg	3.91E-02

Regarding the packaging materials, some assumptions have been made. For example, labels have been considered made of only paper, while they also contain a thin player of plastic and a very small amount of glue. Since SimaPro inputs are not so specific, some simplifications have been established. The company did not precisely know the number of pallets and boxes used in one year. Knowing that each box is positioned on one pallet and that boxes can be of 450 or 850 kg, the minimum and the maximum numbers have been calculated. Once having the average number of boxes (consequently of the pallets), the kilograms of cardboard (or wood) have been calculated.

The *emissions* of the whole processing are already included in the inputs chosen in SimaPro.

4.3 **Impact assessment phase (LCIA)**

4.3.1 *Classification*

The classification assigns the impact categories to the elementary flows. The impact categories taken into consideration depends on the LCIA method chosen. The database CML_IA baseline has eleven environmental impacts:

- Abiotic Depletion Potential (ADP) elements
- Abiotic Depletion Potential (fossil fuel)
- Global Warming Potential (GWP 100 year)
- Ozone Layer Depletion Potential (ODP)
- Human Toxicity Potential (HTP)
- Fresh Water Aquatic Ecotoxicity Potential (FAETP)
- Marine Aquatic Ecotoxicity Potential (MAETP)
- Terrestrial Ecotoxicity Potential (TETP)
- Photochemical Oxone Creation Potential (POCP)
- Acidification Potential (AP)
- Eutrophication Potential (EP)

4.3.2 *Characterization*

The characterization forms potential impacts using conversion factors, obtaining an indicator for the impact category.

Once all the inputs have been uploaded into the SimaPro software, it automatically multiplies the LCI data for the characterization values present in the CML_IA baseline database. The software generates impact scores for the mid-point environmental impact categories, related to 1 kg of frozen packed spinach (the functional unit).

In *table 4-16*, there are the results obtained for each impact category. These outcomes include the environmental impact of spinach through cultivation, transportation, and processing steps for 1 kg of frozen packaged spinach.

Table 4-16: Impacts of 1 kg of frozen spinach

Impact category	*Unit*	*Value*
Abiotic Depletion Potential (ADP - elements)	kg Sb eq.	3.32E-06
Abiotic Depletion Potential (ADP - fossil fuel)	MJ	5.46E+00
Global Warming Potential (GWP - 100 year)	kg CO2 eq.	9.06E-01
Ozone layer Depletion Potential (ODP)	kg CFC-11 eq.	6.91E-08
Human Toxicity Potential (HTP)	kg 1,4-DB eq.	1.03E-01
Fresh water Aquatic Ecotoxicity Potential (FAETP)	kg 1,4-DB eq.	5.41E-02
Marine Aquatic Ecotoxicity Potential (MAETP)	kg 1,4-DB eq.	3.07E+02
Terrestrial Ecotoxicity Potential (TETP)	kg 1,4-DB eq.	1.75E-03
Photochemical Ozone Creation Potential (POCP)	kg C_2H_4 eq.	2.37E-04
Acidification Potential (AP)	kg SO_2 eq.	9.92E-03
Eutrophication Potential (EP)	kg PO_4^{3-} eq.	4.96E-03

For the integrated cultivation, digestate has been applied to soils. Its impact is not included in the analysis, but it has been found in the literature. In the study "Food waste anaerobic digestion in Umbria region (Italy): scenario analysis on the use of digestate through LCA" (Pietro Bartocci, 2020), Bartocci and the other researchers evaluated the environmental impact of digestate for all the 11 impact categories (*table 4-17*). The method used is CML_IA baseline, the same applied for the whole LCA study, and the functional unit is 1 ton of treated food waste.

Table 4-17: Digestate impacts

Impact category	***Unit***	***Value***
ADP elements	kg 1,4-DB eq.	6.47E+01
ADP fossil fuel	MJ	4.04E+02
GWP (100 year)	kg CO_2 eq.	7.22E+01
ODP	kg CFC-11 eq.	4.31E-06
HTP	kg 1,4-DB eq.	4.05E+02
FAETP	kg 1,4-DB eq.	6.47E+01
MAETP	kg 1,4-DB eq.	5.08E+04
TETP	kg 1,4-DB eq.	2.16E+02
POCP	kg C_2H_4 eq.	4.44E-02
AP	kg SO_2 eq.	2.14E+00
EP	kg PO_4^{3-} eq.	8.83E-01

In the study "Environmental impacts of vegetables consumption in the UK" (Angelina Frankowska, 2019), the environmental impact of 1 kg of spinach consumed has been estimated using the ReCiPe method. Thanks to this article, it is possible to deduce that some results of the LCA analysis are in line with the literature. The paper's outcomes are reported in *table 4-18*; there are not all the impact categories because of different measurement units that make comparisons impossible. They are slightly different because the system boundary of the study is "from cradle to grave", comprising farm production, storage, processing, packaging, retail, and household preparation, as well as transport and waste management along the supply chain.

Table 4-18: Angelina Frankowska, 2019's impact results

Impact category	***Unit***	***Value***
GWP	kg CO2 eq.	1.70E+00
HTP	kg 1,4-DB eq.	6.00E-01
FAETP	kg 1,4-DB eq.	4.10E-02
TETP	kg 1,4-DB eq.	4.20E-03
AP	kg SO_2 eq.	5.90E-03

4.3.3 *Normalization, grouping, and weighting*

Since the study's target audience are experts such as university professors, researchers, and students, normalization, grouping, and weighting were not performed. These three optional steps simplify the outcome that can be useful when the listener is not an expert in LCA studies.

4.4 **Interpretation phase**

The interpretation phase includes the identification of significant issues and the evaluation step simultaneously.

A technique for the *evaluation* is the *completeness check*. It aims to verify whether information from the phases of an LCA is sufficient to reach conclusions. Among all the substances part of the processing flow, about 1209 are not defined in the used method. To satisfy the goal and scope section, the application of other methods of analysis can be a valid option to solve these gaps.

Moreover, a significant gap could have been the absence of fresh spinach production from one of the organic fields. It is important to underline this fact because the impact of organic production is overestimated (the inputs are included in the analysis). Nevertheless, the contribution of the organic production over the total is a minimal part, accounting only for 6.4%.

In addition, bio-stimulants, *Bacillus thuringiensis*, and other fertilizers and pesticides are not present in SimaPro software, so the processes chosen are general. Unfortunately, it was not possible to find some scientific articles in the literature regarding specific LCA studies that can integrate this one, like it has been done with the digestate.

Furthermore, it has not been possible to allocate the inputs of the industrial transformation step to each process unit. If it had been possible, the study would have been more precise and complete.

It is important to remember that the Life Cycle Assessment (LCA) analysis is an iterative process, so all these gaps represent the starting point for future implementations and additions.

Another way for carrying on the study *evaluation* is the *sensitivity analysis*. It aims to evaluate how much of the results can be affected by changes. The impact is calculated many times after performing slight random variations in the process. The parameters may have varied regarding the transport step because spinach from integrated cultivation is from different Italian regions. Indeed, in SimaPro the minimum and maximum distances are reported. In addition, other variations can be due to other processes that have been recalled creating of this processing flow.

SimaPro generates a graphic image (in *figure 4-2*), and the vertical red extension of each column varies according to the amplitude of each oscillation that such variation could cause.

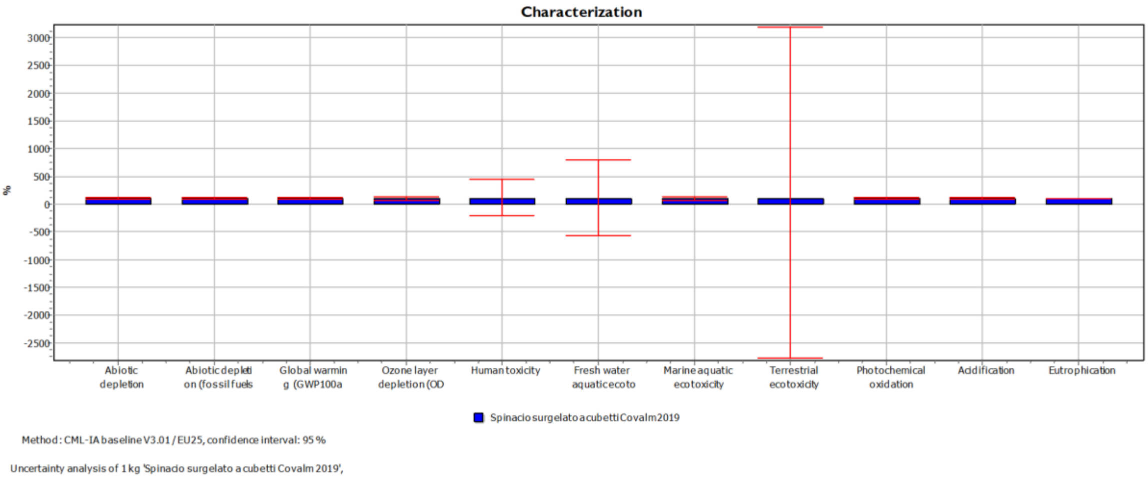

Figure 4-2: Sensitivity analysis

As it is possible to observe from the graphic above, the main variations are for the three ecotoxicity impact categories: Human Toxicity Potential, Fresh water Aquatic Ecotoxicity Potential and Terrestrial Ecotoxicity Potential. To be precise, these variations can’t derive from the transport step. An increase in ecotoxicity from fuels can be due to the particulate matter, but its influence is very low. Indeed, fuels can contribute to other impact categories, such as Global Warming Potential, Photochemical Ozone Creation Potential, Acidification Potential and Ozone layer Depletion Potential. The impact categories affected by the transport have a variation coefficient (CV) below 10 (*table 4-19*).

