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Life Cycle Assessment (LCA): Environmental impacts of wine production in a company in the *Vinho Verde* Region in Portugal

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I am immensely grateful…

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"For those who have strong thinking,

the impossible is just a matter of opinion."

Charlie Brown Jr.

ABSTRACT

Wine is a beverage made from grape juice or just grapes, and is one of the oldest biotechnological processes, with a history of over 8000 years. In recent times, besides the efforts to improve the quality of the product, there has been a huge concern regarding the improvement in sustainability due to the growing recognition of the importance of this matter by the industry. In this context, the study aimed to assess the environmental impacts associated with the production of Vinho Verde, located in the Minho region, using a life cycle analysis (LCA) approach and sensitivity analysis, and thus identify a set of associated environmental impacts. The methodology adopted was based on the ISO 14044 (2006) for LCA, being performed using the GaBi software and the CML database and considering as impact categories the Abiotic Depletion Potential (ADP), Acidification Potential (AP), Eutrophication Potential (EP) and Global Warming Potential (GWP). The winemaking and bottling stages were considered, as well as upstream and downstream stages such as energy production, diesel production, product transportation, and others. The results were expressed in the functional unit of 0.75 L of wine. Thus, it was identified that the biggest contributor in the categories of impact for winemaking was the alcoholic fermentation process with 1.43E-08 kg Sb eq. in ADP, 2.76E-05 kg SO_2 eq. in AP, 6.29E-05 kg PO_4 eq. in EP and 2.56E-02 kg CO_2 eq. in GWP. In bottling, in addition to the other contributors that previous studies pointed out, the technical stopper used stood out. Among the 3 products analysed, glass bottle, PET bottle and bag-in-box (BIB), BIB proved to be the most environmentally viable packaging, with 1.37E-08 kg Sb eq. in ADP, 1.10E-04 kg SO_2 eq. in AP, 8.74E-05 kg PO_4 eq. in EP and 2.07E-01 in GWP 2.56E-02 kg CO_2 eq. Finally, the weight of glass bottles was the parameter most sensitive to variations between those established, indicating great influence on the environmental impact categories evaluated.

Keywords: Life Cycle Inventory; Life Cycle Analysis; Environmental Impacts; Vinho Verde; GaBi software.

RESUMO

O vinho é uma bebida feita do sumo da uva ou apenas da uva, sendo um dos processos biotecnológicos mais antigos, com uma história de mais de 8000 anos. Nos últimos tempos, além dos esforços para melhorar a qualidade do produto, tem havido uma maior preocupação relativamente a melhoria na sustentabilidade decorrente do crescente reconhecimento da importância desta temática por parte da indústria. Neste contexto o estudo teve por objetivo avaliar os impactes ambientais associados à produção do vinho verde, localizada na região do Minho, usando uma abordagem de análise do ciclo de vida (ACV) e análise de sensibilidade, e assim identificar um conjunto de impactes ambientais associados. A metodologia adotada teve por base a ISO 14044 (2006) para ACV, sendo utilizado o software GaBi e a base de dados CML, considerando como categorias de impacto o Potencial de Depleção Abiótica (ADP), Potencial de Acidificação (AP), Potencial de Eutrofização (EP) e Potencial de Aquecimento. Foram considerados os estágios de vinificação e engarrafamento e ainda as etapas a montante e jusante como: produção de energia, produção de diesel, transporte de produtos e outros. Os resultados foram expressos na unidade funcional de 0,75 L de vinho. Dessa forma, identificou-se que o maior contribuinte nas categorias de impacte para a vinificação foi o processo de fermentação alcoólica com 1,43E-08 kg Sb eq. em ADP, 2,76E-05 kg SO_2 eq. em AP, 6,29E-05 kg PO_4 eq. em EP e 2,56E-02 kg CO_2 eq. em GWP. No engarrafamento destacou-se, para além daqueles de outros contribuintes que estudos prévios apontaram, a rolha técnica utilizada. Dentre os 3 produtos analisados, garrafa de vidro, garrafa PET e bag-in-box (BIB), a BIB mostrou-se a embalagem mais viável, com 1,37E-08 kg Sb eq. em ADP, 1,10E-04 kg SO_2 eq. em AP, 8,74E-05 kg PO_4 eq. em EP e 2,07E-01 em GWP 2,56E-02 kg CO_2 eq. Por fim, o peso das garrafas de vidro foi o parâmetro que mostrou-se mais sensível a variações dentre os que foram analisados, indicando grande influência do mesmo sob as categorias de impacte ambiental avaliadas.

Palavras-chave: Inventário de Ciclo de Vida; Análise de Ciclo de Vida; Impactes Ambientais; Vinho Verde; GaBi software;

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LIST OF ABBREVIATIONS

AD	Abiotic Depletion
AP	Acidification Potential
BIB	Bag-in-Box
CML	*Centrum voor Milieuwetenschappen Leiden*
EP	Eutrophication Potential
FU	Functional Unit
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
kha	thousands of hectares
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MHl	millions of hectoliters
NMVOCs	non-methane volatile organic compounds
NOx	Nitrogen oxides
PET	Polyethylene terephthalate
PM2.5	Fine particulate or particulate matter 2.5
OIV	International Organization of Vine and Wine

1. INTRODUCTION

In a competitive international scenario, new markets and new wine-producing countries are emerging. However, Europe remains the largest market for consumption, production, and export of wine. In the European Union is estimated that wine's production in 2020 was 165 Mhl, which represents an increase of 8% (+12 Mhl) compared to 2019 (OIV, 2020b).

According to International Organisation of Vine and Wine (OIV) (2020b), Portugal is in the 11th place in the ranking of the wine production sector. Its annual production in the last 5 years was 6 Mhl (2016), 6.7 Mhl (2017), 6.1 Mhl (2018), 6.5 Mhl (2019) and 6.4 Mhl (2020), with about 194 kha of vineyard surface area in the last year, representing 2.7% of all acreage in the world.

Wine is defined as a beverage made from grape juice or just grape, one of the oldest biotechnological processes globally, with a history of more than 8000 years. From another point of view, the liquid can be classified as a multicomponent solution containing water, ethanol, glycerol, and organic acids as the main constituents, plus the presence of flavours, aroma, and phenolic compounds, depending on the conditions of the winemaking (Pizarro et al., 2007).

Following Maicas & Mateo (2020), the wine process generates several residues characterized by high contents of suspended solids and biodegradable compounds. Despite being considered an environmentally friendly process, it generates between 1.3 kg and 1.5 kg of waste per liters of produced wine, of which 75% is wastewater. Other major residues generated are the organic wastes: grape stems, grape leaves, and grape pomace with seeds, pulp, and skins; inorganic wastes: perlite, bentonite clay, and diatomaceous earth; emission of greenhouse gases: volatile organic compounds, carbon dioxide (CO_2).

The environmental impact assessments of this area have been published in studies principally from 2013 onward. An important aspect is the geographical location of the studies since about 73% of them focused on the evaluation of Italian (61%) and Spanish (12%) wine-production systems, and the remaining 27% of these studies in other parts of the world (Ferrara & Feo, 2018).

Life cycle assessment is used to evaluate environmental impacts with various purposes. It can be applied to identify impacts of the life cycle stages or to improve processes and their environmental aspects. One of its main purposes functions is to compare products that perform the same function and consider each product or process under analysis linked to external factors with which it interacts. This type of analysis contributes to the decision-making or strategic planning in industry, government, or organizations and it can help to select environmental performance indicators and identify the most significant impacts generated (Clark, 2018).

Software were developed to facilitate mass and energy balance calculations, perform comparisons between product life cycles, analyse the flow of materials and energy, and, mainly, perform analysis of environmental impacts and interpretation of results (Campolina et al., 2015). One of these softwares is called GaBi and it is a tool capable of modelling product life cycles and their respective environmental impacts, providing alternatives for improving manufacturing, distribution, recyclability, and sustainability processes (Thinkstep, 2019).

Given the above, this work intends to evaluate the environmental performance of wine production in a winery in north-western Portugal through Life Cycle Assessment (LCA), established by ISO 14040 and 14044 of 2006. Therewith, the specific objectives are to identify the wine production processes that cause the most significant environmental impact according to the selected assessment categories, considering different products, using the GaBi software for this purpose; and to perform a sensitivity analysis considering the changes in the defined parameters, to verify how much it influences the impact categories results.

1.1. REPORT OUTLINE

This MSc thesis is divided into five chapters, including the present one, where the importance of carrying out a wine life cycle analysis, the main objectives to be achieved and the proposed organization to present and discuss the study developed are presented.

Chapter 2 addresses general aspects of wine production and the impacts caused by it, the Life Cycle Assessment proposed by ISO 14040 and 14044 and the analyses applied to the study sector.

The 3rd chapter describes the functional unit, the system boundary, the software used, the inventory data, the application of the methodology was applied, as well as the flowcharts produced for this study are described. In chapter 4, balance results and impact categories are presented and discussed.

Finally, chapter 5 presents the main conclusions of this thesis. Additionally, some improvement actions and suggestions for future work are indicated in order to improve and complete the analysis developed.

2. STATE OF THE ART

2.1. WINE SECTOR

2.1.1. World-Scale Wine Industry

New markets and new wine-producing countries have emerged in the competitive international scenario. However, Europe remains the biggest market for the production, consumption, and export of wine. In fact, the biggest competitors in the world are Europeans: highlighting Italy, Spain, and France, with their centuries-old wine-growing tradition, continuing to be a reference for world winemaking (Lombardi et al., 2016).

The European wine sector is very dynamic and diversified because it is constantly evolving. Within the Union European (UE), this sector uses 3.4 million hectares and encompasses 1.7 million de wine producers, producing 6% of the net agricultural production. It constitutes the first world stance with 60% production, 45% vineyard crops, and about 60% wine consumption. According to Aranda et al. (2005), although the wine is made sustainably, ensuring minimal environmental impact, changes arising from globalization increase its costs.

In accordance with 2020 data, the EU’s wine production is estimated at 165 Mhl, where Italy (49.1 Mhl), France (46.6 Mhl) and Spain (40.7 Mhl) account for 53% of the world's wine production, with a significant increase comparing with 2019. Production increases in the three abovementioned countries by 1.5 Mhl (+3%), 4.4 Mhl (+11%) and 7.0 Mhl (+21%) respectively. However, while Italy’s average remained within the last five years, for France and Spain the discrepancy was greater, with +6% and +8%, respectively. This increase may be related to the warmer spring and summer seasons experienced in these countries that favoured a large and early 2020 harvest (OIV, 2020b).

Regarding sparkling wine, the production is concentrated in some countries like Italy, France, Germany, Spain, the United States, and others. However, it was noticed that the emergence of new countries with a significant increase in sparkling wine production over ten years (2008-2018), including the United Kingdom (+33%/year), Portugal (+18%/year), Brazil (+7%/year), and Australia (+3%/year), considering the average annual growth (Figure 1) (OIV, 2020a).

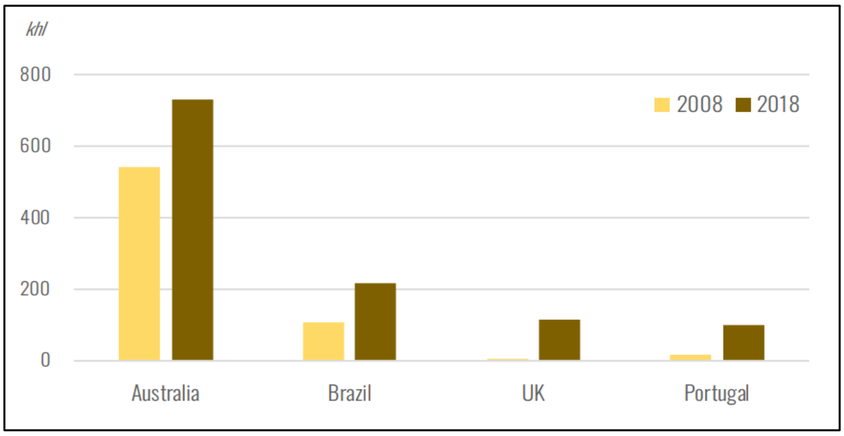

Figure 1: Emerging sparkling wine producing countries.
Source: International Organisation of Vine and Wine (OIV, 2020a).

2.2. THE WINE SECTOR IN PORTUGAL

According to OIV (2020b), Portugal is in 11th place in the ranking of the wine production sector. Its annual production in the last five years was 6 Mhl (2016), 6.7 Mhl (2017), 6.1 Mhl (2018), 6.5 Mhl (2019) and 6.4 Mhl (2020), with about 194 kha of vineyard surface area in the last year, representing 2.7% of all acreage in the world.

In terms of consumption, Portugal occupies the 11th position in the ranking, with an annual consumption of 4.6 Mhl in 2019 and 2020, representing 2% of world consumption. It is also important to highlight that many countries suffered a decrease in the volume of exports comparing the years 2019 and 2020, such as Italy (-2.4%), France (-4.9%) and Spain (-5.9%). Conversely, Portugal showed an increase of 5.3% totalling 3.1 Mhl of wine exported during the last year (OIV, 2020b).

The drop in production from 2019 to 2020 can be explained by the influence of the COVID-19 pandemic on both production and consumption of wine in all countries.

2.3. WINE MANUFACTURING

Wine is defined as a beverage made from grape juice or just grape, one of the oldest biotechnological processes, with a history of more than 8000 years. From another point of view, the liquid can be classified as a multicomponent solution containing water, ethanol, glycerol, and organic acids as the main constituents, plus the presence of flavors, aroma, and phenolic compounds, depending on the conditions of the winemaking (Pizarro et al., 2007).

The wine production includes three main steps: (i) vinification, which involves pressing, clarification, de-sulphiting, and alcoholic fermentation, (ii) conservation and preparation of lots, in which stabilization and filtration happen; and (iii) bottling and storage, being necessary to carry out the bottle sterilization. Along the vinification, grapes are pressed to extract the must, an unfermented liquid from grapes (Quinteiro et al., 2014), where the fermentation process happens.

The vinification is considered a simple process, counting with three principal parts: pre-fermentation, fermentation, and post-fermentation (Bisson, 2004). Pre-fermentation is the key process to producing wine, and the main need for it happens is a sugar source. Many fruits with sufficient sugar can be used, such as litchi, plum, pineapple, banana, blueberry wine, among others (Yang et al., 2021). The more common is the grape wine, and during the first step of the production process, the grapes are crushed and must go directly to the fermentation process if it's a red wine; if it's a white wine, the crushed grapes must be pressed to release the juice and after that go to the fermentation (Bisson, 2004).

The second and principal step of the production process is fermentation, in which the sugar from grapes will be transformed into ethanol. The fermentation process can be divided into three phases: lag, exponential, and stationary, depending on the behavior of the yeasts present in the process. In the lag phase, the yeasts must adapt their metabolism to the level of glucose/fructose present in the medium. In the exponential phase, the quantity of yeast will increase a lot, and in the third and stationary phase, the yeasts will be in equilibrium without significant changes. The second and third phases are responsible for producing ethanol, counting for one-third and two-thirds of ethanol production, respectively (Pizarro et al., 2007).

The post-fermentation process happens when residual sugar concentration is below 2-4 g/L and, usually, it may take 7-10 days for red wines and 15-20 days for white wines (Pizarro et al., 2007). There is more than one kind of post-fermentation. One of which can be the extended maceration, which will increase the extraction of different polyphenols. The pressing process can also be considered a post-fermentation process because the separation of the grape solids from the remaining liquid can be done after the fermentation, depending on the chosen process. Finally, the post-fermentation process comes to the winemaking, in which wines usually undergo maturation in a barrel, tank, or bottle to stabilize (Unterkofler et al., 2020).

It is common to add some enzymes to improve the efficiency of the process, during the production of wines. The enzymes have the main function of catalyzing various biotransformation reactions; they increase the juice yield of the fruit, improve the wine color, promote the formation of aroma, ensure the safe drinking, accelerate the filtration and clarification speed of wine, and shorten the fermentation process, improving the quality of the wines, depending on how they are used. (Yang et al., 2021).

2.3.1. Stages of Wine Production

As reported by the Best Available Techniques (BAT) Directive 2010/75/EU (2019), the main processes and techniques of wine production, also known as vinification processes, are reception, grape crushing and destemming, pressing, alcoholic fermentation, fining, maturation, stabilization and bottling.

Reception: at this stage, the grapes are received at the cellar, being classified by quality, quantity, and variety. Containers are emptied directly into crushing or transport equipment. These empty containers are cleaned, and wastewater is drained.

Grape crushing and destemming: grape crushing (breaking of the skin) takes place in grape mills. In case maceration is necessary, the mash can be stored in vats. Sulphurous acid (H_2SO_3) is added so that this mash does not oxidize. The destemming process of white grapes depends on the variety and type of maturation of the grapes, as well as on the subsequent processing of the mash.

Pressing: in the case of white wine, the mash is transported to the wine press. The resulting unfermented grape juice is called must. Sulphur dioxide (SO_2) can be added at this stage, to eliminate undesirable microorganisms, among which is worth mentioning the fungi and bacteria present in the grape skins, as well as the yeasts used in the process. Solid waste such as pomace is then separated. Regarding red wine, this process occurs after fermentation, when the sugar levels are lower than 0.1%, then the wine is withdrawn from the bottom of the tank and the pomace is transferred to the grape mill to extract the remaining wine.

Alcoholic Fermentation: the fermentation process usually takes place inside large vats or reactors made of stainless steel with or without the addition of pre-cultured yeast. This yeast can be, for example, *Saccharomyces cerevisiae*, responsible for the reaction occurs under strict temperature control (Maicas, 2021). The white and red wines go through the fermentation and pressing processes in an inverted way, because in the case of red the fermentation must occur together with the grape pomace; therefore, pressing comes right after. White wine, on the other hand, must be fermented after separating the pomace; thus, the pressing process takes place previously.

Additionally, malolactic fermentation is a process that usually occurs with red wine, but sometimes also occurs with white wine. In this fermentation, bacteria convert malic acid into lactic acid.

Fining: corresponds to the process where clarification agents are applied in the winemaking process, using gelatine, chitin, albumin, casein, isinglass, some mineral and/or bentonite adsorbents, diatomaceous earth or silica, synthetic polymers and PVPP. In the clarification process, the sedimented compounds must be separated by centrifugation or filtration, removing unwanted suspended particles.

Maturation: is a process that takes place after fermentation, where the wine is cooled to 4-5°C and transferred to containers such as barrels or oak wooden vats used to age the wine. This process allows the wine to stabilize and develop compounds such as softer tannins and more complex flavours. Its maintenance should be done by removing the lees every 3 or 4 months and then, when the barrels are washed and refilled.

Stabilisation: this process is used to avoid the precipitation unwanted tartrate crystals in bottled wine, preventing them from being present at the bottom of the bottle or in the cork. The process is done by rapidly cooling the wine to temperatures close to the solidification/freezing point. After the tartrate has precipitated in the tanks, it is removed with a 10% caustic soda (NaOH) alkaline cleaning solution.

Finally, bottling takes place, which involves microbial stabilization of the wine, preserving the wine from changes that may occur in chemical composition and flavour.

2.3.2. *Vinho Verde*

Wines with the designation of origin *Vinho Verde* (“Green Wine”) are produced in Portugal and are valued in the world of wine. Its origin refers to the natural characteristics of the Minho region, which produce dense green foliage that contributes to the fabrication of a wine light and fresh. It is this profile that the wine is named after, when compared to other more and complex weighty wines (CVRVV, 2021).

According to Portuguese Regulatory Ordinance nº 152/2015, May 26th, to be considered “*Vinho Verde*” must comply with some characteristics, such as total alcohol content equal to or above 8.5 % vol and maximum equal or less than 14 % vol. To red, white, and rose wine, fixed acidity (tartaric acid), equal to or higher than 4.5 g/l, maximum carbon dioxide overpressure of 1 bar (20°C) or concentration less than or equal to 3 g/l. Otherwise, it is necessary to indicate caste, sub-region, and specify "Choice", "Selected harvest", “Reserve”.

Red wines have a particular aroma and intense color, while white wines have a young and fruity aroma associated with a unique freshness. The most used grape variety in the manufacture of red *vinho verde* is Alvarelhão, Amaral, Borraçal, Espadeiro, Padeiro, Pedral, Rabo de Anho and Vinhão, while for the white *vinho verde* is Alvarinho, Arinto, Avesso, Azal, Batoca, Loureiro and Trajadura (Table 1) (IVV, 2021).

Table 1: Able castes to "Vinho Verde" production.
Source: adapted to Annex II - (Portaria 152/2015, de 26 de Maio).

Main name	Recognized synonym	Color
Alvarinho		White
Arinto	Pedernã	White
Avesso		White
Azal		White
Batoca	Alvaraça	White
Cainho		White
Cascal		White
Diagalves		White
Esganinho		White
Esganoso		White
Fernão-Pires	Maria-Gomes	White
Folgasão		White
Gouveio		White
Lameiro		White
Loureiro		White
Malvasia-Fina		White
Malvasia -Rei		White
Pintosa		White
São Mamede		White
Semillon		White
Sercial	Esgana-Cão	White
Tália	Ugni-Blanc, Trebbiano-Toscano.	White
Trajadura	Treixadura	White
Alicante-Bouschet . . .		Red
Alvarelhão	Brancelho	Red
Amaral		Red
Baga		Red
Borraçal		Red
Doçal		Red
Doce		Red
Espadeiro		Red
Espadeiro-Mole		Red
Grand-Noir		Red
Labrusco		Red
Mourisco		Red
Padeiro		Red
Pedral		Red
Pical	Piquepoul-Noir	Red
Rabo-de-Anho		Red
Sezão		Red
Touriga-Nacional . . .		Red
Trincadeira	Tinta-Amarela, Trinca-deira Preta.	Red
Verdelho-Tinto		Red
Verdial-Tinto		Red
Vinhão	Sousão	Red

The maximum yield per hectare of vineyards intended to produce wines and products wineries called "*Vinho Verde*" is 10,666 kg, except when the vines meet the quality and productivity requirement, in which the value is fixed at 13,500 kg for the Alvarinho caste and

15,000 kg for the remaining vines. It is only allowed the production of white *vinho verde* with white grapes, rose *vinho verde* with red grapes and red *vinho verde* with red grapes or red with white grapes, provided that the whites don't represent more than 15% of the total. The must yield resulting from the bagasse separation cannot exceed 75 L per 100 kg of grapes, except for the Alvarinho variety, whose maximum yield is set at 65 L per 100 kg of grapes. (Portaria n.º 152/2015, de 26 de Maio).

2.4. IMPACTS OF THE WINE SECTOR

Following Maicas & Mateo (2020), the wine process generates several residues characterized by high contents of suspended solids and biodegradable compound. Despite being considered an environmentally friendly process, it generates between 1.3 kg and 1.5 kg of waste per liter of produced wine, of which 75% is wastewater (Figure 2).

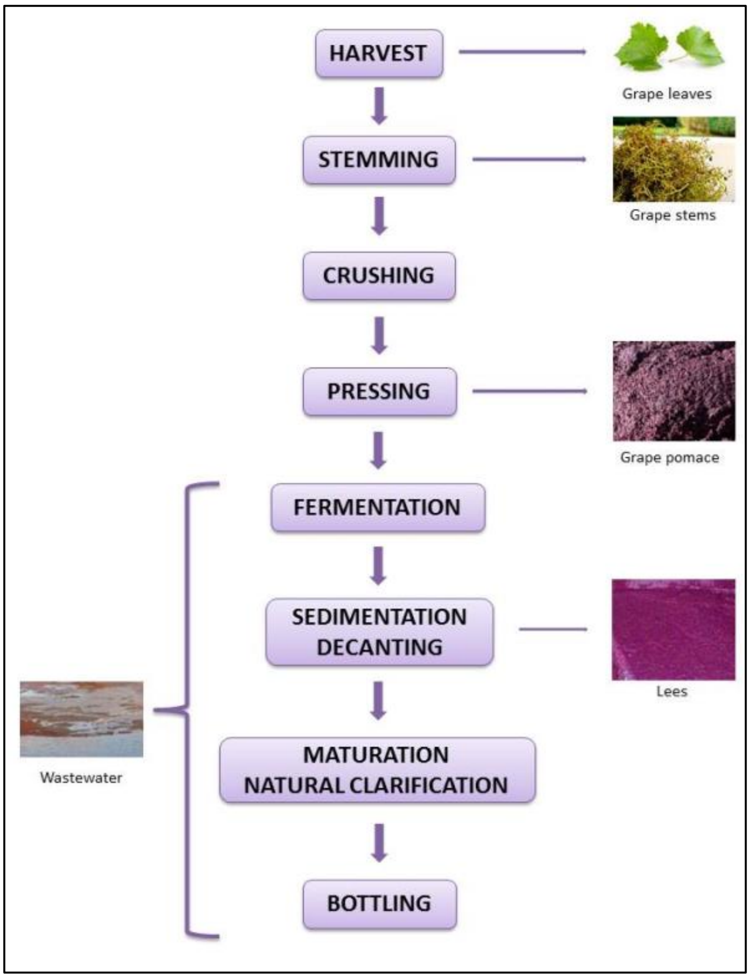

Figure 2: Diagram of the wine production process including the main generated residues.
Source: Maicas & Mateo (2020).

Other major residues generated are the organic wastes: grape stems, grape leaves, and grape pomace with seeds, pulp, and skins; inorganic wastes: perlite, bentonite clay, and diatomaceous earth; emission of greenhouse gases: volatile organic compounds (VOC), carbon dioxide (CO_2).

As stated in Regulation (EU) No 1308/2013 of the European Parliament (2013), grape pomace is the waste from pressing fresh grapes that have already been fermented or not. While wine lees are residues that are deposited in wine containers after fermentation, when product storage becomes necessary. This waste can be obtained by filtering or centrifuging the product.

Grape pomace, also known as grape marc, is generated by pressing whole grape bunches during the production of must (Hogervorst et al., 2017). This waste account for approximately 20% of the total mass of processed grapes (Boussetta et al., 2009; Hogervorst et al., 2017; Panouillé et al., 2007). As reported by Hogervorst et al. (2017) and Mendes et al. (2013) it is estimated the generation of about 1 kg of grape pomace for every 6 L of wine produced.

The use of wastes generated in winemaking such as grape stems, peels, seeds and pulps for incorporation or production of value-added products, is an important strategy to reduce negative environmental impacts (Mendes et al., 2013; Bail et al., 2008).

Furthermore, as stated by Matos & Pirra (2022), the main impacts on winemaking are linked to the use of electrical energy in the equipment, the emissions of VOCs and CO_2 during the fermentation process, and the production of solid waste during the processes, which can be reused in other sectors and the generation of cleaning effluents and possible leaks. The most significant water use occurs mainly in fermentation tanks, cask washing, bottling lines, crush pad and vat sopping.

According to EMEP/EEA (2019), the five main air pollutants responsible for eutrophication, acidification, ground-level ozone pollution and particulate matter formation are sulphur dioxide (SO_2), fine particulate matter (PM2.5), nitrogen oxides (NOx), ammonia (NH_3), and non-methane volatile organic compounds (NMVOCs).

In the phases of wine production as viticulture, vinification, and bottling (packing), can be analysed the impact categories. This Life Cycle Impact Assessment (LCIA) category can be normalized by the local characteristics of a region to define which impact is the one that the wine industry is a higher contributor (Valero et al., 2019). The phase of packaging is associated with categories of ozone depletion, ionizing radiation, natural land transformation, and, to a minor scale, climate change (Arzoumanidis et al. 2013, 2014).

Current practice within wine organizations is largely inadequate and unexplored, and is characterized by the absence of quantitative environmental data necessary to identify and propose environmental improvements in operational processes and products of the wine industry, and with it the improvement of economic and environmental performance (Christ & Burritt, 2013).

2.5. LIFE CYCLE ASSESSMENT (LCA)

The Life Cycle Assessment (LCA) emerged in the 1960s due to concerns with energy resources and the extraction of raw materials. Thus, sought to find ways to account for energy use and project future resource use. In 1963, the first indicators for calculating the energy accumulated in the production of a product were proposed at the World Energy Conference by Harold Smith (SAIC, 2006).

In the 1970s, LCAs were associated with models of economic input-outputs to quantify the raw materials and fuels used and the environmental emissions generated in the manufacturing process of products from one or more industries. These analyses were called Ecobalance in Europe or Resource and Environmental Profile Analysis (REPA) in the United States. This made it possible to make estimates of environmental impacts, but the data was often limited or non-existent since it came from available public or government sources, that is, it was comprehensive rather than specific (Clark, 2011; Hawkins et al., 2007; SAIC, 2006).

Driven by the need for change due to superficiality in obtaining data, assumptions, and approaches within LCA research, in the mid-1990s, it was decided to standardize methods and applications. This standardization materialized by creating a series of LCA standards by the International Organization for Standardization (ISO) between 1997 and 2000 (Hauschild et al., 2018).

This way, it is possible to evaluate material and energy expenses and the impacts a product or process generated, from raw material extraction to disposal (Figure 3)(Clark, 2018).

LCA are used to evaluate environmental impacts in various applications. It can be performed by identifying environmental aspects and impacts caused in the life cycle stages or improving processes. One of its functions is to compare products that perform the same function and consider each product or process under analysis linked to external factors with which it interacts. This type of analysis contributes to the decision-making or strategic planning of industry, government, or organizations, and can help select environmental performance indicators and identify the most significant impacts generated (Clark, 2018).

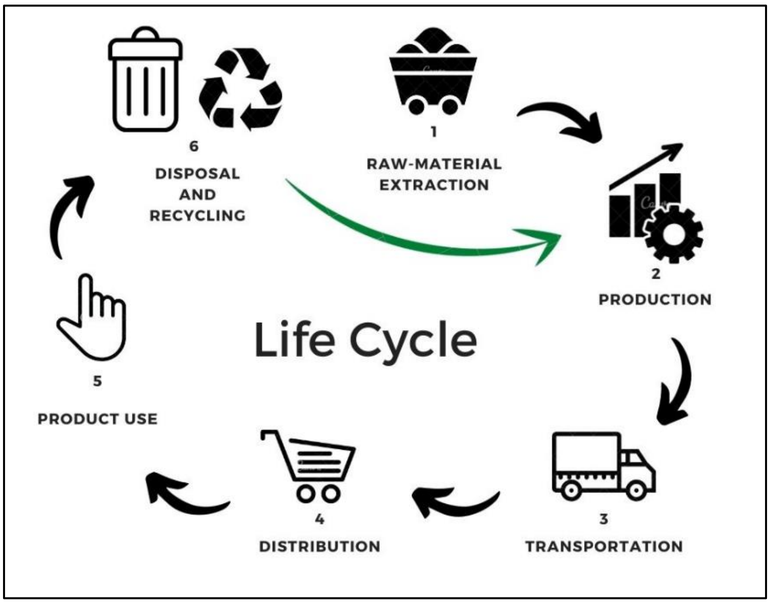

Figure 3: A life cycle for a product.
Source: adapted from Clark (2018).

LCA considers the environmental, social, and economic impacts throughout a product's life cycle, evaluating its impacts in the stages of extraction, processing, manufacturing, repair, maintenance, and disposal or recycling. A thorough analysis enables the identification of the positive and negative aspects of a service or product (Figure 4)(ICCA, 2013).