Table 4-19: Variation coefficients of some impact categories

Impact category	***Variation coefficient***
Human Toxicity Potential	166.14
Fresh water Aquatic Ecotoxicity Potential	363.14
Terrestrial Ecotoxicity Potential	2659.35
Global Warming Potential	8.15
Photochemical Ozone Creation Potential	11.82
Acidification Potential	5.40
Ozone layer Depletion Potential	14.43

A method for the *identification of significant issues* is the *contribution analysis*. It involves the decomposition of the result into contributing elements, expressed as a percentage of the total. It is crucial to have a precise knowledge of the data to understand the highest contributors because they can be helpful to redesign the process and prevention strategies.

The contribution analysis for each impact category is explored, establishing the cut-off at 0.5%. It means that all the elements contributing less than 0.5% have been omitted, considering them non-relevant.

4.4.1 *Abiotic Depletion Potential (ADP) elements (E)*

As it is possible to verify in the graphic (in *figure 4-3*), the most important contributors to the ADP are the emissions derived from the *pesticide* and *inorganic fertilizer productions*. They contribute to 27% and 26%, respectively. Since these chemicals are not applied in organic farming, it can be deduced that it has a lower ADP (E) value than spinach from an integrated approach. The result is in line with the forecast since the ADP (E) concerns the depletion of abiotic resources and their extraction.

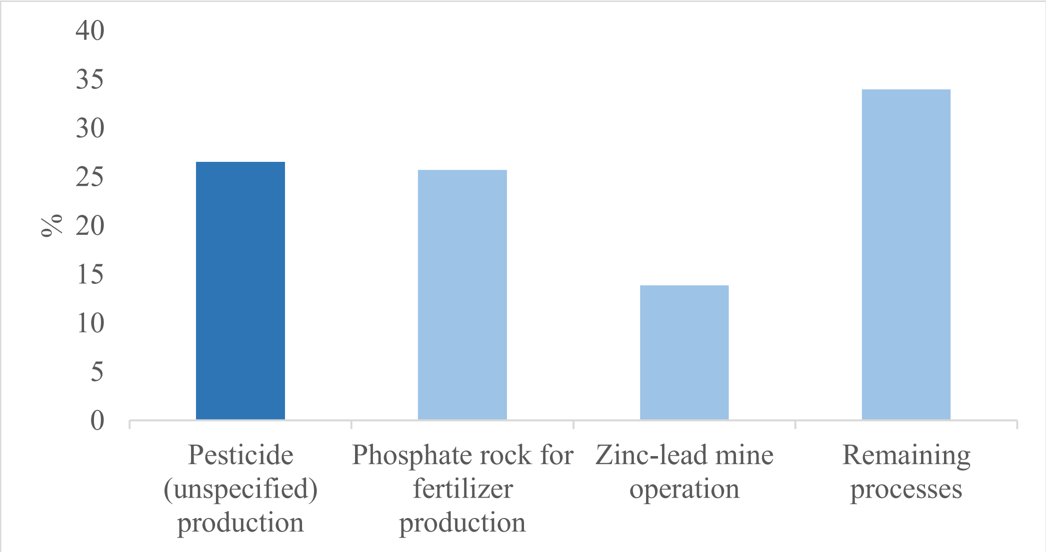

Figure 4-3: ADP (E) contribution analysis

4.4.2 *Abiotic Depletion Potential (ADP) fossil fuel (FF)*

As it is possible to guess, the main responsibility for the depletion of fossil fuel is given by the *production of natural gasses and petroleum* (precisely, the extraction, the use and the operations associated with these materials). Accurately, natural gas production contributes 44%. As it is possible to observe from the graphic in *figure 4-4*, petroleum and gas production can be accomplished through two different methods: off-shore and on-shore. The on-shore involves a drilling ring deep into the earth to reach fossil fuel, while an off-shore is a drilling ring drills underneath the seabed.

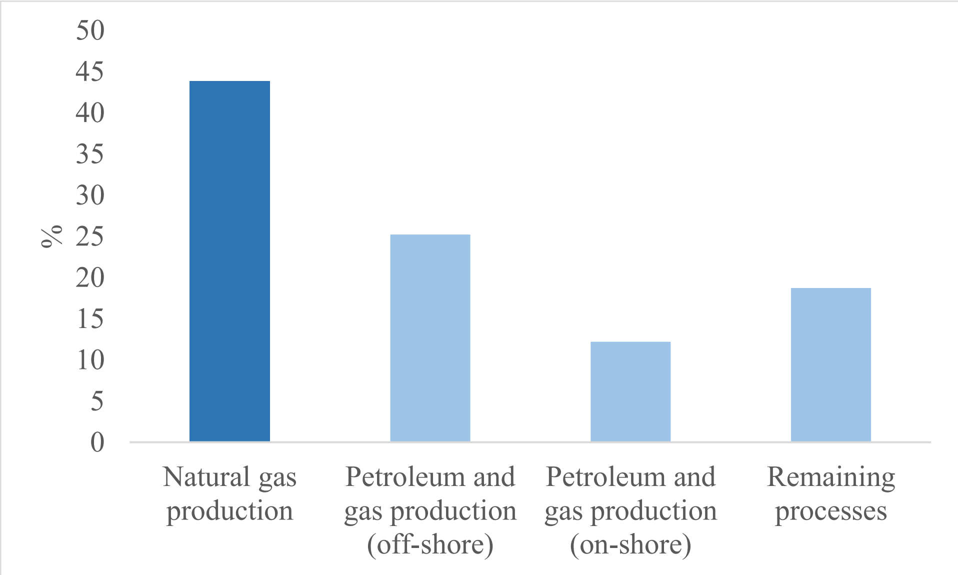

Figure 4-4: ADP (FF) contribution analysis

4.4.3 *Global Warming Potential (GWP)*

The Global Warming Potential is currently the most studied impact category. This study confirms that the *energy sector* is the one contributing the most to global greenhouse gasses emission. The electricity consumption and production contribute up to 41%, as represented in the graphic in *figure 4-5*. This result is in accordance with the United States Environmental Agency's study. In 2019, the largest sources of greenhouse gas emissions were from burning fossil fuels for electricity (25%) and transport (29%) (United States Environmental Agency, 2019). Most greenhouse gas emissions from the electricity sector are made up of carbon dioxide (CO_2). Still, smaller amounts of methane (CH_4) and nitrous oxide (N_2O) are also emitted during electricity generation, transmission, distribution, and consumption. There are many opportunities for the reduction of electricity in the industrial sector:

- Improve energy efficiency (e.g., upgrading the technology)
- Fuel switching (e.g., natural gas use)
- Recycling the materials (e.g., reuse of by-products)
- Increase awareness (e.g., staff training)

In addition to the energy sector, *emissions from integrated farming* contribute to 18% (graphic in *figure 4-5*). Management practices on agricultural soils (such as applying organic and inorganic fertilizers, and the growth of nitrogen-fixing crops) increase nitrogen availability, resulting in nitrous oxide (N_2O) emissions. To reduce the N_2O quantity in air, adjustments of the methods for managing the land and the growing crops are suggested. For example, it is fundamental to avoid over-application because it contributes to increased emissions without enhancing crop production.

The *transport* step accounts for 12% of the total impact score. As for electricity, the main greenhouse gasses are carbon dioxide (CO_2) emissions, resulting from the combustion of petroleum, and small amounts of methane (CH_4) and nitrous oxide (N_2O) caused by fuel combustion. In addition, hydrofluorocarbon (HFC) emissions are produced from the use of mobile air conditioners (HFC can also derive from refrigerated transport, but it is not included in the case study). There are some possibilities to reduce the emissions release: alternative fuel sources (e.g., biofuel), advanced transport means with better fuel efficiency, and the avoidance of the empty return (very difficult for food products because transport means are dedicated).

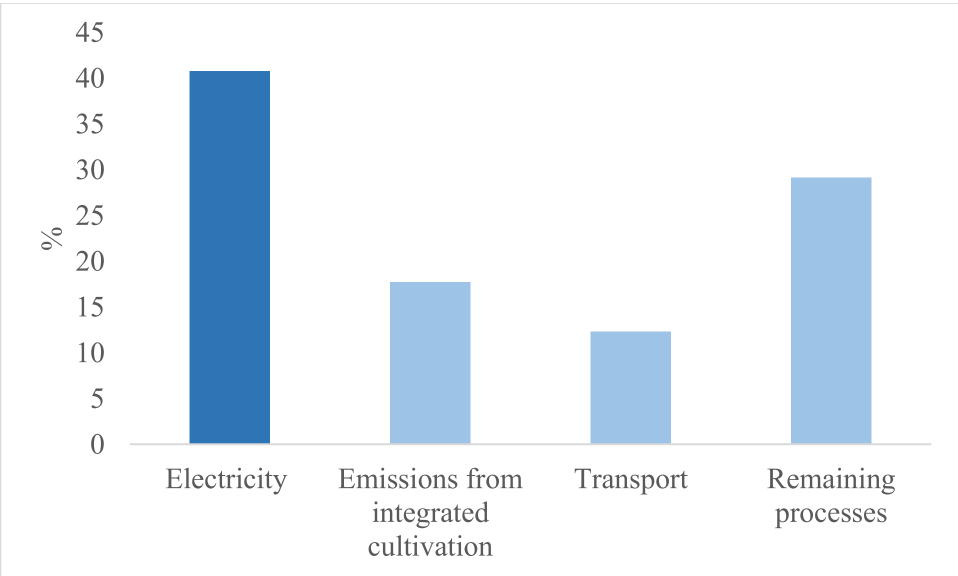

Figure 4-5: GWP contribution analysis

The contribution of each step has been explored. In the graphic (*figure 4-6*), the transformation step is in light blue; the two shades of yellow represent the integrated cultivation and its transport. The two shades of green represent the cultivation and the transportation of organic spinach.