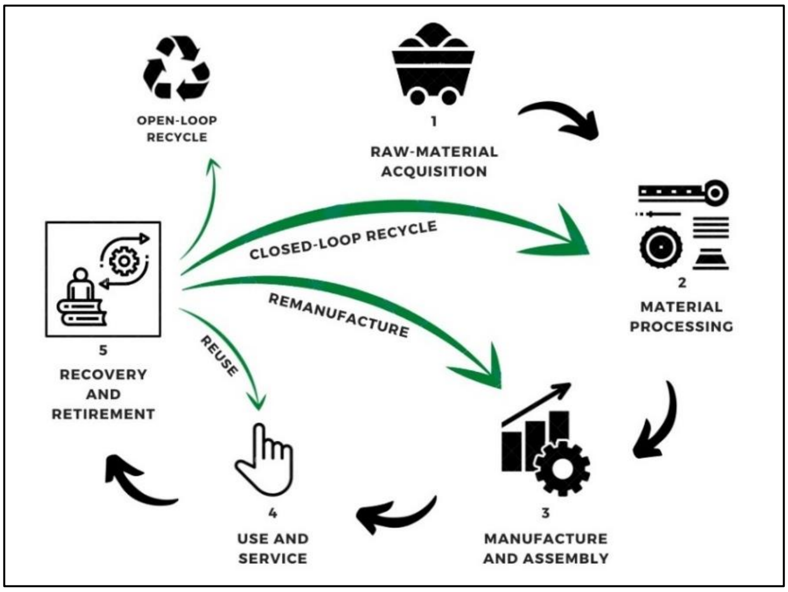

Figure 4: A life cycle assessment.
Source: adapted from Clark (2018).

It’s an important tool used to identify environmental impacts and develop a positive image of a company. However, some factors make its application difficult, such as the unavailability of information and the lack of incentives, making it predominantly applicated in more developed countries (Hauschild et al., 2018).

There are many environmental management techniques, such as environmental impact assessment, environmental performance evaluation, and risk assessment; and the Life Cycle Assessment, which is one of them; however, it should not be used in all situations. Although the LCA does not normally address the social or economic aspects, its methodologies can be applied to these other aspects (ISO 14040, 2006).

In 2006, the standards underwent a reformulation and improvement in life cycle management, inventory, and assessment, making them it currently used (Clark, 2018; ISO 14040, 2006). Therefore, LCA is a young tool with 50 years of history and less than 30 years of intense application and development (PRé, 2020; Ferrara & Feo, 2018; Hauschild et al., 2018).

2.5.1. Life Cycle Assessment Stages

The ISO standard 14040 describes the principles and framework for LCA, while an ISO 14044 standard addresses requirements and guidelines. Although it doesn't present specific details about the LCA methodology, the standards offer an overview of applications and techniques in four steps for its realization: First, define the goal; second, the life cycle inventory; third, the impact assessment of the life cycle, and the interpretation of the results (Figure 5) (ISO - International Standards Organization, 2006; ISO 14044, 2006).

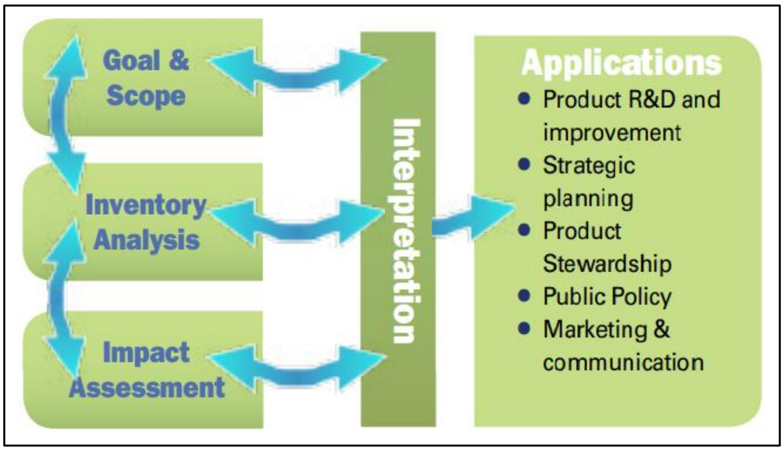

Figure 5: Stages of an LCA.
Source: ICCA (2013); ISO 14040 (2006).

The fundamental structure of the LCA has been constant since the appearance of the first ISO 14040 standard in 1997 (Hauschild et al., 2018). This structure comprises four phases: objective and scope definition, inventory analysis, impact assessment, and interpretation (ISO 14040, 2006).

2.5.1.1. Goal and Scope Definition

The first point in any LCA, is to define and describe the purpose of the study. All decisions taken later must be consistent with the goal definition. Generally, the goal is defined according to ISO considering six aspects: 1 - intended application of the results, 2 - limitations due to the chosen methodology, 3 - reasons for carrying out the study and decision context, 4 - target audience, 5 - comparative studies to be disclosed to the public, and 6 - commissioner of the study and other influential actors (Hauschild et al., 2018).

In addition to the system boundary, the functional unit, allocation procedure, and possible limitations must be considered (ISO 14040, 2006). The system boundary refers to the boundary of the processes that will be covered in the study. They are usually defined considering:

"Cradle-to-gate": From raw material extraction to the factory gate.

"Cradle-to-grave": From raw material extraction through product use and disposal.

"Gate-to-gate": From two defined points along the life cycle, a starting point and an ending point further along in the system (ICCA, 2013).

The functional unit is highly dependent on the aim of the study; it’s a measure for which the results of the LCAs are connected and used later to communicate the LCA results (Schau & Fet, 2008). In other words, it is the unit that mathematically normalizes the input and output data of the system, that’s why, it must be clearly defined and measurable (ISO 14044, 2006). This functional unit can be the mass, volume (Schau & Fet, 2008) or identification of the product, an amount of the function, a quality value, or a time value (ICCA, 2013)

When the study must deal with systems involving several products, the allocation procedures must be considered and applied for reuse and recycling (ISO 14044, 2006).

2.5.1.2. Life Cycle Inventory Analysis (LCI)

Under ISO 14040 (2006), inventory analysis encompasses data collection and the calculation methods to quantify the inputs and outputs of the processes of a product system (Figure 6). It is an iterative process; since data collection takes place, more is known about the system under analysis, making it possible to identify limitations or inconsistencies and review the study procedures and scope to ensure that the objectives are still met.

In this stage, a description of the energy and material flows inside a product system is provided and mainly its interaction with the environment, such as the process emissions and raw materials consumed with the environment (Muralikrishna & Manickam, 2017).

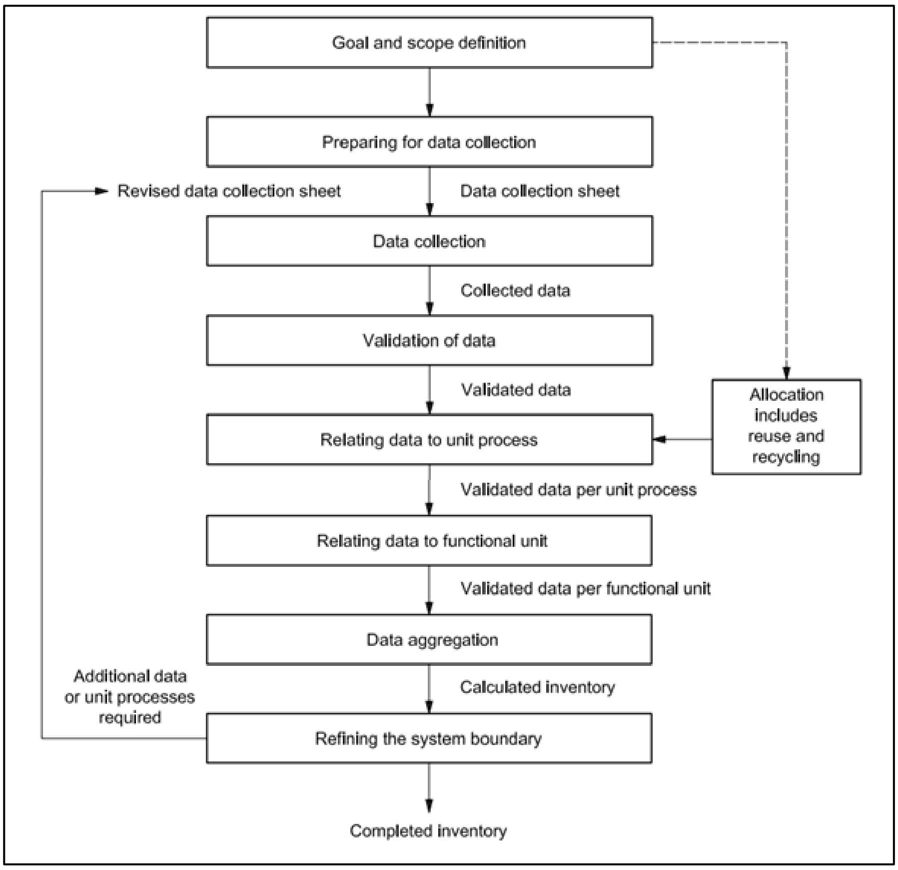

Figure 6: Process of inventory analysis.
Source: ISO 14044 (2006).

Data collection is performed for each process. It can be qualitative or quantitative, obtained through measurement, calculation (explicitly documented), or estimation. A description of each process is necessary to ensure a correct interpretation, which may be performed using flowcharts, specification lists, and instructions, among others. During the collection process, the data must be validated to confirm its reliability through comparative analyses. Thus, these data correlate with the established functional unit, aiming to aggregate data only if they are related to equivalent substances or similar environmental impacts. Lastly, a refinement of the system boundary is performed to verify the need for adjustments and sensitivity analysis (ISO 14044, 2006).

2.5.1.3. Life Cycle Impact Assessment (LCIA)

LCIA comprises the use of equivalency factors, category indicators, impact categories, characterization models, and weighting values to transform the raw data into a measurement of the potential impacts on the environment (ICCA, 2013).

In addition to the elements mentioned as mandatory, the LCI results must be correlated with the selected impact categories, named classification, and the calculation of the results of category indicators, the characterization. All this data must be referenced and aligned with the functional unit (ISO 14044, 2006).

At this stage, according to Laca et al. (2011), the LCI data, its inputs and outputs, are assigned to different impact categories, such as ozone layer depletion, acidification, climate change, toxicity, among others. LCIA usually consists of the following steps (Bradley et al., 2022; Laca et al., 2011):

Classification – the data obtained will be attributed to a characterization model, the impact categories or category indicators that will be used in the study. This selection is based on the types of impacts expected in relation with the activity analised.

Characterization – involves applying equivalence or weighting factors to unify all relevant information in each impact category, e.g., all data contributing to global warming is converted into kilograms of CO_2 equivalent. It assigns the LCI results to the selected impact categories. In this way, you can directly compare LCI results within each category.

If needed, there are optional elements (Bradley et al., 2022; ISO 14044, 2006):

Normalization – magnitude calculation; performs the comparison between the result of the category indicator with a reference, which supports consistency control.

Grouping – sort and classification to impact categories based on indicator results and value choice.

Weighting – convert indicator results or normalized results into an aggregate score based on weighting factors derived from the value choice.

As stated in ISO 14044 (2006), the LCIA data quality analysis may be necessary to better understand the uncertainty, significance, and sensitivity of the LCIA results. Therefore, distinguish whether there are significant differences or not, whether there are significant LCI results, and guide the LCIA iterative process. Among these techniques:

a) Gravity analysis is a statistical procedure that identifies which data contribute most to the result of a given indicator. From this, it is possible to establish the points that should be investigated with higher priority to ensure that correct decisions are made (e.g., Pareto analysis).

b) Uncertainty analysis is a procedure to determine how uncertainties in assumptions and data evolve in the calculations and how this affects the reliability of LCIA results.

c) Sensitivity analysis is a procedure that determines how much change in methodological and data choices affect LCIA results.

2.5.1.3.1. Impact assessment methods for LCA

To support LCA, there are some tools such as GaBi, SimaPro, Team, Umberto, OpenLCA and AMEE, which are modelling software in LCA (Kulczycka et al., 2015; Bradley et al., 2022). These software were developed to facilitate mass and energy balance calculations, perform comparisons between product life cycles, analyse the flow of materials and energy, and, mainly, perform analysis of environmental impacts and interpretation of results (Campolina et al., 2015).

The *GaBi* software is a tool capable of modelling product life cycles and their respective environmental impacts, providing alternatives for the improvement of manufacturing, distribution, recyclability, and sustainability processes, allowing the comparison of different scenarios. It works through the Life Cycle Inventory (LCI) database at its core. Its professional version has approximately 4000 cradle-to-gate processes, in addition to parameterized processes that support the modeling. (Thinkstep, 2019).

GaBi Software System and Databases were developed by PE Europe GmbH and IKP University of Stuttgart. It is used to evaluate the environmental, economic, and social aspects of technologies and processes associated with the life cycle of a product. It can also be used to calculate mass and energy balances for different products, handling a large amount of information. It has worldwide coverage and ecoinvent databases (SAIC, 2006) (Thinkstep, 2019).

The ecoinvent data corresponds to more than 2700 datasets with global/European/Swiss coverage. It has elementary flows for each dataset, including air, soil, and water emissions, land use, fossil resources, and mineral resources (SAIC, 2006).

LCIA also considers widespread impact assessment methods like Centrum voor Millikunde Leiden (CML) 2001, Eco-indicator 99, ecological scarcity method 1997, Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), Environmental Development of Industrial Products (EDIP) 1997, ILCD Recommendation, ReCiPe, EPS 2000, Impact 2002+ and PE LLCIA Survey 2012 (Bradley et al., 2022; SAIC, 2006).

For tools targeting European markets, the prevailing impact assessment methodology is CML (One Click LCA, 2021). Developed by the University of Leiden in the Netherlands (Universiteit Leiden, 2016), the method's main objective is to functionalize ISO14040 standards and provide current greatest practices for midpoint indicators. Resource reduction is seen as the main problem in this method. Thus, the protected area is natural resources. The CML includes nine “core” effect categories, which are commonly used in all LCA studies (Çolak et al., 2022).

The characterization models integrated in these LCIA methodologies convert relevant environmental interventions into category indicators, which can be at a point close to the middle or end of the environmental mechanism established for a given impact category (Bradley et al., 2022). For this reason, these LCIA methodologies are generally classified into midpoint approaches (e.g., ozone layer depletion potential, global warming potential) or endpoint approaches (e.g., human health impacts measured in disability-adjusted life years) (Figure 7) (Bradley et al., 2022; Corominas et al., 2020; Bare et al., 2000).

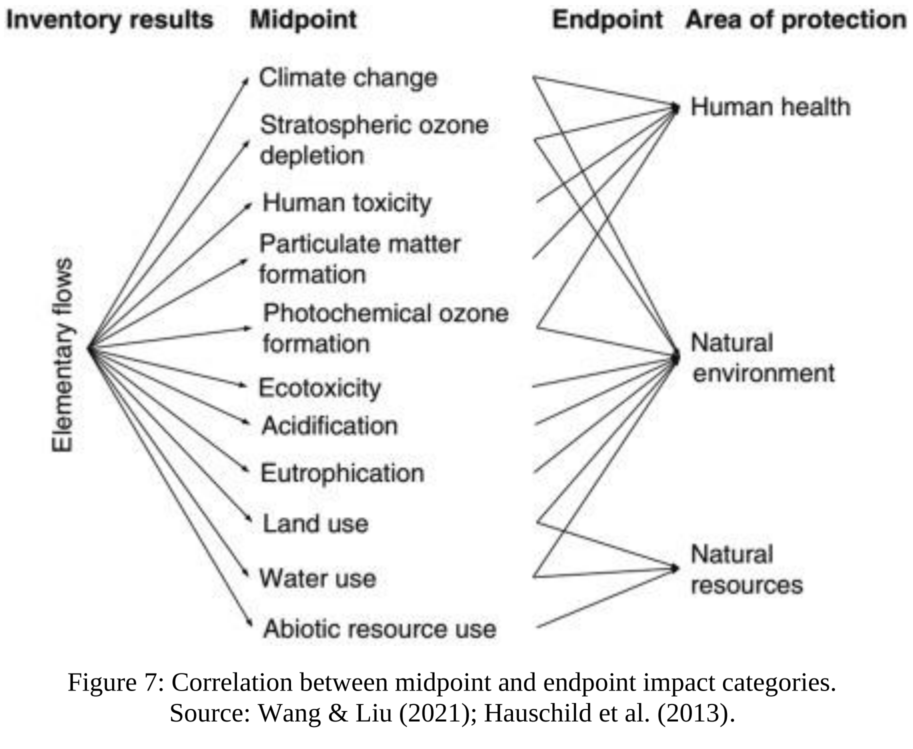

Figure 7: Correlation between midpoint and endpoint impact categories.
Source: Wang & Liu (2021); Hauschild et al. (2013).