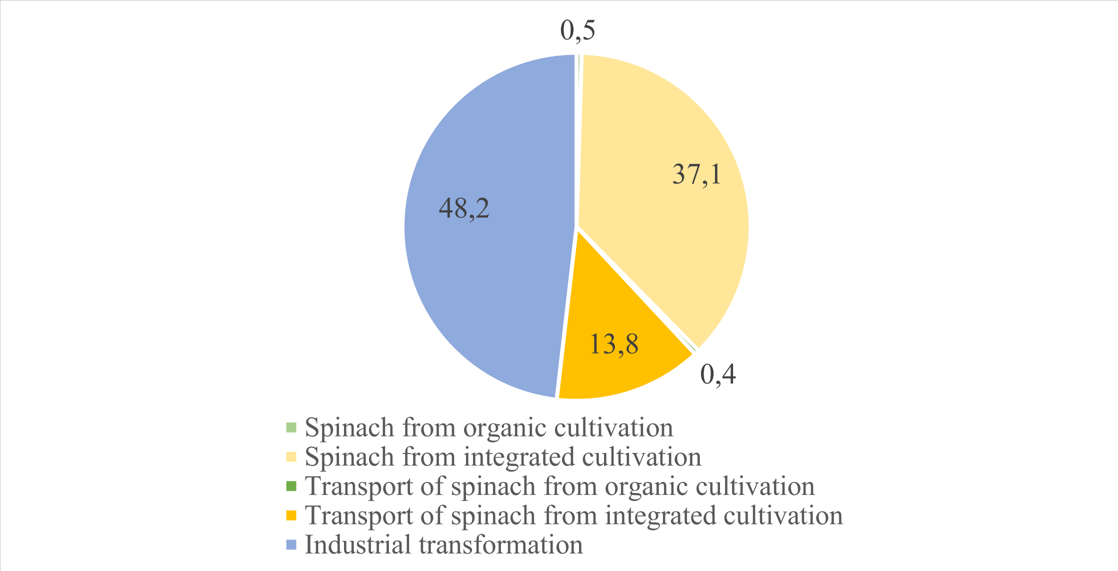

Figure 4-6: Steps contribution to GWP

As it is possible to observe from the graphic, half of the total GWP impact is due to the *industrial transformation*. As previously stated, the most considerable responsibility belongs to the enormous amount of electricity used to produce frozen spinach. Indeed, each process unit is powered by electricity. The reduction of electricity consumption is not reasonable since the company must work, but some strategies can be considered.

The most immediate example is the energy production from renewable resources because it has a lower environmental impact. There are many solutions, but the implementation of photovoltaic panels is one of the easiest. In addition, some of the components produced in the industrial line, such as heat and cold, can be reused. Cogeneration and trigeneration should be evaluated. Indeed, a cogeneration plant has been implemented in the company for production. Last but not least, the substitution of engines with more efficient ones should be considered since it is expected an efficiency reduction over the years.

Furthermore, another option for reducing the GWP impact can be the packaging reduction to minimize the energy and the emissions for its production. The company is already using a tiny amount of packaging because it mainly produces for other brands. In this case, loose frozen spinaches are placed inside large cardboard boxes with just a layer of plastic. The possibility of reducing the packaging can be taken into consideration just for the frozen spinach sold with the company's brand. Alternatively, it is plausible to find more sustainable packaging materials or increase the product quantity inside the packaging.

The GWP results about the *integrated farming* (*table 4-20*) are higher than the organic one. This outcome is mainly due to direct and indirect N_2O emissions from inorganic fertilizers, a well-known greenhouse gas.

Table 4-20: GWP results of integrated farming

Step	*Value (kgCO₂eq.)*
Spinach from organic cultivation	4.38E-03
Spinach from integrated cultivation	3.36E-01
Transport of spinach from organic cultivation	4.00E-03
Transport of spinach from integrated cultivation	1.25E-01
Industrial transformation	4.36E-01
Total	*9.06E-01*

4.4.4 *Ozone Layer Depletion Potential (ODP)*

Ozone layer depleting substances are chlorofluorocarbons (CFCs), halogens and hydrochlorofluorocarbons (HCFCs). The main responsibility to produce them is due to the *natural gas pipeline processing*, contributing to 39% (graphic in *figure 4-7*). Secondly, the *electricity consumption* contributes to 28%.

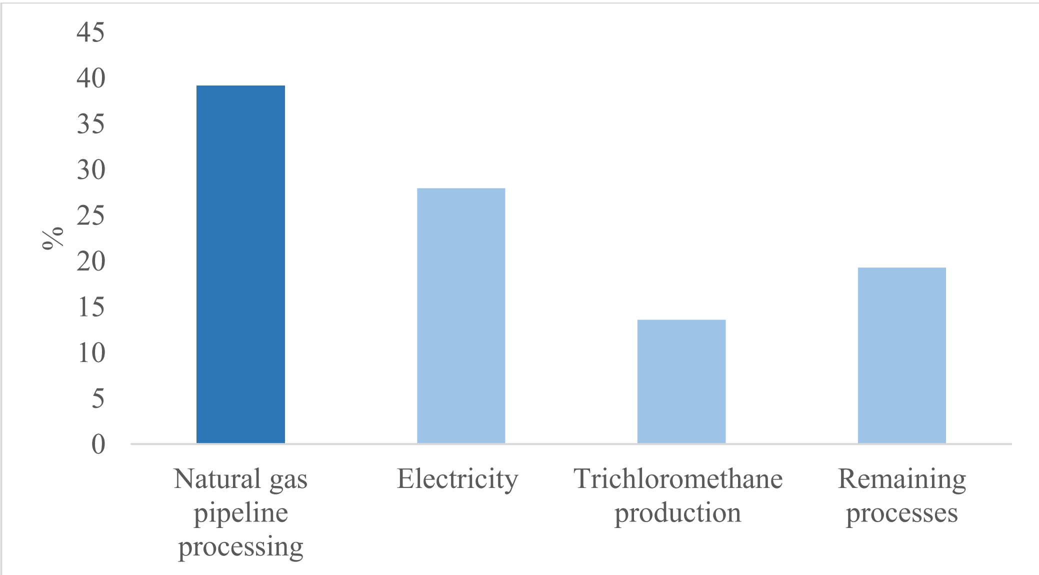

Figure 4-7: ODP contribution analysis

4.4.5 *Human Toxicity Potential (HTP)*

Toxic chemicals for human health are arsenic, sodium dichromate, and hydrogen fluoride. They can be emitted into water or air, exerting a carcinogenic effect in humans. In this study, toxic substances derive mainly from the electricity and the production of many other materials such as ore and ferrochromium. The treatment of sulfidic tailing and the electricity have a similar contribution: 17% and 16%, respectively (graphic in *figure 4-8*).

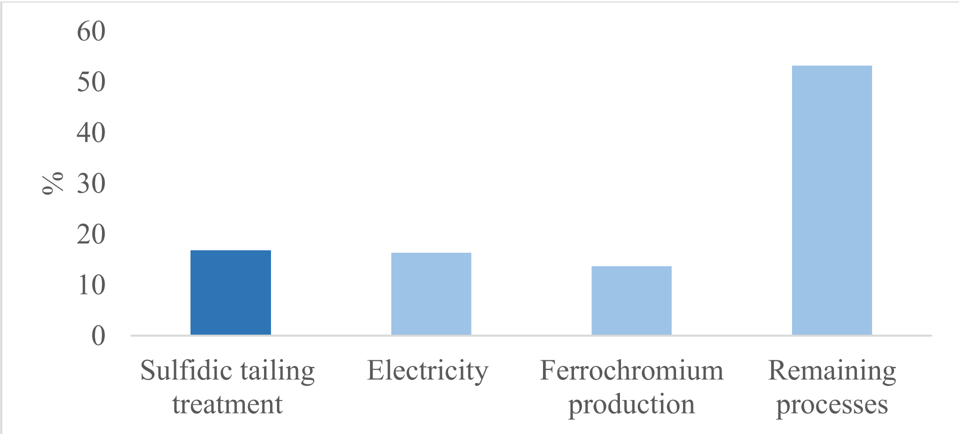

Figure 4-8: HTP contribution analysis

4.4.6 *Fresh Water Aquatic Ecotoxicity Potential (FAETP)*

The impact in freshwater is due to emissions of toxic substances, such as heavy metals, to water. This case study mainly produces these substances by ore, lignite, and coal treatments (graphic in *figure 4-9*). These three accounts for 23%, 17%, and 17%, respectively.

This situation is not confirmed in the study "Environmental impacts of vegetables consumption in the UK" (Angelina Frankowska, 2019) which evaluates the environmental impact of 1 kg of spinach consumed; using the ReCiPe method. In this research paper, the processing has a notable impact related to the energy used for freezing. Probably, this difference is due to the system boundaries because, in this case, it is "cradle to grave."