A trade-off is often necessary, as midpoint indicators limit uncertainty, while endpoint indicators tend to normalize and aggregate the impacts of all categories with the view to streamlining the results for decision-makers (Corominas et al., 2020; Reap et al., 2008; Pennington et al., 2004; Bare et al., 2000).

The endpoint approach characterizes damage at the end of the chain of causality, linking an interaction with the ecosphere, to a transformation of it (midpoint) to damages in one of the LCA's protected areas (resources, ecosystems, human health). Endpoints represent the end of these causal chains and require more categories of environmental impacts to be linked to generate an outcome. This result is less transparent and more uncertain. For example, characterizing climate change using radiant forcing in CO_2 equivalents is more reliable than estimating the damage of these changes to endpoints in ecosystems (Corominas et al., 2020).

In the CML method where the characterization factors focus on midpoints of the global and European geographic context (Çolak et al., 2022), the following impact categories are considered (Guinée et al., 2002):

- Acidification Potential (AP),
- Eutrophication Potential (EP),
- Freshwater Aquatic Ecotoxicity Potential (FAETP),
- Global Warming Potential (GWP 100 years),
- Human Toxicity Potential (HTP),
- Marine Aquatic Ecotoxicity Potential (MAETP),
- Ozone Layer Depletion Potential (ODP),
- Photochemical Ozone Creation Potential (POCP),

Therefore, the regional validity of the CML method can be considered global, except for the Acidification Potential (AP) and Photochemical Ozone Creation Potential (POCP) categories, which are based on European factors (Çolak et al., 2022; Farjana et al., 2019).

Each category above represents a type of environmental impact; For example, the carbon footprint (CF), is related to emissions of greenhouse gases into the air and can result in adverse effects on ecosystem health, human health and material welfare (PRé, 2020; Ferrara & Feo, 2018)

2.5.1.4. Life Cycle Interpretation

It consists of evaluating the results obtained in the previous stages (LCI and LCIA) to identify the significant issues, evaluate that regarding sensitivity and consistency checks, make recommendations, conclusions, and verify limitations (ISO 14044, 2006). To

(Muralikrishna & Manickam, 2017), the interpretation of a life cycle encompasses the determination of data sensitivity, a result presentation, and a critical review.

The significant issues may arise from inventory data, such as discharges, emissions, energy, waste, and/or impact categories, such as climate change, resource use, or individual/group unit processes like energy production and transport. The purchase of sensitivity analysis is to evaluate, establish and enhance the reliability of results (ISO 14044, 2006).

2.6. LIFE CYCLE ASSESSMENT APPLIED TO THE WINE SECTOR

For a long time, the environmental issues of wine production have been unexplored (Christ & Burritt, 2013; Ferrara & Feo, 2018). In fact, the environmental evaluations in this area, just appeared recently, when many studies have been published, principally from 2013 onward. The first aspect that comes out is the geographical location of the studies: about 73% of them focused on the evaluation of on Italian (61%) and Spanish (12%) wine-production systems, and the remaining 27% of these studies in other parts of the world (Ferrara & Feo, 2018).

The second aspect is related to a definition of the studies' objectives, in which the main purpose is to evaluate the environmental performances to specific wines, since the utilization of specific grape varieties in wine production require different production processes, and consequently, affects the environmental performances in viticulture and vinification phases of the considered products (Ferrara & Feo, 2018).

According to the Web of Science (WoS) there are 31531 publications reported to life cycle assessment, and the oldest study found in this database is from the authors James Fava and Allan Page in the year 1992 (Fava & Page, 1992) (keyword: "life cycle assessment" or "LCA"; search date: 13/05/22) (Figure 8).

There has been annual exponential growth since 2006, from 310 publications to 4428 in 2021. This can be justified by the update of ISO 14040 and 14044 that took place in the same year. In just five months of 2022, 1199 publications were made in this area.

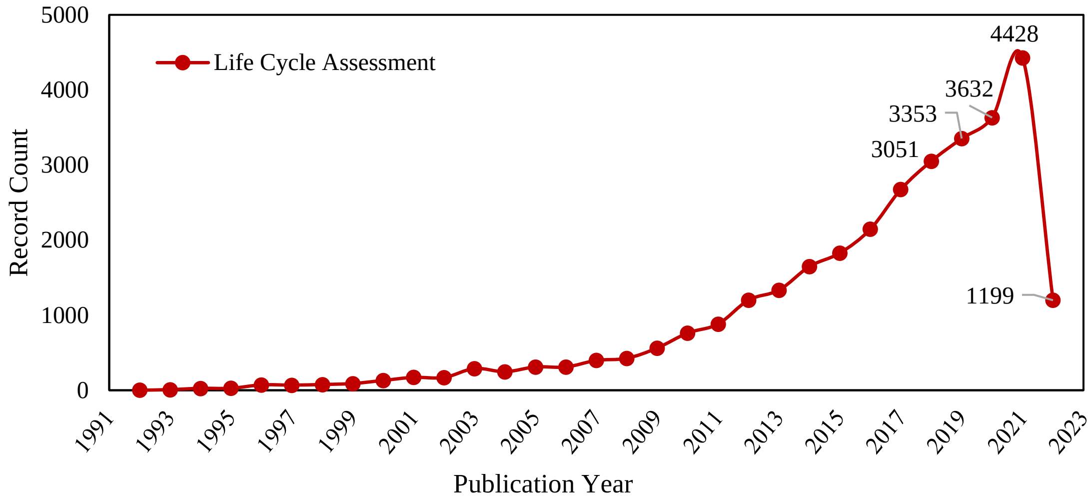

Figure 8: Papers published on LCA over the years until May/2022.
Source: WoS with the keyword “life cycle assessment” or “LCA”).

From the year 2005, the first wine-related LCAs was reported in Germany (Schlich & Fleissner, 2005), and Italy (Ardente et al., 2006; Pizzigallo et al., 2008), adding up to 188 papers published up to the date of the research (keyword: “life cycle assessment” and “wine”; date of search: 05/13/22).

Only in 2013 and 2014 studies were carried out in Portugal related to the life cycle assessment of “*Vinho Verde*” (Figure 9) (keyword: “life cycle assessment” and “*vinho verde*”; date of search: 13/05 /22). The first paper used 0.75 L as a functional unit, a “cradle-to-gate” system boundary (including vineyard, vinification, and distribution), using the CML 2001 methodology, the SimaPro software and the Ecoinvent database (Neto et al., 2013), while the second is aimed at evaluating the use of fresh water in the production of each bottle of *vinho verde* using different methodologies (Quinteiro et al., 2014).

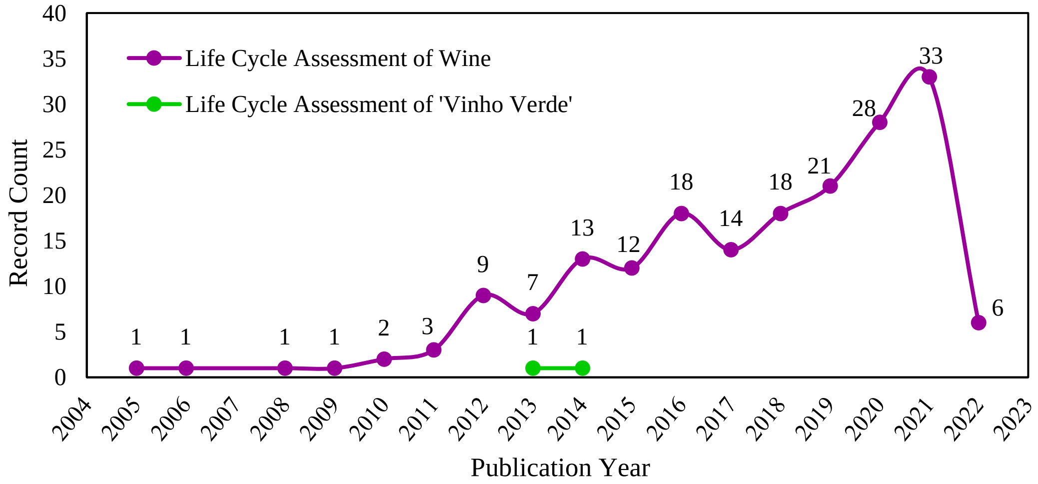

Figure 9: Papers published on wine sector LCA over the years until May/2022.
Source: WoS with the keyword “life cycle assessment” and “wine” and “*vinho verde*”.

Similar results were obtained using the Scopus database. Therefore, a compilation of papers on wine life cycle analysis was carried out with different characteristics, on both platforms, highlighting relevant information for the realization of this study such as location, functional unit, the impact assessment method used, the categories chosen in each of them and their respective software (Table 2).

Table 2: List of papers with different approaches to LCA in the wine sector.

Reference	Location	FU[1]	Method	Impact Categories[5]	Software
Ardente et al. (2006)	Italy	0.75 L of wine	POEMS[4], EPS, IPCC 2000	EC, CF, WD.	n.a.[3]
Pizzigallo et al. (2008)	Italy	1 t of wine	Ecoinvent	GWP.	SimaPro
Gazulla et al. (2010)	Spain	0.75 L of wine	CML	AP, EP, GWP, POCP.	GaBi
Point et al. (2012)	Canada	0.75 L of wine	CML	ADP, AP, EC, EP, FAETP, GWP, ODP, POCP, TETP.	SimaPro
Benedetto (2013)	Italy	0.75 L of wine	CML	ADP, AP, EP, GWP.	GaBi
Neto et al. (2013)	Portugal	0.75 L of wine	CML	ADP, AP, EP, FAETP, GWP, HTP, MAETP, ODP, TETP.	SimaPro
Quinteiro et al. (2014)	Portugal	0.75 L of wine	CML	EP, FAETP, MAETP.	GaBi
Amienyo et al. (2014)	Australia	0.75 L of wine	CML	ADP, AP, EP, FAETP, GWP, HTP, MAETP, ODP, POCP, TETP.	GaBi
Meneses et al. (2016)	Spain	0.75 L of wine	ReCiPe	ALOP, CC, FE, HTP, TA, WD.	n.s.[2]
Gallucci et al. (2020)	Italy	1 kg of hollow glass	CML	ADP, AP, EP, GWP, POCP, WD.	GaBi
Ncube et al. (2021)	Italy	0.75 L of wine	ReCiPe	GWP, TA, FE, ME, HT, WD	SimaPro
Harb et al. (2021)	Lebanon	0.75 L of wine	ReCiPe	AP, CC, EP, FAETP, FE, HTP, ODP, POCP, WD.	SimaPro
Ramos & Ferreira (2022)	Portugal	1 kg of wine's pomace	ReCiPe	CC, FE, HT, ME, ODP, POCP, TA.	SimaPro

Note: [1]Functional Unit. [2]n.s. – not specified. [3]n.a. – not applicable. [4]POEMS – Product Oriented Environmental Management System. [5]ADP: Abiotic Depletion Potential, ALOP: Agricultural Land Occupation, AP: Acidification Potential, CC: Climate Change, CF: Carbon Footprint, EC: Energy Consumption, EP: Eutrophication Potential, FAETP: Freshwater Aquatic Ecotoxicity Potential, FE: Freshwater Eutrophication, GWP: Global Warming Potential, HTP: Human Toxicity Potential, MAETP: Marine Aquatic Ecotoxicity Potential, ME: Marine Eutrophication, ODP: Ozone Depletion Potential, POCP: Photochemical Ozone Creation Potential, TA: Terrestrial Acidification, TETP: Terrestrial Ecotoxicity Potential, WD: Water Depletion.

According to Jourdaine et al. (2020), Ferrara & Feo (2018), Rugani et al. (2013), who conducted reviews of LCA articles in this sector, the most common system boundaries are viticulture, winemaking, bottling and distribution. The category that is repeated in almost all studies is the Global Warming Potential (GWP) (Rugani et al., 2013) or related to it. The same goes for the functional unit, which is predominantly a 0.75 L bottle.

Most studies aim to provide information on the critical processes of LCA, seeking to improve or update the ecological profile of different types of wine or to compare and combine impact results (Rugani et al., 2013).

Conforming to Matos & Pirra (2022), in Portugal, few studies have been done on the environmental impacts in the wine sector:

- Pirra (2005) and Duarte et al. (1998) focused on determining the water footprint of a bottle of wine.
- Martins et al. (2018) assessed the sustainability of Portuguese wines.
- Quinteiro et al. (2014) carried out a Life Cycle Assessment considering the use of fresh water in the wine industry.
- Matos & Pirra (2020) considered the production of water for wine production.

Furthermore, Neto et al. (2013), carried out a LCA in the Minho Wine region; Costa et al. (2020) identified the water use and wastewater generation in irrigated viticulture and oenology remains; Saraiva et al. (2020) evaluated the water footprint in the wine sector based on field experiments in LCA and Ramos & Ferreira (2022) focused on the co-products valorisation of wine and olive industry.

3. METHODOLOGY

3.1. STUDY AREA

Portugal is divided into several wine growing areas, with the Minho Wine Region located in the very north-western part of the country (Fraga et al., 2014). This zone also known as "*Vinho Verde*" is located between the river Minho at the north, which forms part of the border with Spain, the river Douro at the south, the mountains of Peneda, Gerês, Cabreira and Marão at the east, and the Atlantic Ocean at the west. It is the largest Portuguese Demarcated Region and one of the largest in Europe (CVRVV, 2022c).

This region includes municipalities from Melgaço, at the north end, to Vale de Cambra at the south end (IVV, 2021; Portugal, 2015)(Figure 10).

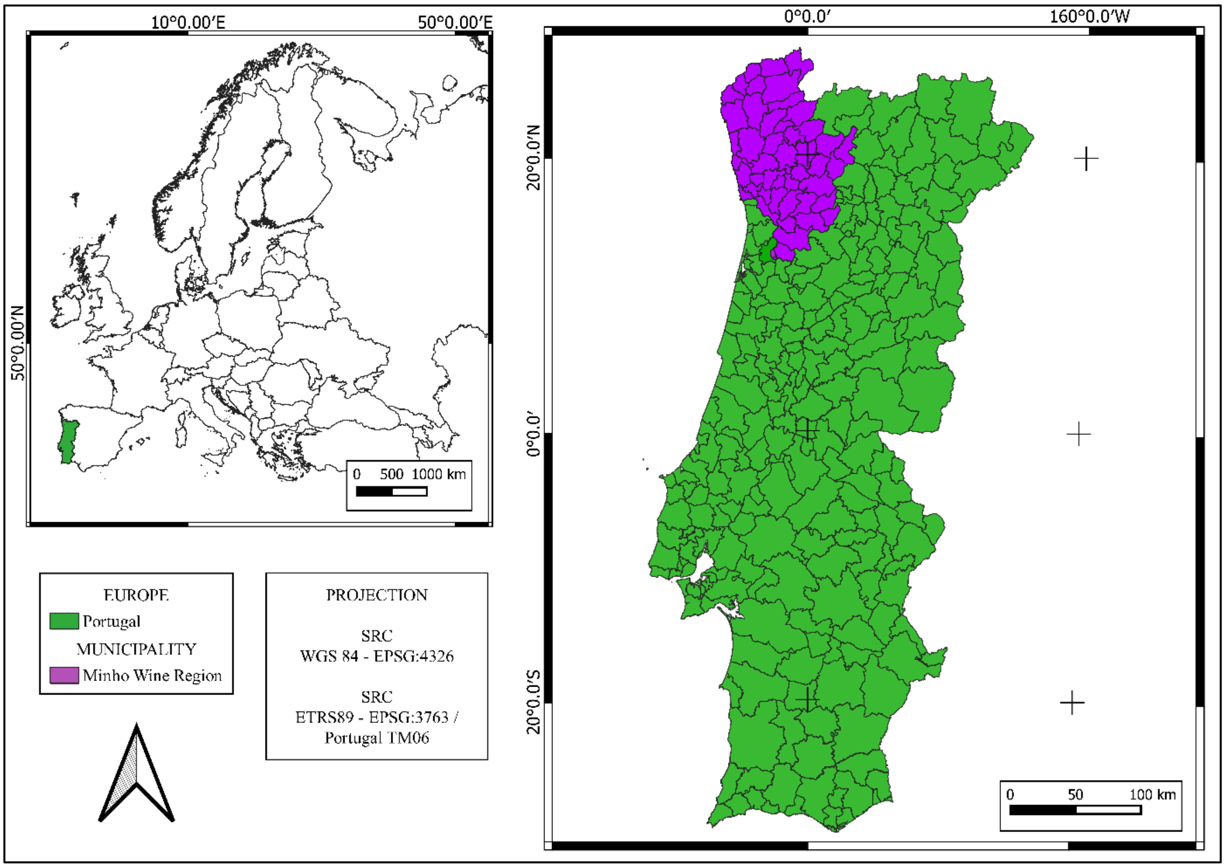

Figure 10: Study area location map adapted from Portugal (2015).
Source: authorship.