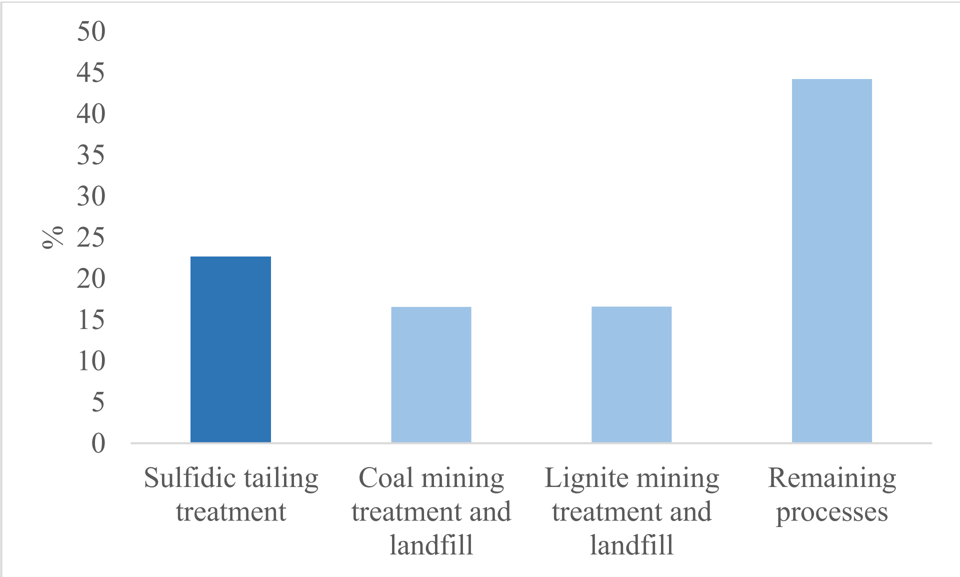

Figure 4-9: FAETP contribution analysis

4.4.7 *Marine Aquatic Ecotoxicity Potential (MAETP)*

Electricity consumption, aluminium production, and sulfidic tailing treatment are the main contributors to the ecotoxicity in the marine aquatic environment (graphic in *figure 4-10*). The most contributing one is the electricity production and consumption, counting for 48%.

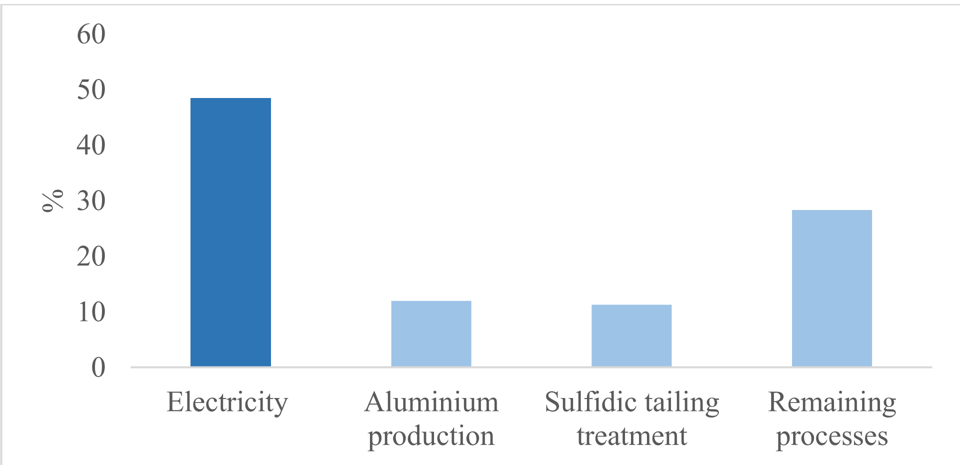

Figure 4-10: MAETP contribution analysis

4.4.8 *Terrestrial Ecotoxicity Potential (TETP)*

Pesticide emissions to agricultural soil dominates terrestrial ecotoxicity. Indeed, the primary substances contributing to its ecotoxicity derive from the production of the seeds, contributing to 89% over the total score (graphic in *figure 4-11*).

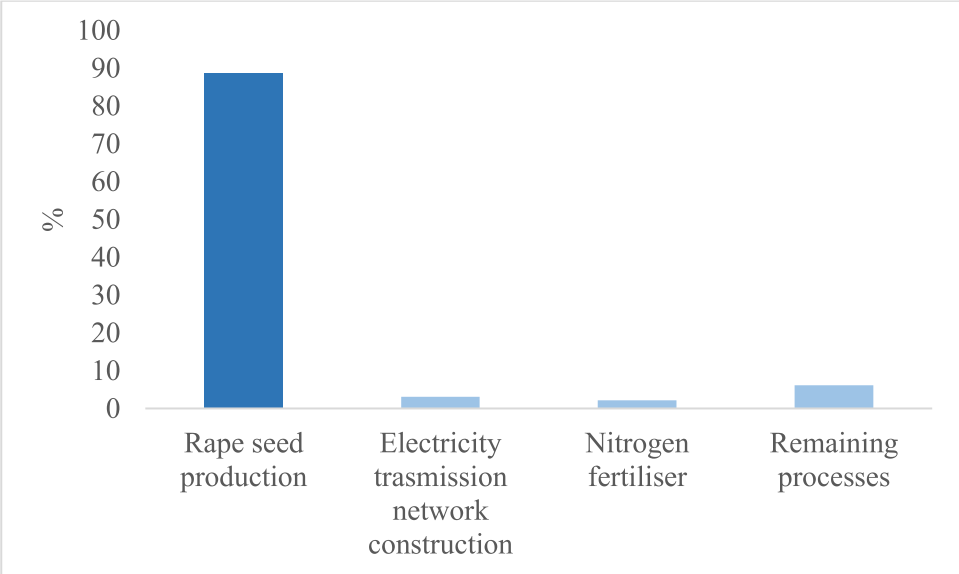

Figure 4-11: TETP contribution analysis

4.4.9 *Photochemical Ozone Creation Potential (POCP)*

Nitrogen oxide (NO), carbon monoxide (CO), sulphur dioxide (SO_2), and non-methane volatile organic compounds (NMVOC), responsible for developing ozone at the atmosphere level, are mainly produced by electricity (consumption and production) and transport. They are responsible for 46% and 14%, respectively (graphic in *figure 4-12*).

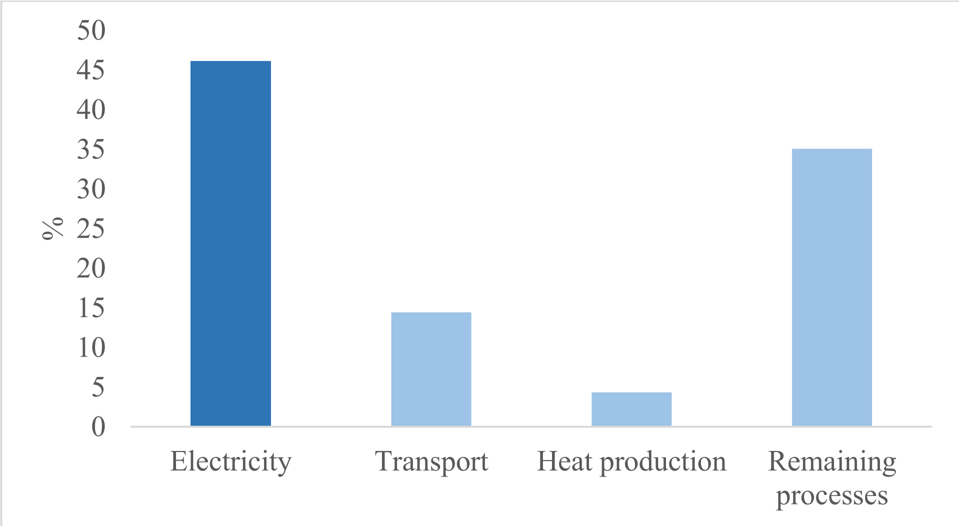

Figure 4-12: POCP contribution analysis

4.4.10 *Acidification Potential (AP)*

The acidification of soil and water is mainly due to ammonia (NH_3), nitrogen oxides (NO_x) and sulphur oxides (SO_x). In this case study, the most contributing elements are the emissions from the integrated cultivation and substances produced by the electricity consumption and production (graphic in *figure 4-13*). The emissions from the cultivation step account for more than 50%. It is reasonable to attribute a higher impact to the integrated farming than to the organic farming because fertilizers release direct and indirect emissions of ammonia and nitrogen oxide.

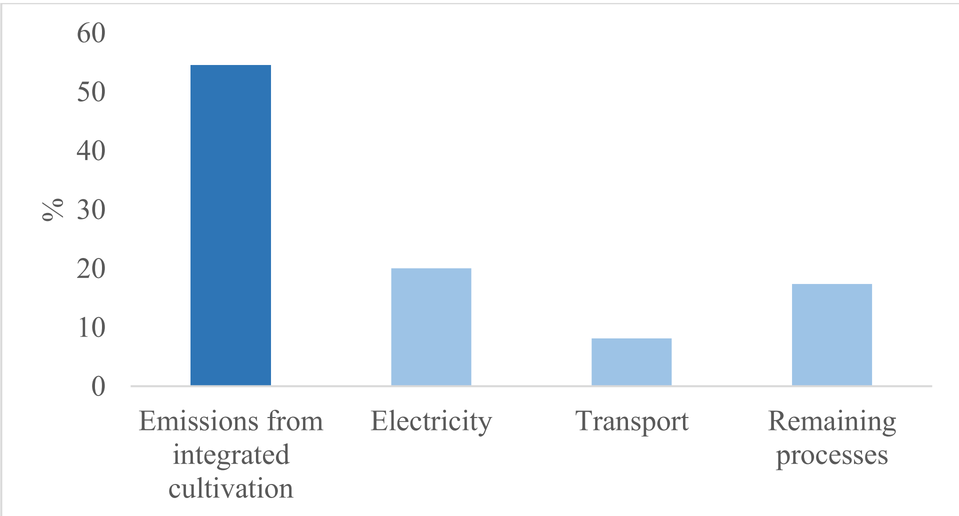

Figure 4-13: AP contribution analysis

4.4.11 *Eutrophication Potential (EP)*

As it is possible to observe in graphic in *figure 4-14*, the eutrophication is mainly due to the emissions derived from the integrated cultivation (85%). This outcome is not surprising because eutrophication is caused by ammonia, nitrates, nitrogen oxide, and phosphorous, increasing the nutrient load in soils, water, and air. Only in minimal part, electricity (2%) and fossil fuel emissions (4%) contribute to the total POCP impact.

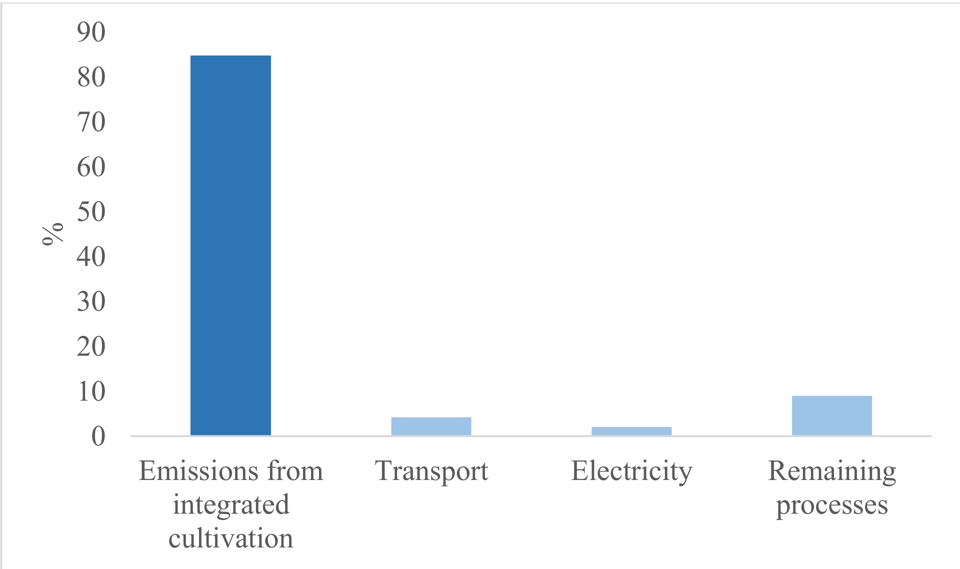

Figure 4-14: EP contribution analysis

5. MITIGATION STRATEGIES

Nowadays, the Life Cycle Assessment study is necessary to meet specific market demands. Indeed, it is possible to implement strategic and marketing communications to convey the sustainability commitment. In doing so, many certifications can be obtained, which can prove the company's behaviour and improve the company's brand reputation.

Moreover, an LCA analysis helps bring out critical situations often ignored or hidden along the food supply chain. These can be responsible for higher costs, inefficiency, and significant environmental impacts increase.

In addition to all modifications and corrections that can be made along the food production chain, such as technology advancements, agricultural management improvements and transport efficiency betterment, the wastes amount in processed vegetable products remain a lot. They are destined to discard because they can't be marketed as they are below the commercialization standard. However, these wastes can be valorised for further utilizations. For example, spinach contains many phytochemical molecules which can be recycled (Maelle Derrien, 2018).

Conventionally, spinach waste valorisation occurs through a biogas plant. By fermenting carbohydrates, proteins, and fats contained in the biomass, biogas is produced. This happens thanks to a micro-bacterial decomposition of the substrate under anaerobic conditions. The fermentation residue left over from the substrates at the end of the process can be used as fertilizer to improve soil fertility and biodiversity. Indeed, it generally contains water, nitrogen, phosphorus, potassium, sulphur, and trace elements.

These processes occur into fermenters and the substrates are shifted by agitators to avoid the formation of surface scum and sinking layers. The crude biogas from the biogas plant must reach the right natural gas quality (methane content about 50%), so it is subjected to other processing that aims to filter out carbon dioxide, hydrogen, oxygen, and sulphur. The quantity and methane content obtained from a ton of biomass may vary depending on the composition of the substrate. The higher the methane content of the end-product, the more-energy rich the biogas. Finally, the gas is dehumidified and then can be used to generate electricity and heat. Indeed, many biogas plants have combined heat and power units (CHP).

A biogas plant has many strengths. First, it is versatile because it can be powered by a wide range of raw materials. Undoubtedly, an added value is also conferred by the fact of being able to reuse residues that would otherwise be treated as wastes. In addition, it can generate many other products with an economic value:

- An endothermic engine (the so-called co-generator) converts the biogas into electric energy. This totally renewable electric energy can be sold to the electricity distribution network and used for the anaerobic digestion plant.
- If the biogas is purified into methane, it can feed the gas network or used as fuel for transports.
- Even the process leftovers can be employed again on soils, reducing the use of synthesis products, and bestowing significant environmental benefits.

Unfortunately, heat is generally not valorised.

This choice was made by ORTO Verde. The biogas plant is placed in Osimo (AN) and it comprises eight elements, covering a surface of about 300 ha:

1. Solid biomass dispenser (dimension: 60 m^3)

Figure 5-1: Biomass dispenser

2. Liquid product loading tank (dimension: 50 m^3)
3. Horizontal pre fermenter with reel agitator

Figure 5-2: Pre fermenter

4. Circular post fermenter for the methanogenesis (biogas is accumulated in domes of 2400 m^3 capacity each one)

Figure 5-3: Post fermenter

5. Tank for liquid digestate accumulation (dimension: 5 m^3)
6. Tank for solid-liquid digestate separation
7. Trenches for raw materials storage (dimension: 3700 m^2)
8. Co-generator engine

ORTO Verde's biogas plant is powered by plant biomass (e.g., corn silage), zootechnical effluents (e.g., poultry manure) and agro-industrial by-products. The final aim is the anaerobic biomass fermentation for energy production. This biogas plant has a power of 999 kW. In *table 5-1*, the plant power plan and the linked biogas production are reported.

Table 5-1: Correlation between substrates quantity and biogas production

Substrate typology	***Substrate quantity (tons/year)***	***Biogas production (m^3/year)***
Corn silage	1.60E+04	3.40E+06
Poultry manure	3.00E+03	2.70E+05
Agro-industrial by-products	2.50E+03	1.80E+05
Total	*2.15E+04*	*3.85E+06*

As previously mentioned, together with the biogas, another product is the digestate. Starting from 2.15E+04 tons/year of substrate, 1.80E+04 tons/year of digestate is produced and it is distributed on members fields from February to November.

Biogas sustainability is well known and studied. As long as part of the substrates derive from residues of other industrial productions, biogas plant construction is justified, and the electric energy production is incentivized.

Other innovative options for the waste valorisation are explored in the following paragraphs.

5.1 **Lutein extraction**

Spinach (*Spinacia oleracea*) production accounts for about 25% of wastes that can be valorized to produce value-added food products (Maelle Derrien, 2017). Spinach contains a high level of polyphenols (phenolic acid), carotenoids (lutein and zeaxanthin), chlorophyll, vitamins (A, B9, K), and minerals (Fe, Mg, Mn). Especially, it's rich in lutein containing from 3,9 to 9,5 mg/100 g fresh weight (Maelle Derrien, 2018).

An example of a circular economy can be lutein extraction from spinach wastes. Lutein can have different destinations, even the production of a functional product.

Lutein (chemical name β, ε-carotene-3,3′-diol) is a carotenoid belonging to the class of xanthophylls, and it appears yellow-orange crystalline. It is lipophilic, solid and its thermodynamically stable configuration is the all-trans (*figure 5-4*). Lutein can usually be found in flowers, grains, fruits, vegetables, bacteria, algae, and yeast. In green leafy vegetables, like spinach, carotenoids have light-harvesting capabilities so that they can be found in thylakoid membranes of the chloroplasts (Mario Ochoa Becerra, 2020).

all-trans Lutein.

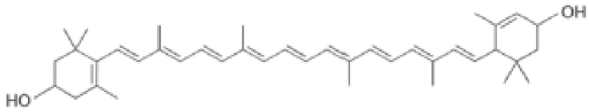

Figure 5-4: Lutein structure

The main health benefit is its *antioxidant* potential, but lutein can also *protect the eye* from UV radiations and is essential to *brain development* (Mario Ochoa Becerra, 2020). It can *prevent cardiovascular and cancer diseases* and possess *anti-inflammatory* properties (Maelle Derrien, 2018). In addition, like most carotenoids, lutein has a *pro-vitamin A* function.

For exerting these beneficial effects, the lutein recommended dose is of 6 mg/day. Even if no dietary reference intake (DRI) has been established, some trials showed that lutein could be administered even at 18 mg/day without adverse effects or toxicity (Benjamin M. Steiner, 2018).

Many *extraction methods* have been studied, and they include conventional and emerging strategies. The main four are:

- *Solvent extraction*

Among the conventional technologies, lutein can be extracted using solvents such as acetone, hexane, isopropanol, methanol, diethyl ether or a mixture of them (Mario Ochoa Becerra, 2020). Even if lutein is lipophilic, its extraction with liquid polar solvents (such as water, ethanol, ethanol-water mixture or acetone) gives a higher extraction yield than the extraction using non-polar solvents (e.g. liquid hexane and supercritical CO_2) because lutein structure includes polar functional groups (e.g. hydroxyl-, epoxy-, keto) that increase its water-miscible properties (Laura Jaime, 2014). For an efficient extraction from plant material with high moisture, acetone and ethanol are preferred (Mario Ochoa Becerra, 2020).

Natural plant molecules are predominantly extracted using solvents, but they are toxic, hazardous, require steps for their elimination, and waste disposal is a concern. Supposing the final aim is the addition of lutein in food products for human consumption, a solution can be the use of ethanol since it has been labelled "as generally recognized as safe substance" (GRAS) by the Food and Drug Administration (Food and Drug Administration, 2020).

- *Supercritical fluid extraction*

Among the emerging technologies, supercritical fluid extraction is the most employed. Supercritical carbon dioxide (SC-CO_2) is a green extraction technology used for the extraction of phytochemicals. It is a renewable source, non-flammable and non-toxic. It is possible to recover the functional components by a simple pressure drop, and CO_2 is recycled. Ethanol, added to SC-CO_2, enables modifying the supercritical fluid's polarity and allows the better release of lutein from the matrix because lutein can form a hydrogen bond with it. SC-CO_2 is a non-polar solvent, while ethanol (possessing the GRAS status) is used to enhance the extraction capacity of molecules exhibiting intermediate solubility, as in the case of lutein (Maelle Derrien, 2018)

- *Ultrasound-assisted extraction*

- *Pulsed Electric-Field extraction*

As well as the extraction methods, the lutein applications are many. Lutein can be used as a dietary supplement, food, fish, or animal feed, and in the pharmaceutical industry.