Although most of the region has granitic formations, there are two narrow strips that cross it in the northwest-southeast direction, one of ancient schists and the other of composed of coal and slate formations from the Silurian period (CVRVV, 2022a).

The soil is generally characterized by shallow depth, predominantly franco-sandy (light) soils, with a sandy textures, low phosphorus, and high acidity level. For this reason, they are soils with low levels of natural fertility, however, due to the agrarian systems practiced for a long time in the region, the soils have acquired considerable fertility. This is due to two main types of human interventions in the environment: intense and persistent incorporation of organic matter in the soil and construction of terraces that control the relief (CVRVV, 2022a).

Orographically, the region presents a gradual elevation from the sea towards the interior, exposing the entire area to the influence of the Atlantic Ocean, a phenomenon reinforced by the orientation of the valleys of the main rivers, which running from east to west facilitating the dispersion of sea winds. It has soils mostly of granitic origin, a mild climate and high precipitation (CVRVV, 2022c).

Variations in the typology of microclimates and soils justify the division of the region into nine sub-regions (Amarante, Ave, Baião, Basto, Cávado, Lima, Monção and Melgaço, Paiva and Sousa) with different varieties recommended for wine production (CVRVV, 2022c).

The Geographical Indication Minho is used for wine, designated as "*Vinho Regional Minho*", semi-sparkling wine, liqueur wine, sparkling wine, rosé, white and red wines. The guarantee of the authenticity and quality of these wines is given by the Guarantee Seal of Minho, which the *Vinhos Verdes* Wine Commission has certified since 1959 (CVRVV, 2022b).

3.1.1 Winery and its main processes

The studied winery is in the Wine Minho Region and has a production of more than 80% of *Vinho Verde* from the total wine it produces. It has over 60 years of production, with a wide offer of products. The main activities are vinification, bottling and distribution of wines.

In 2020, around 48 thousand hectoliters of wines were bottled. The winery produces white, red, rosé and sometimes semi-sparkling wines, depending on demand.

The production process takes place all year long. By using grapes from regional vineyards, obtained from the harvest period, from August to October, and purchased must in the other months of the year.

The vinification processes of red and white wines differ in some stages, while the production of rosé is just a variation of the red wine production where the colour is less intense, and the flavour is sweeter.

In this way, it is possible to observe that, in addition to the difference in grape varieties, the biggest difference in the production stages is related to the the pressing and fermentation processes, as well as the existing clarification of the white. Moreover, the malolactic fermentation, occurs mostly in the red. The production processes of these wines are presented in Figure 11, in which the green path represents the white and the pink one represents the red wines production.

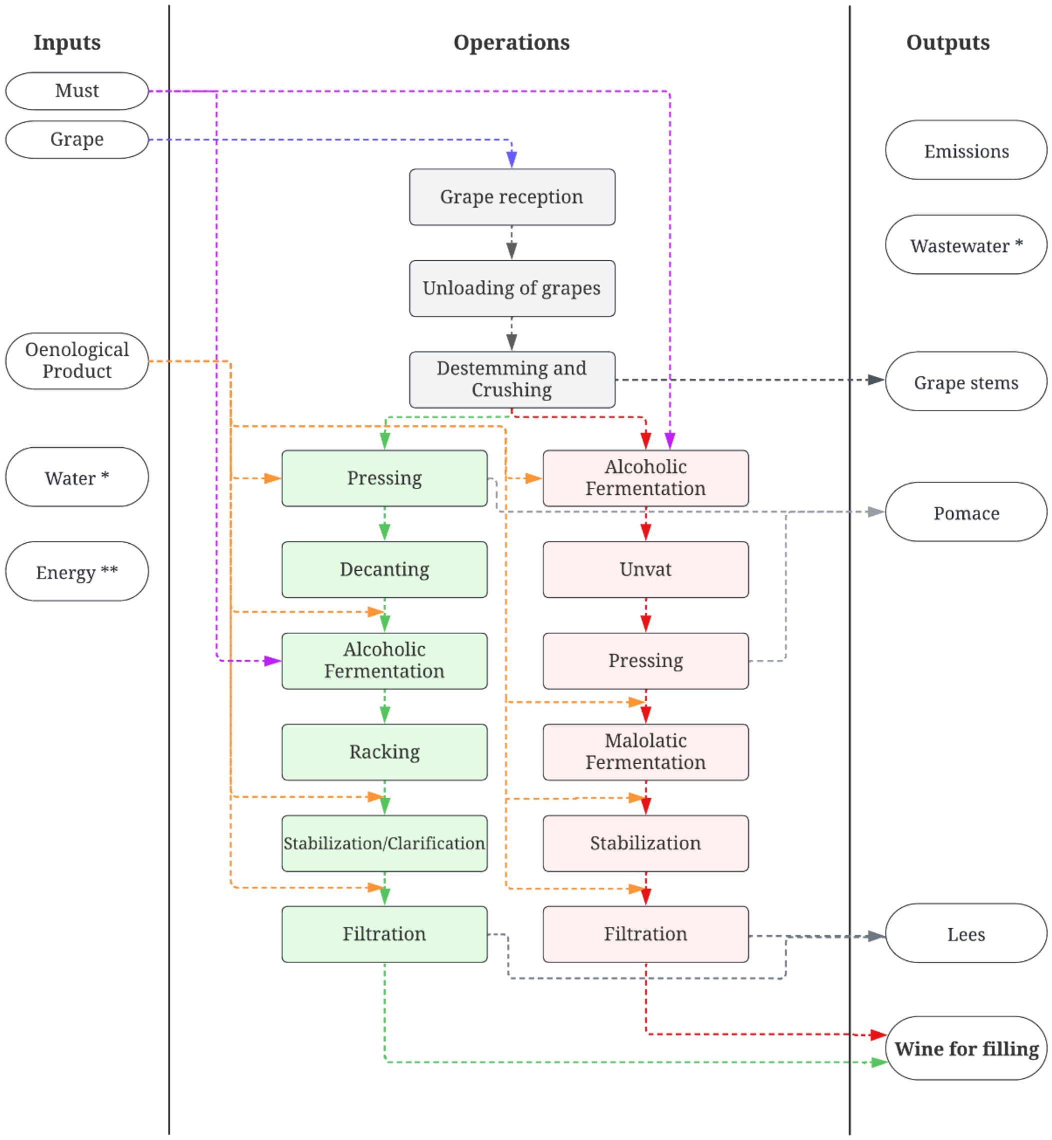

Figure 11: Vinification process flowchart.
Note: *For cleaning process of all equipment. **Electricity is used throughout the vinification process.

The main inputs for winemaking are the grapes, which are inserted right at the beginning of the operations, the must that, when purchased, is placed directly in the fermentation, and the oenological products that can be added at different stages according to the conditions of the grape/must or the characteristics required for the product. The main outputs are wastewater, organic waste, emissions, and wine ready to be bottled. Water is used mostly in the cleaning process of the equipment, generating wastewater which is discarded into the sewage system as shortly afterwards. Besides, electricity is used to provide power to the winery.

The bottling process takes place through three lines one which is automated for glass bottles (line 1); and two semi-automated for polyethylene terephthalate (PET) bottles (line 2) and Bag-In-Box (BIB) packages. Thus, at the end of wine production, three distinct products are generated (Figure 12).

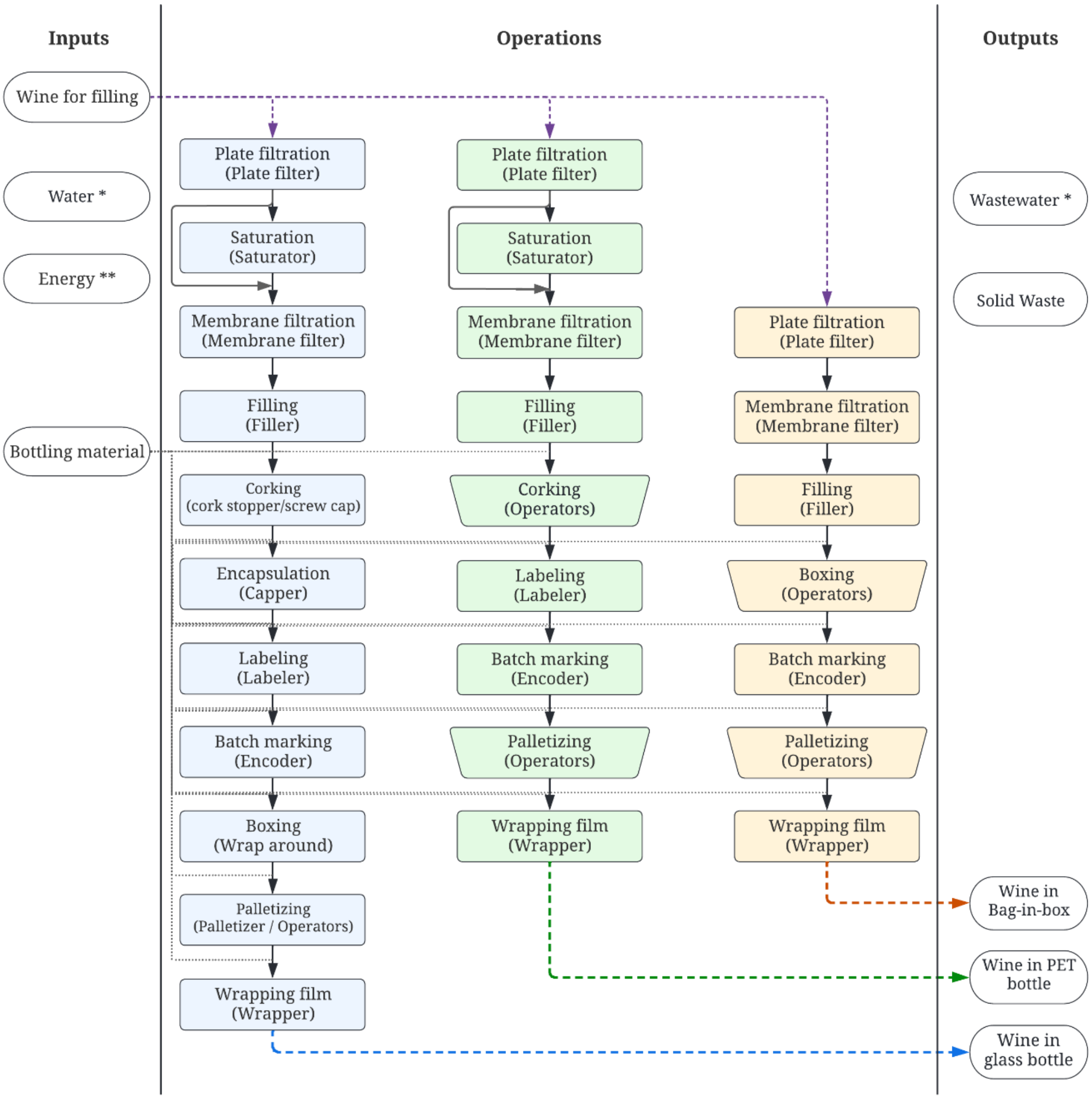

Figure 12: Bottling process flowchart.

Note: *For cleaning process of all equipment and bottle rinsing. **Electricity is used in the entire bottling process.

The main bottling inputs are wine and packaging materials, while the outputs are solid waste and ready-to-use products from the respective production lines. Water and electricity are used in the entire process of bottling, to the same end as the vinification process.

3.1.2. Description of winery operations

The vinification process in the winery takes place during the harvest period. It starts with receiving the grapes, which are weighed and unloaded into a stainless-steel grape hopper (Figure 13A). In this stage destemming takes place, where the grape stems are removed (Figure 13B) to avoid the unpleasant taste caused by the woody material or microorganisms that may be present in it.

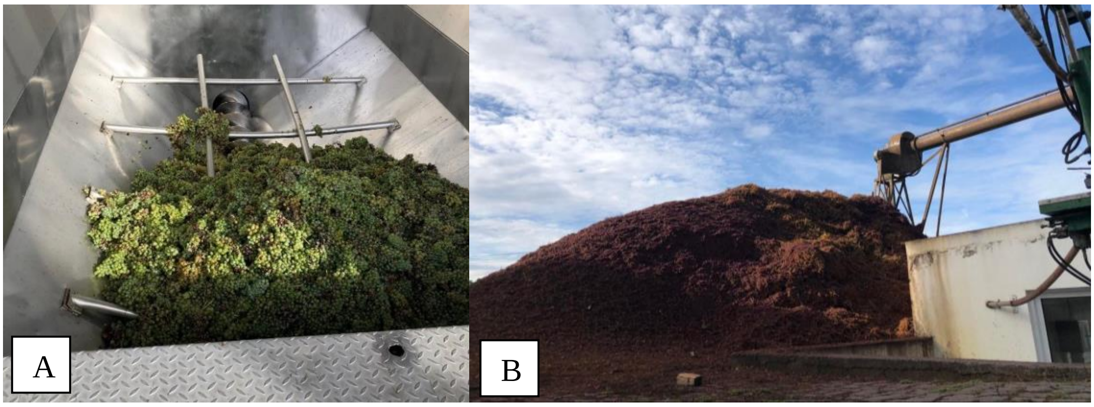

Figure 13: A – Hopper with grapes for destemming. B - Grape stems.

After sorting, the grapes are then sent to the crushers to start the crushing process. This first contact is necessary to break the skin and facilitate the fermentation process, which occurs subsequently in the case of red wines. Differently, pressing is carried out before fermentation for white wines (Figure 14A), where the grape pomace is removed (Figure 14B).