5.1.1 *Lutein as food colourant*

Lutein has a yellow-orange colour. Indeed, due to its pigmentation, the main application is to brighten the colours of poultry feathers and deepen the yellow of egg yolk, acting as a natural food colourant (Maelle Derrien, 2017). It's an approved additive E161b extracted from the plant *Tagetes erecta* (European Commission). Manufacturers and consumers are paying more and more attention to "clean labels", so replacing synthetic colorants is now a trend.

5.1.2 *Lutein-enriched functional product*

Lutein can be applied to develop functional food since it has many beneficial effects. It has been discovered that milk can be a good delivery system for lutein, so the production of lutein-enriched milk is an opportunity. Consequently, the investigation of lutein fortified dairy products is an occasion and attractive to people with micronutrient deficiencies (Mario Ochoa Becerra, 2020).

There are two ways for incorporating lutein inside an animal-based food product like milk and, in both cases, the production of lutein-enriched cheese is possible:

- Lutein can fortify dietary cattle feed

A research study (Chen-xing Liu, 2018) confirms that, after two months, the milk lutein content from lutein-fed cows is 3-fold higher than milk from cows that followed the regular diet. After cheese production, most of the lutein can be found in the final product. Only 15%-20% of lutein is lost in the whey. This positive result shows the possibility of including lutein in cheese thanks to the lutein-enriched feed (Chen-xing Liu, 2018). If the lutein-rich cheese is compared to a control cheese, no significant differences in composition, water activity, and texture have been identified.

Regarding the functional properties, there aren't substantial variations in the flowability and meltability. In contrast, the stretchability is higher in lutein-enriched cheese. The lutein content was stable during the storage, but a reduction was identified in other studies due to oxidative mechanisms. (Chen-xing Liu, 2018).

- Lutein can be added directly to milk

As an example, in the production of *Cheddar lutein-enriched cheese*, lutein is added just before hooping to retain the carotenoid (S. T. Jones, 2005). While, in the production of *Prato lutein-enriched cheese*, lutein is added together with emulsifiers because of the high amount of oil in emulsion (milk contains about 87.3% water and 3.9% lipids). According to the hydrophilic-lipophilic balance (HLB) value, the emulsifier was chosen, and polysorbate 80 determined the lowest loss of lutein in the whey (Mirian T. K. Kubo, 2013). No degradation of lutein was observed during the storage at 4.5°C for 24 weeks.

In developing a lutein-enriched functional food is essential to consider three aspects:

1. Maintaining lutein integrity

Lutein integrity is affected by *high temperatures* (above 60°C). Once lutein is exposed to high temperature, bonds are converted from trans to cis form that is thermodynamically less stable. In the presence of *atmospheric oxygen*, lutein can undergo autoxidation. Oxidation leads to the formation of low molecular weight compounds and loss of pigmentation and bioactive properties. In addition, an extreme pH (below 4 and above 8) can induce de-esterification and cis-trans isomerization of the molecule. As the last factor, *light* can cause the formation of colourless compounds of low molecular weight. Techniques such as freezing, the inclusion of antioxidants, the exclusion of oxygen in vacuum-sealed and airtight containers decrease the loss of carotenoids during processing and storage (Mario Ochoa Becerra, 2020).

2. Increasing bioaccessibility

Bioaccessibility refers to all the gastrointestinal digestion processes that led to the release of compounds from a food matrix to the gastrointestinal tract, becoming accessible for absorption. Food matrix composition, processing level, and interaction with other components influence the level of bioaccessibility. For example, in lutein-enriched cheese, lutein bioaccessibility is positively affected by the inclusion of fats in the meal because it stimulates the biliary and pancreatic secretion, which aids the absorption of lutein. The absence of high-fat content in the lutein-enriched functional product is linked to low lutein bioaccessibility (Mario Ochoa Becerra, 2020).

3. Increasing bioavailability

Bioavailability includes the fraction of the ingested component or bioactive compound that reaches the systemic circulation and is ultimately used. From the total lutein intake, a lower amount is assimilated and used for storage and metabolic functions. To observe beneficial effects, the required lutein dose is about 6 mg/day, but it is difficult to achieve in a regular human diet due to the low concentration and bioavailability of lutein in fruits and vegetables (Mario Ochoa Becerra, 2020). Because regular dietary consumption of lutein does not reach the levels associated with its benefits, it is essential to take food formulation and engineering approaches to increase the bioavailability of lutein to yield significant health benefits. Consequently, these bioactive compounds need some solutions for increasing bioavailability, inhibiting the chemical degradation, maintaining the system's physical properties, isolating other food components, and improving the absorption in the gastrointestinal tract. Among them, there are oil-in-water emulsions, nano-emulsions, microencapsulation, and liposomes (Mario Ochoa Becerra, 2020).

As all functional food, the European Food Safety Authority (EFSA) gave scientific opinions on the substantiation of health claims related to lutein and protection of DNA, proteins and lipids from oxidative damage (ID 3427), protection of the skin from UV-induced (including photo-oxidative) damage (ID 1605, 1779) and maintenance of normal vision (ID 1779, 2080) according to Article 13(1) of Regulation (EC) No 1924/2006 (European Food Safety Authority, 2011). For all these potential claims, the Panel concluded that it is impossible to declare these relationships due to lack of evidence.

To conclude, it is important to specify that lutein-enriched functional products haven't been put into practice at the industrial level yet, so it is unclear if it's worth it economically and if the consumers will accept it. Furthermore, another LCA study should be conducted to evaluate the environmental sustainability of this process, knowing that the use of solvents for the extraction should be avoided since it is not the most environmentally friendly method. Unfortunately, a study like that is not currently available in the literature.

5.2 **Implication of Hermetia illucens (Black Soldier Fly – BSF)**

Hermetia illucens, also called Black Soldier Fly (BSF), is an insect belonging to the order Diptera (family Stratiomyidae). It is native to warm temperate zones of America, but it has spread across all continents. Since it is holometabolous, its life cycle comprises four stages: eggs, larvae, pupae, and adult. Larvae are voracious, and they feed on decomposing organic materials (e.g., fruit and vegetable wastes, manure, distillers' grain, food waste, rice straw). For this reason, it is a good candidate for being implied in a circular economy approach. Several methods for BSF rearing have been developed, and the most positive aspect of industrial rearing is that BSF is a gregarious insect, so it is suited for living with many other subjects in a reduced space. Its rearing requires a temperature between 29 and 31°C, a humidity of 50-70%, oxygen supply, and a lot of food (R. Salomone, 2017).

In the context of spinach waste valorisation, a new strategy can be the utilization of them for mass-rearing of edible insects. In addition, other products such as protein for animal feed and fat-rich resources for biodiesel production can be extracted from BSF.

5.2.1 *Compost source as fertilizer*

Hermetia illucens fed with spinach wastes can have many potential utilizations. One of them is the conversion of spinach wastes to natural compost by the insect. It has been studied that BSF larvae can be fed by organic wastes (such as livestock manure and food wastes) and produce compost, composed mainly of larvae faeces, that can be comparable to commercial fertilizer. R. Salomone, 2017, estimated the conversion rate for compost production in a pilot plant. From 10 tonnes of food waste input and 300 kg of dried larvae, 3.346 kg of compost was produced.

Youngcheol Choi, 2009, found no differences in chemical amounts (e.g., Ca, Mg, K, Na, P_2O_5) between insect-derived compost and commercial one. The growth pattern of cabbage has been demonstrated to be almost identical, showing the efficacy of the compost derived by insects.

In this case, the insect-derived fertilizer was free of heavy metals, but the chemical composition of the insect compost may change according to the food waste the insect consumes. Insect-derived compost can be directly applied to agriculture boosting green technologies use (Youngcheol Choi, 2009).

An important fact is that the same insect individuals can be the source for BSF compost production, but also for other goods (e.g., biodiesel, animal feed).

5.2.2 *Lipid source for biodiesel production*

Like all insects, *Hermetia illucens* establishes metabolic reserves during the immature stages (larva, pupa, nymph) because they need them during non-feeding life cycle periods (e.g., diapause or metamorphosis). Insects possess a "fat body" structure, a nutrient and energy storage system in the spaces between organs. Fat content varies between orders and species, but also it depends on the type of food ingested by the insect. For example, BSF larvae fed with poultry manure contain 34.5% fat, but those fed with pig manure only 28.0% (F. Manzana-Agugliaro, 2012).

Hermetia illucens "fat body" has great potential in biodiesel production. Biodiesel is a mixture of mono-acyl esters of animal and vegetable fatty acids (F. Manzana-Agugliaro, 2012) that can easily substitute fuels from non-renewable sources. This system has a significant advantage because it can simultaneously degrade the organic or food wastes and produce animal biomass that can be used for biodiesel production. In addition, *Hermetia illucens* can give insect-derived compost during their rearing, being the source of two products.

The biodiesel production is done in two steps (*figure 5-5*). The acid-catalysed esterification converts free fatty acid in the crude fat into biodiesel and decreases the crude fat's acidity. The fatty acids with the greatest potential for biodiesel production are saturated fatty acids C16 (palmitic acid) and C18 (stearic acid) because they have a high calorific value and good potential viscosity. Besides, the esterification is performed by using methanol. The second step consists of mixing the crude fat and biodiesel with methanol and the catalyst NaOH. After the alkaline-catalysed transesterification reaction, the mixture forms a double layer. The upper one is biodiesel and should be separated from methanol.

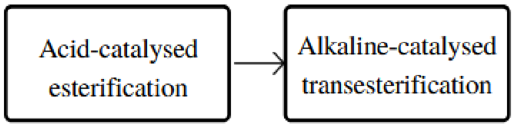

Figure 5-5: Biogas production steps

The study “Insects for biodiesel production” (F. Manzana-Agugliaro, 2012) exploits the production of biodiesel from BSL fed by manure and not food wastes. Nevertheless, to understand the biodiesel conversion, the yields of biomass, crude fat, and biodiesel for 1000 larvae grown in 1 kg of manure after 10 days at room temperature are reported in *table 5-2*.

Table 5-2: Biodiesel conversion

	Cattle manure	***Pig manure***	***Chicken manure***
Biomass (%)	127.6	207.4	327.6
Crude fat (%)	38.2	60.4	98.5
Fat yield (%)	29.9	29.1	30.1
Biodiesel (g)	35.6	57.8	91.4

It is important to compare the environmental benefits associated with biodiesel production from *Hermetia illucens* dried larvae lipids with conventional production systems.

In the study R. Salomone, 2017, the environmental impact of biodiesel production is assessed. Researchers compare the biodiesel production from rapeseed and from BSF larvae lipids. The functional unit is 1 kg of lipids, and the method used is CML 2 baseline 2000, except for Global Warming Potential (GWP), for which the IPCC 2007 GWP 100a v. 1.02 method was used. The impact categories deemed important to compare are the Global Warming Potential, the Energy Use, and the Land Use. *Table 5-3* reports the results, and they are in reference to the functional unit of 1 kg of lipids. Producing 1 kg of lipids from dried larvae, instead of rapeseed, to generate biodiesel caused an increase of 0.2 kg CO2 eq. for the GWP, and 9.8 MJ for Energy Use; and a decrease of 6.44 m^2a for Land Use impact category (R. Salomone, 2017).

Table 5-3: Comparison between rapeseed and dried larvae impacts

Impact category	*Unit*	*Value*	
		Rapeseed	*Dried larvae*
Energy Use	MJ	1.10E+01	2.08E+01
Global Warming Potential (100 years)	kg CO2 eq.	2.70E+00	2.90E+00
Land Use	m^2	6.50E+00	6.00E-02

The study highlighted that electricity is the most significant problem due to its substantial use during the drying step. Thus, reducing energy use is not feasible, but producing it through renewable sources can decrease the GWP impact category because of lower emissions. In addition, these increases can be due to the fact that for producing 1 kg of lipids, 2.86 kg of dried larvae or 1.84 kg of rapeseed is needed (R. Salomone, 2017).

A substantial reduction in LU was expected because *Hermetia illucens* is gregarious, so a large number of larvae can be reared in small spaces. It has been suggested that BSF density is 2.5 larvae per cm^2 of surface area (Tomberlin JK, 2002).

5.2.3 *Protein and lipid sources for animal feed*

Once *Hermetia illucens* is fed by spinach wastes, it can be an alternative, or it can be used as a complete replacement for animal feed. BSF can be included in the diet in several ways: as meal, powder, oil, dried etc.

BSF larvae have already been formulated as a component of complete diets for poultry, swine, and for several commercial fish species. In addition, BSF meal and oil are already considered an animal-grade alternative to fish meal and fish oil used to feed carnivorous fish and in other animal diets, due to their high protein and lipid contents even when fed plant-based waste streams (Shelomi, 2017).

When a lipid-enriched diet feeds BSF, it can accumulate lipids in the body that are more palatable than vegetable oils to fish. Indeed, fat-enriched pre-pupa are suitable fish feed, and there aren’t modifications in fish growth rate and vision development. Moreover, *Hermetia illucens* larvae can act as a feed replacement for maize or soy-based poultry feeds. No differences have been found in comparison to the control for the productive performances, the breast meat weight, the yield, the flavour perceptions, oxidative status, and cholesterol composition. However, insect supplementation increases the level of less desirable saturated and monounsaturated fatty acids (Shelomi, 2017).

Reptiles can be fed with dried BSF larvae. It has been demonstrated that reptiles can survive, even if they will reach smaller dimensions. This smaller size is due to the low palatability of *Hermetia illucens* to reptiles, so it is recommended to be used as a partial alternative (Shelomi, 2017).

BSF larvae use as feedstuff for ruminants is less successful because of the high chitin and fat content, which has a negative effect on fermentation and digestibility (Leah W. Bessa, 2020).

Even if specific studies regarding the correlation between insect nutritional profile and BSF spinach feed should be assessed, many articles exploit these relations. In other words, the BSF protein and fat composition depend on what the insect consumes. In *table 5-4*, there is the specific percentage of fats and proteins contained in black soldier flies fed by vegetables. Luckily, a study comparing different diets found out that different vegetable wastes do not significantly affect the resulting BSF meal's fatty acid profiles (Shelomi, 2017).

Table 5-4: Lipid and protein BSF profile

Diet	*% Fats*	*% Proteins*
Vegetable wastes	37.1	39.9
Restaurant wastes (vegan)	38.6	43.1

The environmental impact caused by the production of dried larvae, used as a protein source for feed, should be assessed.

In the study "Environmental impact of food waste bioconversion by insects: Application of Life Cycle Assesment to process using Hermetia Illucens" (R. Salomone, 2017), researchers compare the protein source from BSF larvae with the production of soybean flour, which is one of the primary sources of proteins for fishmeal formulations. The LCA analysis considers 1 kg of proteins as the functional unit; and the method used is CML 2 baseline 2000, except for Global Warming Potential (GWP), for which the IPCC 2007 GWP 100a v. 1.02 method was used. *Table 5-5* reports results for the Global Warming Potential, the Energy Use, and the Land Use impact categories. Producing 1 kg of proteins from dried larvae instead of soybean meal caused an increase in Global Warming Potential (0.4 kg CO2 eq.) and Energy Use (11 MJ). However, a decrease in Land Use (8.65 m^2) has been observed (R. Salomone, 2017).

Table 5-5: Comparison between soybean flour and dried larvae impacts

Impact category	*Unit*	*Value*	
		Soybean flour	***Dried larvae***
Energy Use	MJ	4.10E+00	1.51E+01
Global Warming Potential (100 years)	kg CO2 eq.	1.70E+00	2.10E+00
Land Use	m^2	8.70E+00	5.00E-02

As for lipid extraction, electricity is the most significant problem, mainly due to the drying step. A mitigation strategy for EU and GWP can be the use of renewable energy. The land use reduction is due to the gregarious characteristics of the BSF.

As opposed to the lipids, 1 kg of proteins are produced by similar amounts of soybean flour and dried larvae. 2.08 kg of dried larvae or 2.17 kg of soybean flour is needed to get 1 kg of proteins.

5.2.4 *Protein and lipid sources for human consumption*

Animal feed is not the only option; black soldier fly is also investigated for human consumption. *Hermetia illucens* was one of the 2000 insect species already consumed by humans many years ago, but it is not common anymore. Mainly, it is due to the wide range of substrates BSF can grow. The idea of eating an insect that feeds on wastes is simply unpleasant. However, it can convert wastes into quality proteins, fats, and minerals.

BSF larvae's ability to recycle wastes is an advantage over other insect species but it is also a big obstacle and safety risk factor for humans. Insects are subjected to microbial (e.g., *Salmonella enteritidis*, *Enterococcus coli*, *Enterobacteriaceae*, *Clostridium botulinum*) or chemical (e.g., heavy metal accumulation) contamination. Processing them by powdering, heating, drying, UV treating, high-energy microwaving, pasteurizing, acidifying, or otherwise treating the meal against microbes, parasites, and bacterial spores would reduce the chance of microbial contamination relative to the whole, unprocessed insects (Shelomi, 2017).

The EU safety regulations report microbial limits for meat and seafood, but they do not specify the relevant microorganisms to insects, so further investigations should be considered.

In addition, in 2015, the European Food Safety Authority gave a scientific opinion (EFSA, 2015) regarding the production and consumption of insects as food and feed. It suggests the use of cleaner waste streams (such as spent grains and pre-consumer vegetable matter) to produce BSF larvae for human consumption. Thus, this EFSA statement permits BSF larvae to be fed by spinach wastes because their rearing in a controlled farming environment reduces potential risks.

Moreover, cross-reacting allergens from BSF larvae to consumers is a matter of concern. Together with crustaceans, *Hermetia illucens* larvae contain tropomyosin and arginine kinase pan allergens (Leah W. Bessa, 2020). In addition, there is also the risk of encountering novel allergens.

Regarding the nutritional aspects, the macro- and micronutrients found in BSF larvae are ideal for humans (Leah W. Bessa, 2020). In *table 5-6*, nutrient contents are reported; they are ranges of value because the composition changes during the larval stage. Compared to other edible insects (mealworms and cricket) and other nutrients sources (beef and chicken), *Hermetia illucens* larvae can be considered a good food ingredient. However, the most abundant fatty acids are saturated; the greatest is the lauric acid (C12:0) (Leah W. Bessa, 2020).

Table 5-6: BSF macro- and micronutrients content

Nutrients	***Content***
Proteins	30-53 g / 100 g dry matter (DM)
Isoleucine	40-41 g / 100 g DM
Leucine	61-75 g / 100 g DM
Lysine	54-65 g / 100 g DM
Methionine + Cysteine	14-47 g / 100 g DM
Phenylalanine + Tyrosine	31-110 g / 100 g DM
Threonine	36-42 g / 100 g DM
Tryptophan	6 g / 100 g DM
Lipids	20-41 g / 100 g DM
Chitin	2-9 g / 100 g DM
Iron	2.1-3 mg / 100 g DM
Zinc	6.8-15 mg / 100 g DM
Calcium	840-934 mg / 100 g DM

The problems for black soldier fly larvae as edible insects are the same as all insects: *cultural and sensorial barriers* are the two main challenges.