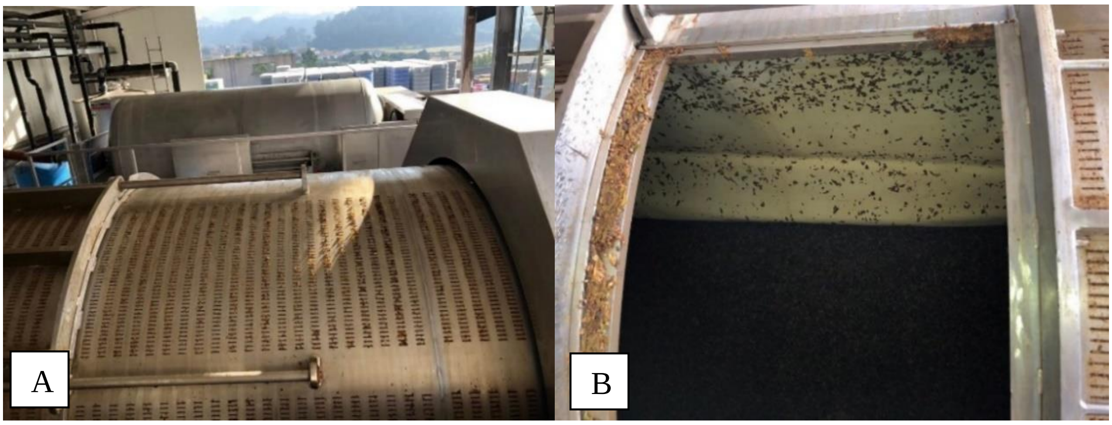

Figure 14: A - Closed press with white grapes and pomace. B - Residual pomace after pressing

In the production of white wine there is a decantation of one to two days, between pressing and fermentation processes, to remove any remaining impurities present in the must that is produced. Since the objective is to leave the white wine as clarified and clean as possible, the management of the processes presented above is performed as stated so that only the fruit juice reaches the fermentation (Figure 15). On the other hand, in red wines production, there is an interest in extracting the colour, tannins and aromatic compounds from the grape skins during the fermentation process.

Figure 15: Separation of the liquid part (must) from the solid part (pomace) after pressing.

The fermentation process, which takes approximately 7 to 14 days, is carried out in stainless steel vats with a capacity of 30,000 litres (Figure 16A). In this step, the must is fermented (Figure 16B), by inserting enzymes and yeasts, under controlled conditions according to the necessary alcohol content (such as the temperature that directly interferes with the reactions), the amount of sugar present in the must, and the characteristics desired for the wine that will be produced.

Figure 16: A - Stainless steel tanks in the fermentation process. B - White must fermenting.

After alcoholic fermentation (and pressing in red wine production), malolactic fermentation may occur. This second fermentation is usually done for red wine to reduce acidity and/or provide a spicy effect by producing carbon dioxide. When the grapes are very ripe, the amount of malic acid is lower, slowing down the reaction. In the case of white wines, this type of fermentation is avoided due to the loss of the most intense aromas and freshness, which are desired characteristic of this typology.

Clarification is carried out in white wine, mainly with gelatines, to agglutinate fine particles after the fermentation process. Stabilization and maturation take place for both types of wines in tanks where the wine is stored before bottling.

The product (wine) passes from the tanks to the filters during the transfer process. Filtration is carried out with tangential filters or with the insertion of diatomite, depending on the wine’s characteristics at the end of vinification. In these last stages the lees, which are residues from the refining processes, are discarded.

The bottling phase, where the wine produced is bottled, is associated to the preparation of materials, the filling process, packaging, and storage of the final product for later distribution to the consumer. This phase requires a series of steps and the insertion of various materials in their respective production lines, such as glass bottles, corks, capsules, adhesive, cardboard boxes, plastic film, PET bottles and plastic bags (BIB).

On line 1, the glass bottles are aligned, rinsed (Figure 17A), filled with wine, corked, encapsulated (Figure 17B), and labelled. Then, it’s grouped inside boxes to be stored and properly transported, which similarly occurs for PET bottles (line 2) and BIB packaging (line 3).

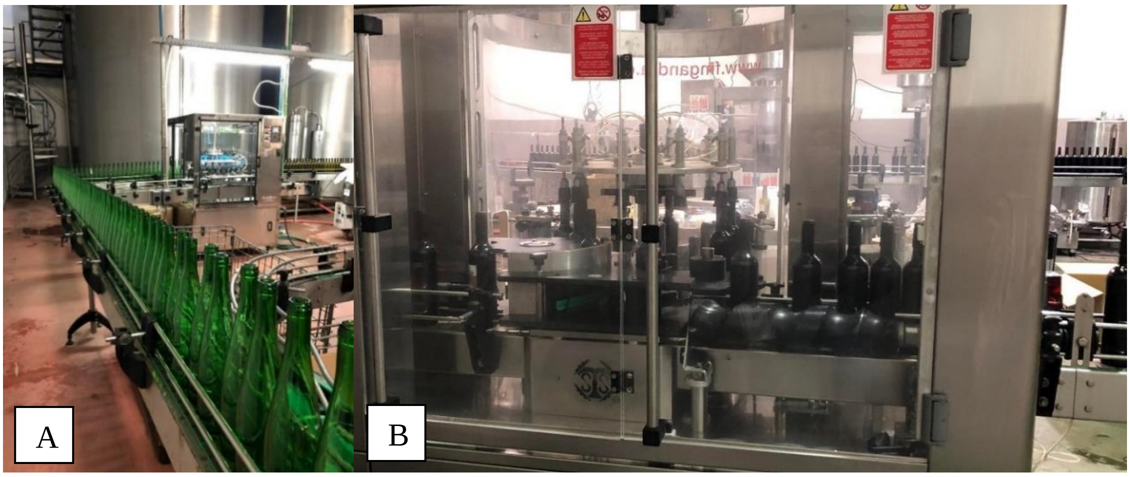

Figure 17: A - Glass bottles in alignment process for rinsing. B - Glass bottles with corks in the encapsulation process.

In the PET bottling process, the bottles are washed and filled with wine, but the insertion of the PET plastic stopper is done manually, as is the process of removing the product from the production line, its organization and consequent palletization. Bag-in-Box, in turn, have the simplest process, where wine is filled mechanically (Figure 18), while boxing and palletizing are manual.

Figure 18: Bag with wine before the boxing process (BIB).

At this stage, the main waste generated is glass; plastic; and cardboard, from discarded, broken or defective materials, in any of the steps of the bottling sector.

In a general context, there is the generation of wastewater from vinification and bottling, where water is usually used for cleaning and disinfection of environments addition to the auxiliary processes that support the entire production process.

3.2. GABI SOFTWARE

According to Sphera (2012), the GaBi software system is a tool that creates life cycle modelling and balance sheets. Life cycle engineering is a method of evaluating the environmental, technical, and economic impacts of products, services, and systems, as well as socioeconomic aspects.

GaBi's visualization approach allows for the construction of system and product models as they would be drawn on paper. This software provides support for managing large datasets and modelling product lifecycles, calculating different types of balances, and assisting in the analysis and interpretation of results. Furthermore, it can be used to model and analyse process chain systems; create a reference for the study objectives, perform material and energy analyses, and define reference quantities.

Its system is modular, composed of plans, processes, and flows, so being considered a clear and intuitive structure. The individual life cycle stages (e.g., manufacturing, distribution, use or disposal phases) can be grouped and processed separately from one another.

Data related to life cycle inventory and life cycle impact assessment are separate from each other, so these individual modules can be easily managed and are combined only during balance sheet calculation.

Another characteristic of this type of system is that the software and the databases are not dependent on each other, and therefore, all information related to the product, such as material properties, eco-profiles, among others, are stored in the database.

3.3. FUNCTIONAL UNIT AND SYSTEM BOUNDARY

The methodology is based on the ISO 14044 standard, which provides further instruction on the development of LCA stages. After defining the location and goal, the functional unit and the system boundary are defined.

The functional unit (FU) used in this work is a 0.75 L wine bottle. Worth highlighting that this unit is an efficient and consistent way of evaluating qualitative and quantitative aspects of wine production processes (Rugani et al., 2013), in addition to being the size of the wine bottles produced, and the FU used in most studies on LCA in this area, facilitating comparisons between them, as shown in Table 2 (section 2.6).

A fundamental issue in the analysis of comparability and completeness of the results of an LCA is to delimit the production system. Defining a gate-to-gate analysis (e.g., from vinification to bottling) approach, more accurate impact category scores can be provided, as data are usually collected within the same denomination and for a limited number of production processes (Rugani et al., 2013).

On the other hand, when the approach encompasses upstream agricultural practices (e.g., viticulture, organic agriculture), consumption, end-of-life processes, modelling based on scenarios and case studies is necessary, depending on the scale condition, and especially data availability, which is not always accessible to carry out consistent modelling (Rugani et al., 2013).

In accordance with Vázquez-Rowe et al. (2013), it can be argued that appellations that receive grapes from individual producers should disregard the agricultural phase, as in these cases this activity does not directly depend on the management of the winery. However, it should be highlighted that this does not change the fact that the appellations are made with strict quality standards, with specific guidelines for monitoring the agricultural practices of the vineyards in terms of pest control, fertilization or permitted grape varieties.

The winery possesses its own vineyard that represents a tiny percentage of all the wine that is produced. The grapes used by the winery come from local producers in the *Vinho Verde* region. Due to the large number of suppliers, with different viticulture management (machinery, phytosanitary products, irrigation), it was not possible to quantify the vineyard stage and include it in this study.

Thus, the established approach was gate-to-gate, with the system boundary encompassing the winemaking and bottling processes. In this context, data on the transport of grapes, bottling materials and oenological products will also be considered (Figure 19).

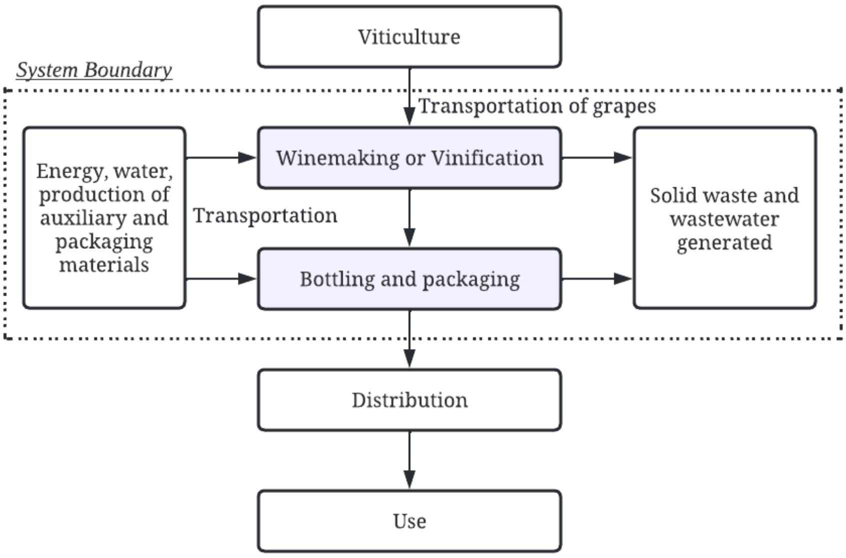

Figure 19: System boundary of study.
Source: adapted from Martins et al. (2018).

Data on the production of oenological products and materials packaging were considered when these data were available in the GaBi software database.

3.4. INVENTORY ANALYSIS

3.4.1. Data Acquisition

In the LCI stage, a series of data were collected by creating an inventory. Data collection was carried out “in loco”, with the collaboration of managers, through the application of detailed questionnaires or internal reports that aim to extract relevant primary information from each stage of production. On the other hand, information unknown to managers was obtained through interviews with those responsible for the sector under analysis, bibliographic references, and for the set of databases available in the software (secondary data). Empirical data were avoided.

The primary qualitative and quantitative data from the 2020 campaign were considered to the vinification and wine bottling. All inventory data is considered primary data. The secondary data are those obtained through software database.

Data will be separated into inputs and outputs; the inputs still can be separated in indirect and direct inputs. As indirect inputs, the data of materials fabrication that subsidize the production process can be considered, such as those upstream and downstream of the analysed stage (considering the system boundary), for example, external transport (from origin to the cellar), energy production, water treatment for supply, production of packaging materials, raw material extraction, among others.

On the other hand, direct inputs can be considered all those indispensables to the production process, in other words, where each element is directly related to the system, such as the amount of energy, water, grapes, materials packaging used, among others.

In the outputs, the data produced downstream (or “gone out”) of each analysed process were considered, such as solid waste, wastewater, and the final product. In this context, reuse, or recycling processes within or between processes are included.

After collection, all data obtained were correlated with the functional unit (0.75 L wine bottle).

3.4.2. General data

General primary data to quantity of wine produced, grapes vinified, purchase of must, and quantity of materials purchased for bottling are fundamental to identify and perform the necessary calculation to evaluate the impacts from producing a bottle of wine (FU) (Table 3).

Table 3: General data on wine production in the winery in 2020.

Parameters	Total quantity	Unit
Bottled wine	4,897,941.25	L
Grapes received	1,132,887	kg
Must purchased	3,509,577.00	L
Electricity	325,482	kWh

3.4.3. Vinification

Vinification represents the processes of wine production. The main input data at this stage are purchased grapes and musts, oenological products, and electricity; During the processes, the produced must suffers losses (outputs), as solid residues (stems, pomace and lees); emissions (air, water and soil); also include in this phase the production of energy in each process, production of diesel and use of transport (truck). Although water is not used to make wine, it is used for cleaning equipment, which was considered in auxiliary processes.

From the generated biomass residues, grape stem and pomace become by-products, used as compost for agricultural crops and in the production of brandy (by other companies), respectively (Table 4).

Non-methane volatile organic compound (NMVOC) and Carbon Dioxide (CO_2) represent the main gaseous emissions, specifically, in the alcoholic fermentation process. To calculate the amount of NMVOC emitted by FU, of which ethanol stands out, the methodology of the EMEP/EEA (2019). While for CO_2 it was not considered (Benedetto, 2013), since the amount of CO_2 recovered from the atmosphere through photosynthesis is equal to that resulting from the fermentation process (Notarnicola et al., 2003; Paim, 2020). The fermentation process had the input and output values calculated by reference to the studies of Cavaglia et al. (2019 and Mena (2015), due to difference in density of must and wine.

This study was not carried out by type of wine due to insufficient data and the difficulty in separating data from electricity.

Table 4: Main vinification data in functional unit (0.75 L).

Inputs	Quantity	Unit	Transport	Distance	Source
Grapes	0.993	kg	Euro 6, 12 – 14 t (9.3 t payload capacity)	39.5	Inventory data
Must purchased	0.651	L	Euro 6, > 32 t, (24.7 t payload capacity)	426.1	
Oenological Products	0.00068	kg	-	-	
Electricity in Vinification	0.0432	kWh	-	-	*
Outputs	**Quantity**	**Unit**	**Source**		
Grape Stems	0.026	kg	Marçal (2014) and Teixeira (2017)		
Grape Pomace	0.186	kg	Inventory data		
Lees	0.056	kg			
Wine	0.75	L			
NMVOC emissions	0.006	kg	EMEP/EEA (2019)		
Emissions from electricity production	-		GaBi software database version 10.6		
Emissions from diesel production	-		GaBi software database version 10.6		
Emissions from transport use	-		GaBi software database version 10.6		

Note: *The use of electricity is detailed in the subchapter 3.4.5. 1)Truck type, gross weight, and payload, respectively. 2)From origin to winery (in kilometres).

Oenological products are used to aid in the fermentation process and in the clarification and stabilization of the wine in order to remove unstable compounds and obtain a product that will not show significant changes in the aging phase. (Puškaš et al., 2021).

The winery uses around 25 types of oenological products, of which only 12 could be quantified (Table 5). The use of these products is related to the characteristics of the must in the fermentation process and the wine to be obtained, therefore, they suffer variations in use throughout the year. For greater reliability of the data, a sampling with production data by castes of the year of study was used.

Of the 12 quantified products, only four could be inserted into the software due to the lack of processes that represent them in the database. Figueiredo et al. (2014) had the same limitation.

Activated carbon, bentonite, diammonium phosphate and diatomite are oenological products that originate from mineral extraction. In the alcoholic fermentation process: activated carbon is an adsorbent usually used for bleaching and stain removal, to correct wine characteristics, such as colour by clarification; bentonite is also an adsorbent used to eliminate impurities, preserving aroma and colour; diammonium phosphate is a nutrient used to stimulate yeast growth (yeast nutrition and protection) ensuring a complete fermentation. Finally, diatomite is a mineral with excellent adsorption capacity too, since it is a porous material, used in filtration process.