To increase consumer acceptability, *Hermetia illucens* larvae can be employed as functional ingredients in food applications. Many studies should be carried on optimizing the yield of each component (protein, fat, chitin) while maintaining their integrity and functionality.

For example, BSF larvae have been investigated as a potential butter or margarine substitution. Using 75% of BSF larvae lipids inclusion as a butter replacement has been discovered to have similar functionalities to butter. Moreover, it does not affect the sponginess and crumbliness of cakes made of BSF larvae butter (Leah W. Bessa, 2020).

Other possibilities are the extraction of chitin and chitosan because they have emulsion capabilities and antimicrobial properties (no studies have been conducted on BSF) and the insect use as a protein alternative.

Many Eastern countries are familiar with eating insects. Probably, with the global push for sustainable and healthy foods, also Western consumers are beginning to accept insects as a food source slowly.

5.2.5 *Legislative context of BSF*

Regarding insects as feed, *Hermetia illucens* fulfils the requirements for insect farming and pet animal feed established by the Regulation (EU) 2017/893 (European Commission, 2017), which lists the species currently reared in the European Union. The features that include BSF in this list are that:

- it is not pathogenic;
- it does not have adverse effects on plants and animals;
- it is not a vector of human, animal, or plant pathogens;
- it is not protected and is defined as invasive alien species.

Additionally, the regulation indicates that BSF should be fed by non-animal products or a limited set of them.

The legislative framework is still in its infancy regarding insects as food, even because the European Union has very stringent rules regarding food safety. Recently, edible insects have been included in "novel food" rules, following the Regulation (EU) 2283/2015 (European Parliament, 2015). Currently, *Hermetia illucens* larvae are not considered on the list of accepted edible insects in the novel food regulation.

If in the European Union BSF can only be reared or destined for animal feed, insects are sold for human consumption in the United States of America. However, the Food and Drug Administration (FDA) has not explicitly accepted insects as food; in fact, no specific regulations govern the edible insect market. Insects are considered food if they are produced to be used as food, so the requirements are the same as all the other foodstuffs, and they should be produced according to good manufacturing practices and safety obligations (Leah W. Bessa, 2020).

Nevertheless, until the international body Codex Alimentarius changes the appellation of "impurities" to insects, many barriers should be overcome to becoming a legally well-accepted foodstuff (Shelomi, 2017).

5.3 Comparison between the two waste disposals

After listing several possibilities to derive maximum benefit from spinach wastes, it is essential to consider whether they are worthwhile in terms of environmental impact. In this section, a comparison between conventional and innovative waste disposal systems is carried out.

Generally, vegetable wastes are subjected to anaerobic digestion into a biogas plant. Wastes are transformed into digestate and biogas (mainly methane and carbon dioxide) by microorganisms. Digestate can be applied again on the soils as a fertilizer, while the biogas can be used as a fuel. However, as previously explored, it is also possible to create a circular system where *Hermetia illucens* larvae are fed by vegetable wastes to produce compost, biodiesel and/or animal feed.

In the study "Environmental impact of food waste bioconversion by insects: Application of Life Cycle Assesment to process using *Hermetia Illucens*" (R. Salomone, 2017), researchers developed an LCA including in the system boundaries the food wastes transport, the larvae production, the substratum production (produced from food wastes), compost and dried larvae production. The functional unit is 1 ton of biodigested food waste, and the method used is CML 2 baseline 2000, except for Global Warming Potential (GWP), for which the IPCC 2007 GWP 100a v. 1.02 method was used.

In *table 5-7*, the LCA results are reported, and they represent two different scenarios. The "avoided production" situation includes environmental credits associated with the avoided production of conventional feed and fertilizer. Since this process allows the substitution of conventional ways of providing raw materials for feed and fertilizers, the product system is credited for these forms of avoided material production.

Table 5-7: Impacts of the two scenarios

Impact category	***Unit***	***Value***	
		Without avoided products	***With avoided products***
Abiotic depletion	kg Sb eq.	9.10E-02	-1.17E+00
Acidification	kg SO2 eq.	5.80E-02	-1.26E+00
Eutrophication	kg PO_4^{3-} eq.	1.40E-02	3.60E-02
Global Warming Potential (100 years)	kg CO2 eq.	3.02E+01	-4.32E+02
Ozone Layer Depletion	kg 1,4-DB eq.	1.40E-06	-2.30E-06
Human Toxicity	kg 1,4-DB eq.	3.10E+00	-1.38E+00
Fresh Water Aquatic Ecotoxicity	kg 1,4-DB eq.	1.53E+00	-9.10E-01
Marine Aquatic Ecotoxicity	kg 1,4-DB eq.	3.60E+03	1.74E+00
Terrestrial Ecotoxicity	kg 1,4-DB eq.	4.30E-02	-2.80E-02
Photochemical Oxidation	Kg C_2H^4 eq.	2.40E-03	-2.10E-02

As it is possible to observe from the table above, in the column "with avoided products" results, there is a significant negative contribution to impacts for almost all the impact categories. The highest benefits are connected to the GWP. Thus, these results, including the avoided productions, indicate that the *Hermetia Illucens* system reduces the environmental impacts compared to the conventional production of N fertilizer.

Conversely, the impacts of 1 ton of biowaste subjected to anaerobic digestion are reported in *table 5-8*.

Table 5-8: Impacts of 1 ton of biowaste subjected to anaerobic digestion

Impact category	***Unit***	***Value***
Abiotic depletion (E)	kg Sb eq.	3.56E-04
Abiotic depletion (FF)	MJ	3.04E+03
Acidification	kg SO2 eq.	2.04E+00
Eutrophication	kg PO_4^{3-} eq.	1.08E+00
Global Warming Potential (100 years)	kg CO2 eq.	4.30E+02
Ozone Layer Depletion	kg 1,4-DB eq.	1.03E-05
Human Toxicity	kg 1,4-DB eq.	7.36E+01
Fresh Water Aquatic Ecotoxicity	kg 1,4-DB eq.	9.15E+01
Marine Aquatic Ecotoxicity	kg 1,4-DB eq.	2.06E+05
Terrestrial Ecotoxicity	kg 1,4-DB eq.	1.79E+00
Photochemical Oxidation	Kg C_2H^4 eq.	3.09E-01

The amount of spinach wastes obtained for the production of frozen packaged spinach is 1312.04 tons. *Table 5-9* shows the comparison of the two ways of waste management: spinach wastes destined to biogas plant and used as *Hermetia Illucens* feed. To calculate the impact of the waste disposal through BSF, the “without avoided products” scenario has been used because it is considered the worse of the two.

Table 5-9: Comparison between two waste managements

Impact category	***Unit***	***Value***	
		Biogas	***BSF***
Abiotic depletion (E)	kg Sb eq.	4.67E-01	1.19E+02
Acidification	kg SO2 eq.	2.68E+03	7.61E+01
Eutrophication	kg PO_4^{3-} eq.	1.42E+03	1.84E+01
Global Warming Potential (100 years)	kg CO2 eq.	5.64E+05	3.96E+04
Ozone Layer Depletion	kg 1,4-DB eq.	1.35E-02	1.84E-03
Human Toxicity	kg 1,4-DB eq.	9.66E+04	4.07E+03
Fresh Water Aquatic Ecotoxicity	kg 1,4-DB eq.	1.20E+05	2.01E+03
Marine Aquatic Ecotoxicity	kg 1,4-DB eq.	2.70E+08	4.72E+06
Terrestrial Ecotoxicity	kg 1,4-DB eq.	2.35E+03	5.64E+01
Photochemical Oxidation	Kg C_2H^4 eq.	4.05E+02	3.15E+00

From the reasonings and calculations made, the results show that the impact is lower when the waste disposal follows the *Hermetia Illucens* system. This is valid for all impact categories; the only exception is for abiotic depletion (E).

Thus, according to these calculations, the creation of a BSF system can be a valid option for replacing the common anaerobic digestion in biogas plants, reducing the environmental impacts for almost all the impact categories. It is just a starting point; further studies should confirm this outcome.

6. CONCLUSIONS

The final aim of this LCA study is to evaluate the environmental impact associated with the production of 1 kg of frozen spinach (including the integrated/organic cultivation, transportation, processing, and packaging) and find mitigation strategies for reducing the impact.

Although there are not many similar studies, it is possible to understand the added value that the study embodies. This analysis can be considered representative of frozen spinach derived by integrated farming, due to the company's extensive pool of primary data provided. Instead, further LCA studies should be carried out to improve the results consistency of frozen spinach production from organic farming.

The impact category of greatest current media and political interest is the GWP; and the frozen spinach production generates 9.06E-01 kg CO_2 eq. The step that most influences this result is the industrial transformation, followed by the integrated farming approach.

The imminent need to reduce emissions globally is emphasized by the decisions also taken at the European level with the Green Deal approval. The key concepts of this initiative are: reduce, reuse and recycle of products and materials. The practical implementation of these pillars in the food sector can be included in a closed economic system, also known as "circular economy", which aims to reduce wastes and losses.

Regarding the case study, the wastes reduction depends mainly on the cultivation step, where the balance between good quality product, small chemicals use, and high yield should be obtained. At the industrial level, wastes reuse and recycling can be performed to get a more sustainable supply chain. Among the suggested options, lutein, a high-value phytochemical, can also be extracted from spinach wastes. Lutein can be reused as a food colourant or be part of a functional product due to the many health benefits it confers. In addition, spinach wastes can be used to feed insects, such as *Hermetia illucens.* Subsequently, insect faeces, proteins and lipids can be the raw materials for generating other products, such as compost and biodiesel. Other LCA studies will need to assess to verify the effective impact reduction.

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8. ACKNOWLEDGEMENT

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