Table 5: Inputs of Oenological products data in vinification for functional unit (0.75 L).

Oenological Product	Quantity	Unit	Transport[1)]	Distance[2)]
Diammonium phosphate – DAP	0.000075	kg	Euro 6, up to 7.5t (2.7 t payload capacity)	48.0
Bentonite	0.0003	kg		59.0
Activated carbon	0.00015	kg		69.0
Diatomite	0.000158	kg		28.0
Yeast (Fermol Millennium)*	0.00015	kg		28.0
Polyvinylpolypyrrolidone – PVPP*	0.0003	kg		59.0
Nutrient (Oenostim)*	0.000225	kg		44.0
Gelatine (Goldenclar Instant)*	0.00015	kg		48.0
Enzyme (Endozym)*	0.00003	kg		28.0
Metatartaric Acid*	0.000075	kg		69.0
Gum arabic (Hi-flow)*	0.000001	kg		59.0
Potassium sorbate*	0.000150	kg		69.0

Note: *Products that data is not available in the GaBi database. [1)]Truck type, gross weight, and payload, respectively. [2)]From origin to winery (in kilometers).

The mentioned emissions collaborate for the characterization of wastewater, being a mixture of water, chemical residues (hygiene, oenological products), biomass residues, and leftover must, while to bottling process, is characterized by water, hygienical products and leftover wine, as evaluated by Teixeira (2017).

3.4.4. Bottling

Bottling data collection was carried out by reading supplier invoices, production data, and weighing the materials used.

For PET bottles and BIB packaging, a mass approximately 6.67 times smaller was used, since both have a capacity of five litres. Ferrara & de Feo (2020), performed the adjustment of package sizes to facilitate comparison between them.

The mass data that could not be quantified in the company were obtained through technical documents from the suppliers themselves, also through arithmetic averages, as is the case with the glass bottle. Although glass bottles are mostly standard size (0.75 L), there are different formats, such as Bordeaux, Rhone and Burgundy, which have different masses. (Vidrala, 2020).

In the case of the technical wine cork used, it was necessary to resort to literature, since its production process was not included in the GaBi database. For this, we used the results of impact factors from the study of Amorim (2019), who carried out a LCA of the natural and technical wine cork, using 1000 pieces as a functional unit. In this way, it was possible to quantify the impacts of the cork in the production process just by adjusting it to the functional unit in 1 piece (Table 6).

Table 6: Results of the impact categories for 1000 wine cork.

Impact Categories	Quantity	Unit	Source
CML2001 - Abiotic Depletion (ADP)	1.42E-05	kg Sb eq.	Amorim (2019)
CML2001 - Acidification Potential (AP)	0.1473	kg SO_2 eq.	
CML2001 - Eutrophication Potential (EP)	0.0348	kg PO_4 eq.	
CML2001 - Global Warming Potential (GWP 100 years)	34.3013	kg CO_2 eq.	

The screwcap, on the other hand, despite having been quantified, could not be inserted in the software flowchart, as this process was not represented in the database. Furtado et al. (2021), describes the production components of the saranex screw cap as Polyethylene (PE) and Polyvinylidene Chloride (PVDC), however, it does not indicate the proportions of this composition, making it impossible to create a new process in the software with these data.

With this, it was possible to calculate the use of each material for the production of 0.75 L of wine in each bottling line (Table 7), as well as the payload of the truck used and the distances between the supplier and the winery for each one of them.

Table 7: Input data of the three bottling lines in the functional unit (0.75 L).

Bottling in glass bottles (Line 1)					
Material	Quantity	Unit	Transport$^{1)}$	Distance$^{2)}$	Source
Glass bottle	0.43	kg	Euro 6, > 32 t, (24.7 t payload capacity)	226.4	Inventory data
PVC Capsule	0.0005	kg	Euro 6, up to 7.5 t, (2.7 t payload capacity)	73.3	
Screw Cap*	0.004	kg			
Adesive/Label	0.0005	kg	Euro 6, up to 7.5t (2.7 t payload capacity)	54.4	
Cardboard	0.026	kg	Euro 6, 14 - 20t (11.4 t payload capacity)	62.8	
Plastic film	0.0026	kg	Euro 6, up to 7.5 t, (2.7 t payload capacity)	33.40	
Cork	0.001	pcs.	Euro 6, up to 7.5 t, (2.7 t payload capacity)	70.1	Literature
Bottling in PET bottle (Line 2)					
Material	Quantity	Unit	Transport$^{1)}$	Distance$^{2)}$	Source
PET bottle	0.0135	kg	Euro 6, 7.5 t – 12 t (5 t payload capacity)	42.5	Inventory data
PET cap	0.0020	Kg			
Bottling in Bag-in-Box (BIB) (Line 3)					
Material	Quantity	Unit	Transport$^{1)}$	Distance$^{2)}$	Source
Bag (PE-LD)	0.0009	kg	Euro 6, up to 7.5 t, (2.7 t payload capacity)	14.90	Inventory data
Cardboard	0.027	kg	Euro 6, 12 – 14 t (9.3 t payload capacity)	62.83	

Note: *There was no process in the software $^{1)}$ Truck type, gross weight, and payload, respectively. $^{2)}$From origin to winery (in kilometers).

The main outputs of these processes are solid waste that is sent to a material recycling company. As it was not possible to quantify the percentages generated in each production line and knowing that the vast majority is generated by the process of line 1, these residues were inserted as outputs from the glass bottle (Table 8).

Table 8: Output data of the line 1 bottling in the functional unit (0.75 L).

Bottling in glass bottles (Line 1)					
Material	Quantity	Unit	Transport$^{1)}$	Distance$^{2)}$	Source
Plastic	0.000647	kg	Euro 6, 12 – 14 t (9.3 t payload capacity)	15.0	Inventory data
Card	0.00097	kg			
Wood	0.0000949	Kg			
Glass	0.00182	Kg			

Note: $^{1)}$ Truck type, gross weight, and payload, respectively. $^{2)}$From winery to destination.

As in vinification, the main emissions from electricity production, use of transport trucks, diesel production are calculated by the GaBi software database. The same occurs for the production of materials used in bottling, which already contains the main inputs and outputs of its production within its processes.

3.4.5. Electricity

The studied winery does not have data on the amount of electricity used in each stage of its production process. For that reason, it was used as a basis the study of Alimonti & Pecci (2022), which identified the percentage spent on electricity in all stages of winemaking, as well as bottling and auxiliary processes (Figure 20). Approximate values were found in study of Malvoni et al. (2017). The objectives of these works were to analyse the energy consumption in Italian wineries and verify technical problems in the plant, promoting solutions to save electricity and increase the efficiency of the system used.

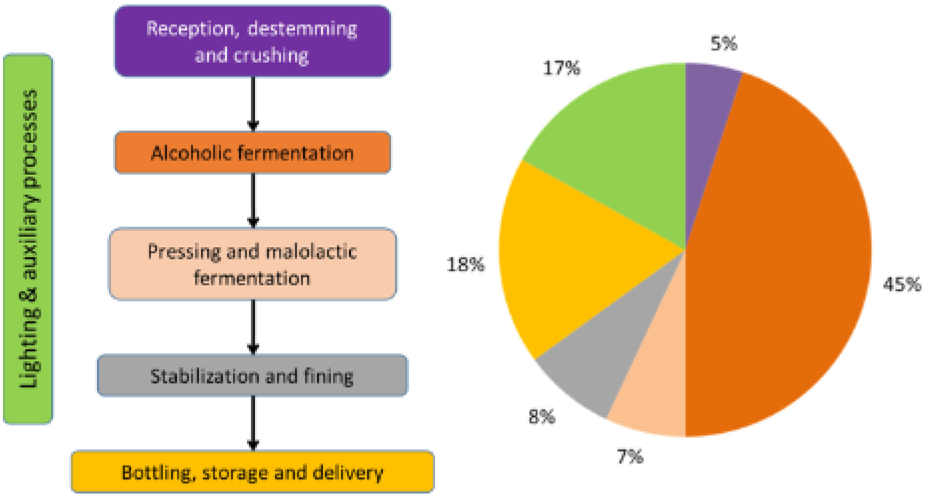

Figure 20: Scheme of distribution (%) of energy consumption used as base.
Source: Alimonti & Pecci (2022).

For the correct application of these data, the flowcharts (steps) of the company's winemaking, its production and energy consumption data were correlated with the percentage data from the literature. From this, the processes were added in the software, considering pressing and malolactic fermentation after the fermentation process. In each production process, their respective data in kWh were entered using the Gabi process for producing electricity in Portugal – *PT: Electricity grid mix Sphera* considering the annual consumption of 325482 kWh (Table 1Table 9).

The energy consumption of bottling (18%) was divided proportionally with the amount of bottled wine in each type of packaging, glass bottle (94%), PET bottle (2.5%) and Bag-in-box (3.5%).

Table 9: Energy consumption data used by process, in functional unit (0.75 L).

Processes		Quantity	Unit	Source
Reception, destemming and crushing		0.00332	kWh	Adapted from Alimonti & Pecci (2022)
Alcoholic fermentation		0.02990	kWh	
Pressing and malolactic fermentation		0.00465	kWh	
Stabilization and filtration		0.00532	kWh	
Bottling	Glass	0.01124	kWh	
	PET	0.00030	kWh	
	BIB	0.00042	kWh	
Auxiliary processes		0.01130	kWh	

3.4.6. Auxiliary Processes

For auxiliary processes, water input data, cleaning products used, energy consumption related to lighting and supply of the winery's electric forklifts, and wastewater outputs generated in the winemaking and bottling processes were considered. Even being considered as auxiliary processes, the cleaning and lighting results were analysed separately.

Water

In order not to overestimate the impacts caused by the input of cleaning water in each process, the entire amount generated in the auxiliary processes plan was considered. The winery does not provide water consumption data since its supply comes from groundwater capture (borehole) and there is no hydrometer to perform water consumption readings.

Thus, the study by Matos & Pirra (2020) was used, who compared the water consumption of three wineries in the Douro region in Portugal. Data calculation was based on winery production and specific water consumption in the literature. (Table 10).

Table 10: Data on the specific water consumption for every 0.75 L of wine produced in winery.

Process	**Consumption**	**Percentage**	**Source**
Reception, destemming and crushing	0.23 L	3.49%	Adapted from Matos & Pirra (2020)
Alcoholic fermentation	1.82 L	27.50%	
Pressing and malolactic fermentation	0.41 L	6.15%	
Stabilization and filtration	2.59 L	39.14%	
Bottling	1.57 L	23.72%	
Total	**6.62 L**	**100%**	

The values found show that to produce a 0.75 L bottle of wine, approximately 6.62 L of water are used. Although this value has not been observed in Portugal, as there is also variability in the size of wineries, there are countries such as the USA, South Africa and Italy that presented similar values (Costa et al., 2020; Matos & Pirra, 2020).

Cleaning Agents

The main cleaning agents used in the winery are Sodium hydroxide (NaOH) (50% of caustic soda) and Sodium hypochlorite (NaClO). (Table 11). These processes were inserted in the software with their respective transports (*GLO: Truck, Euro 6, up to 7.5t - 2.7t payload capacity*) and the distance from the supplier to the winery. For this purpose, data from the invoices were used.

Table 11: Data on the amount of cleaning agents used per functional unit (0.75 L).

Parameters	**Quantity**	**Unit**	**Distance from origin**	**Source**
Sodium hydroxide (NaOH) (50% caustic soda)	0.000531	Kg	48 km	Inventory data
Sodium hypochlorite (NaClO)	0.00049	Kg	48 km	

Wastewater

For wastewater, the same value of water consumption was considered, since all water after being used is discarded with cleaning agents, organic matter, and other pollutants. To this end, the characteristics of this wastewater were added to the outputs, which have biodegradable and non-biodegradable components and nutrients, as shown in the studies of Marçal (2014) and Teixeira (2017) as the company does not have data on the quality of the wastewater produced (Table 12).

Table 12: Characteristics of the winery's wastewater.

Parameters	**Concentration**	**Unit**	**Source**
Biological Oxygen Demand (BOD)	0.0027	(kg O_2/L)	Adapted from Teixeira (2017)
Chemical Oxygen Demand (COD)	0.00413	(kg O_2/L)	
Total Suspended Solids (TSS)	0.00217	(kg TSS/L)	
Nitrogen (N)	0.000083	(kg/L)	
Phosphorus (P)	0.00000875	(kg/L)	

After the insertion of these outputs, all the wastewater generated is sent to the municipal wastewater treatment plant.

3.4.7. Description of the processes adopted in GaBi software

Each process was chosen according to the characteristics that most represented the real process. Whenever available in the database, the processes that contained the acronym PT were used, indicating that this dataset contained therein are related to the Portuguese scenario, otherwise, the EU-28 processes were used. The acronym GLO stands for global datasets.

The main selected processes will be described based on the software database documentation (Sphera, 2022).

PT: Electricity grid mix

This dataset represents the specific average supply of electricity from Portugal to final consumers, including transmission/distribution losses of electricity supply, own electricity consumption and electricity imports from neighbouring countries. All data are calculated considering various sources of information for the corresponding reference year, and all forms of electrical production. For emissions, measured/calculated data of NOx, SO_2, N_2O, CO, CO_2, CH_4, NMVOC and particulate matter (PM) are used, taken from national inventory reports. The inventory is based on primary industry data and secondary literature data.

In Portugal, the energy mix corresponds to 26.18% of electricity from natural gas; 22.85% hydro; 21.16% from the wind; 20.13% hard coal; 4.29% biomass (solid) and other smaller values representing electricity from fuel oil and photovoltaics. As a result, the country imports around 9% of consumed energy.

EU-28: Diesel mix

This dataset represents the production of diesel and covers the entire supply chain of the refinery's products. This includes drilling wells, producing, and processing crude oil, as well as transporting crude oil through pipelines and ship to the refinery. The mixture of biogenic components and fossil fuel are individually modelled. The inventory of this dataset is primarily based on industry data and, if necessary, is completed based on secondary data.

GLO: Truck, Euro 6

This dataset is linked to the use of transport. Truck as a heavy or light vehicle for road transport. Its main inputs are diesel and cargo; and outputs: load and combustion emissions (ammonia, benzene, sulphur dioxide, carbon dioxide, nitrogen dioxide, methane, carbon monoxide, nitrogen monoxide, nitrous oxide, NMVOC, PM 2.5 particles). NMVOC emissions from the truck are the result of imperfect combustion, which leads to evaporative losses through the tank.

EU-28: Container glass

Container glass is the largest sector of the EU glass industry, accounting for almost 60% of total glass production. The most important containers in this sector, representing 75% of the total production, are beverage bottles, such as wines, beers, soft drinks, mineral water, followed by bottles for the food industry.

The main raw materials for melting are glass-forming materials such as silica sand and broken glass; intermediate/modifying materials such as sodium carbonate, limestone, feldspar; and colouring agents, as iron chromite, iron oxide. To produce glass consumes a lot of energy, and the main sources are natural gas, fuel oil and electricity.

In this way, many factors were taken into account such as the production of energy carriers; energy carrier supplies; power plants; electrical network; thermal energy (process steam); transport processes; energy carriers; refinery products.

EU-28: Carton from Folding Boxboard

The Folding Boxboard (FBB) dataset covers all relevant process steps, from the arrival of wood, recovered paper, purchased pulp and other inputs at the factory gate to the production of boxes ready for delivery to the packer/filler. Its inventory is based on primary data collected from the industry. Being represented the average production technology of plants that together represent about 71% of the total annual production of FBB in Europe.

EU-28: PET bottle

The dataset of this process represents the production mix of commercial PET bottle production technologies in Europe.

3.5. ENVIRONMENTAL IMPACT ANALYSIS

The GaBi professional version 10.6, developed by Sphera Solutions GmbH, was used to the develop the LCIA, since it has a professional database with worldwide coverage and supports life cycle analysis. This tool was developed to, among other applications, automatically track all material, energy, and emission flows, perform life cycle calculations, perform life cycle assessment, life cycle and life cycle reports in the workplace (Thinkstep, 2019).

To evaluate the impacts, the CML 2016 method proposed by Guinée (2002) in its latest version (August 2016) was used. This method is generally selected for its coverage of a wide range of environmental impacts relevant to wine (Amienyo et al., 2014) as intermediate method, the midpoint, also helps to eliminate uncertainties, allowing the analysis of individual impacts, rather than aggregating them into a single measure of environmental damage, such as endpoint.

The selection of impact categories was based on the literature, but also on the most relevant data from the inventory to ensure greater reliability of the results. As reported by Ferrara & Feo (2018), the most common categories used for the wine sector are Abiotic Depletion Potential (ADP), Acidification Potential (AP), Eutrophication Potential (EP), and Global Warming Potential 100 years (GWP), the same can be observed in studies of Amienyo et al. (2014); Aranda et al. (2005); Benedetto (2013); Gallucci et al. (2020); Gazulla et al. (2010); Neto et al. (2013); Point et al. (2012); Vázquez-Rowe et al. (2012).

According to Hauschild et al. (2018) and Paim et al. (2020), in the classification step, the elemental flows of the LCI are assigned to the impact categories with which it contributes. In another words, the elementary flows of inputs (resources) and outputs (emissions) of substances related to the inventory are assigned to impact categories according to their capacity to cause environmental problems. Hauschild et al. (2018) cites as examples, the water consumption as a precursor of water uses impact category or emission of CO_2 into the atmosphere is attributed to global warming. But some of the substances emitted can have multiple impacts that can be separated into two modules:

- The first in parallel: when a substance causes several simultaneous impacts, such as SO_2 which causes acidification and is toxic to humans if inhaled.
- The second in the series: when a substance has an adverse effect that causes something else, such as SO_2, which in addition to causing acidification, can mobilize heavy metals in the soil that are toxic to humans and ecosystems.

In any case, these problems are solved automatically by the LCA software, based on pre-programmed classification tables.

Guinée (2002) and Hauschild et al. (2018) state that characterization is when all elementary flows of the LCI are evaluated according to the degree of that contribute to a given impact. This contribution in terms of a common unit (characterization factor) for each category allows aggregation into a single score: the indicator result.

Hauschild et al. (2018) adds that for this, the amount of all elementary flows *E*, classified within a selected impact category *c*, are multiplied by their respective characterization factor *CF*, and summed over all emissions or extractions of relevant resources i, obtaining an indicator result IS for the analysed environmental impact category. These results are expressed in the same specific unit for all elementary flows within the same impact category. This can be represented by equation 1 below:

$$ISc = \sum_{\mathrm{i}}(CFi * Ei) \qquad \text{Equation (1)}$$

A characterization factor (FC) represents the quantitative contribution of an elementary stream to a specific environmental impact category. In other words, is calculated to represent as realistically as possible the cause-effect chain of events of impacts on the environment (for all contributing flows).

Based on Guinée (2002), Hauschild et al. (2018), ICCA (2013), Paim et al. (2020), Shepherd et al. (2001) the selected categories were described.

3.5.1. Abiotic Depletion Potential (ADP)

For the maintenance of its subsistence, the main seeks biotic and abiotic resources. Therefore, Abiotic Depletion (AD) is associated with the use or extraction of abiotic resources, highlighting the use of fossil resources, minerals, and metals, which leads to a reduction in the availability of resources for future generations.

The unit used is kg antimony equivalent (Sb) or MJ per functional unit. The first, however, allows greater comparison between the abiotic depletion potentials as they are closer to the Sb unit. The calculation is performed using equation 2:

$$ADP = \sum_{i}(CFi * Ei) \qquad \text{Equation (2)}$$

In this context, each acronym represents – ADP: Abiotic depletion potential for a intervention *i* obtained in kg Sb-eq. kg^{-1}. CFi: Characterization factor of intervention (resource extraction) of the abiotic depletion category. Ei: Amount of elementary flow of this same intervention.

3.5.2. Acidification Potential (AP)

Acidification Potential (AP) category addresses the relative effect of total emissions of acid gases such as hydrofluoric acid (HF), hydrochloric acid (HCl), sulphur oxides (SO_X), nitrogen oxides (NOx), ammonia (NH_3), and nitrogenous acids (HNO_3). These acidifying pollutants have a major impact on groundwater and surface water, soil, biological organisms, and ecosystems, in addition to corrosion of various materials. This category is defined in the unit of sulphur dioxide equivalent (kg SO_2-eq. kg^{-1}) and the calculation is expressed by equation 3:

$$AP = \sum_i (CFi * Ei) \qquad \text{Equation (3)}$$

In this context, each acronym represents – AP: Acidification potential for a substance *i* obtained in kg SO_2-eq. kg^{-1}. CFi: Characterization factor of intervention (substance emission) of the acidification category. Ei: Amount of elementary flow of this same intervention.

3.5.3. Eutrophication Potential (EP)

The Eutrophication Potential (EP) is related to the emissions of compounds containing nitrogen (N) and phosphorus (P) directly or indirectly in the soil and in water bodies during the life cycle of the product. Nutrient enrichment can cause excessive growth of biomass in water bodies such as algae. This biomass prevents the passage of light, and consequently reduces the level of dissolved oxygen in the water, also altering its physical, chemical, and biological characteristics.

This category is evaluated in kg of phosphate equivalent (kg PO_4-eq. kg^{-1}) and can be calculated using equation 4:

$$EP = \sum_i (CFi * Ei) \qquad \text{Equation (4)}$$

In this context, each acronym represents – EP: Eutrophication potential for a substance *i* obtained in kg PO_4-eq. kg^{-1}. CFi: Characterization factor of intervention (substance emission) of the eutrophication category. Ei: Amount of elementary flow of this same intervention.

3.5.4. Global Warming Potential (GWP)

Global Warming Potential (GWP) refers to an increase in the average surface temperature of planet Earth. The Greenhouse Gases (GHGs) have different influences on warming. Due to the time, they remain in the atmosphere and their different radioactive properties, these influences can be expressed in a common measure based on the impact caused by carbon dioxide (CO_2). Therewith, all these gases are quantified in kg of CO_2

equivalent. The CO_2-eq is obtained by multiplying the GHG emission by its global warming potential (GWP) for a given period, according to equation 5:

$$GWP = \sum_i (CFia * Ei) \qquad \text{Equation (5)}$$

In this context, each acronym represents – GWP: Global Warming Potential for a substance emitted i obtained in kg CO_2-eq. kg^{-1} to emission. CFi: Characterization factor of intervention (emission) over one-year a, of the global warming category. Ei: Amount of elementary flow emitted of this same intervention.

The LCA interpretation phase corresponds to the analysis of the results of the selected categories, to evaluate the stages and processes that are most potentially harmful to the environment and then identify opportunities for improvement.

3.6. SENSITIVITY ANALYSIS

For the sensitivity analysis, a set of data was chosen, considering it more variable or uncertain, to verify its influence on the results of environmental impact.

The sensitivity analysis was performed considering the parameters electricity, yield of the grape and glass bottle, to verify how much each of them would be able to change the proportions of the impact for each of the categories: ADP, AP, EP and GWP (Neto et al., 2013). Thus, the most sensitive parameters will present a greater range of variation, while the less susceptible to such changes will present a variation closer to 0%.

According to the winery's electricity data for the years 2018, 2019 and 2020, it was possible to establish a variation of -5% and +7% in the annual electrical consumption. This is a factor that must be highlighted, as the winery does not quantify consumption by process and may vary according to the amount of wine produced.

Therewith, a variation of -4% and +6% in the yield of the grapes was also considered, based on the study of Laca et al. (2021), as the amount of grape juice, grape stems and grape pomace may vary annually, depending on weather conditions, practices, and characteristics of each harvest.

As for bottling variation, was considered the parameters usually established by studies of Amienyo et al. (2014); Paim (2020) and Point et al. (2012) to reduce the weight of glass bottles by 30%, as well as a minimum variation of +10%, as heavier bottles are commonly used for sparkling and sparkling wines that require greater resistance.

This analysis was performed using the GaBi analyst that uses a positive and negative variation, given in percentage (%). After the calculation, a table is generated indicating the influence of changing these parameters on the selected categories.

4. RESULTS AND DISCUSSION

4.1. IMPACT ASSSESSMENT

4.1.1. Analysis by Process

The environmental impact analysis of the vinification and bottling stages was carried out considering the four impact categories analysed, where all the values presented are kg of equivalent indicator per FU (0.75 L).

The total of winemaking impacts obtained in each category was 2.03E-08 kg Sb-eq. for Abiotic Depletion Potential (ADP); 3.80E-05 kg SO_2-eq. for Acidification Potential (AP); 1.68E-04 kg PO_4-eq. for Eutrophication Potential (EP); and 3.40E-02 kg CO_2-eq for Global Warming Potential (GWP). Neto et al. (2013), who carried out the study focused on the production of *vinho verde*, obtained similar values for the EP category, and slightly higher values for the ADP, AP and GWP categories.

Winemaking has four main processes considered in the analysis, which correspond to Reception, Destemming and Crushing (1); Alcoholic Fermentation (2); Pressing and Malolactic Fermentation (3) and Stabilization and Fining (4).

Among the processes, alcoholic fermentation stands out in most categories, representing about 71% of the impacts on ADP and AP, with the value of 1.43E-08 kg Sb-eq., and 2.76E-05 kg SO_2-eq., respectively. In the GWP category, this proportion is 75% of the impacts (2.56E-02 kg CO_2-eq. kg^{-1}), while in the EP category, it represents 38%, since the stabilization and fining process has a greater contribution, with 50% of the global impact, approximately 8.31E-05 kg CO_2-eq. kg^{-1} (Figure 21).

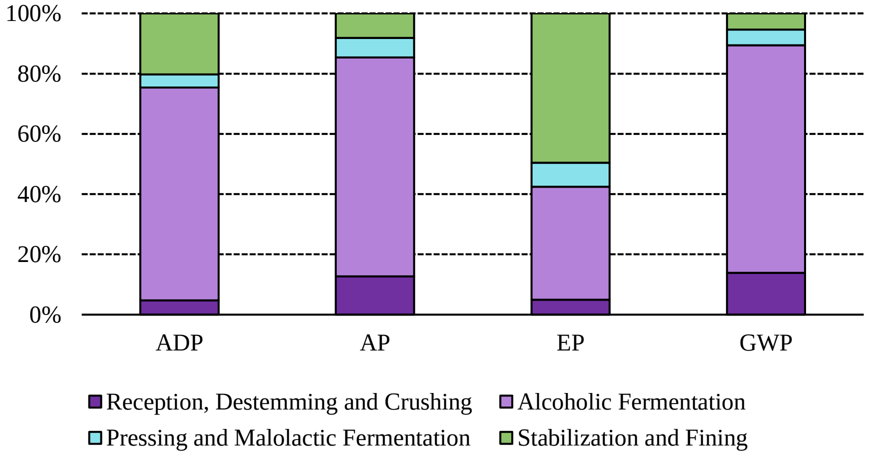

Figure 21: Impacts of winemaking processes for the four categories selected, for FU (0.75 L).

The impacts of fermentation are mainly associated with the production of oenological products used; the amount of electricity required (45% of the total consumed) to keep the vats at adequate temperatures for the yeast reactions; and the hygienization phase, that consumes about 27% of winery water, which is mixed with sodium hypochlorite (NaClO) and sodium hydroxide (NaOH) (50% caustic soda) components. As there is no use of water directly in wine production, all the water consumed is used for washing vats and equipment. (Costa et al., 2020; Matos & Pirra, 2020).

Stabilization and Fining processes, in turn, have a great contribution in the EP category, as cleaning in this process requires even more water, corresponding to 39% of the total consumed. All this used water, mixed with the products and impurities after cleaning, generate wastewater, which has higher pollutants content, such as BOD and COD, than those of domestic sewage (Bolzonella et al., 2019) and do not receive any type of treatment before being discharged the Municipal Wastewater Treatment Station.

In addition to the above, it is worth mentioning the impacts related to the transport of grapes, purchased must, oenological products and materials necessary to produce wine, which include the use of the truck and the production of diesel. Therefore, the contribution of the main factors to the impact of winemaking was also considered. (Figure 22).

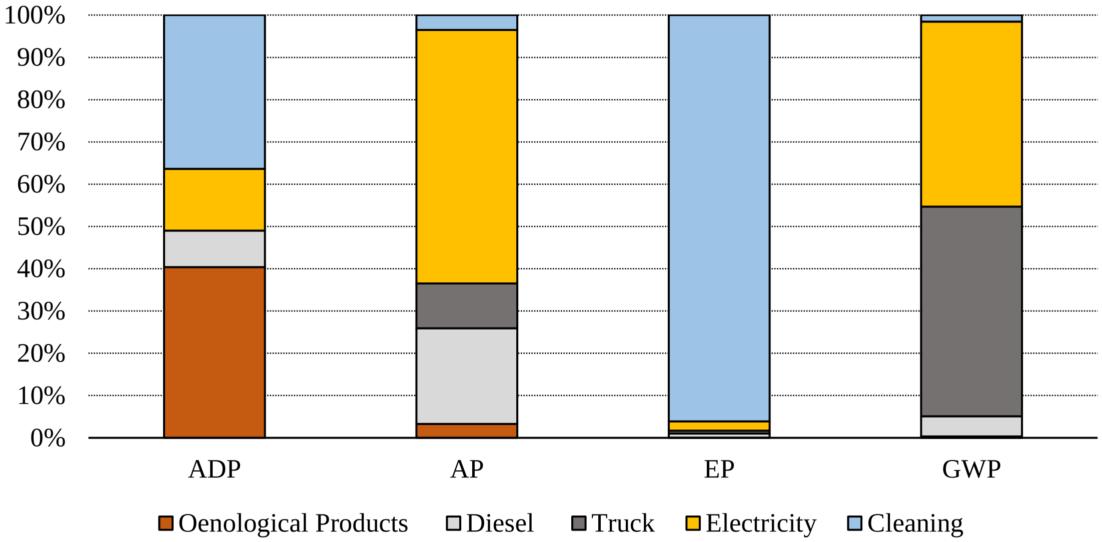

Figure 22: Impacts of factors associated with vinification, for all selected categories per UF (0.75 L)

In the ADP category, which represents a total of 2.03E-08 kg Sb-eq., the production of oenological products stood out, contributing with 40% of the impacts (8.20E-09 kg Sb-eq.). This contribution can be explained by the composition of these products being linked to the extraction of abiotic resources, such as activated carbon, bentonite, diatomite and diammonium phosphate minerals. The second largest contributor was the cleaning process with 35%, which has this representation due to the use of chemical compounds (NaClO e NaOH).

In the AP category where the total value was 3.80E-05 kg SO_2-eq., the main SO_2 emissions are associated especially with the processes of electricity production and diesel production (Fusi et al., 2014; Neto et al., 2013), representing about 60% and 23%, respectively. In smaller proportions, the use of transport, oenological products and cleaning are considered.

For the EP category, the total value of 1.68E-04 kg PO_4-eq., with the highest representation for the cleaning process, approximately 96%. This factor can be explained by the high use of water in the winery, and consequent contribution to the generation of effluents with high organic and inorganic loads, especially during the harvest period. Another potentiator is the use of cleaning agents based on compounds rich in phosphorus, one of the main causes of eutrophication. (Costa et al., 2020; Johnson & Mehrvar, 2020; Teixeira, 2017). The percentage of electricity may be associated with the production of electricity by water source.

Finally, the total impact of the GWP category was 3.38E-02 kg CO_2-eq. This category is especially linked to the emission of greenhouse gases and has as the biggest contributors the use of trucks to transport products representing 50%, the production of electricity with 44% and diesel representing 5%. Electricity is a relevant factor to this category which is justified by the fact that the largest source of Portugal's electricity mix, for the reference year (2018) comes from natural gas (26.18%) and hard coal (20.13%) (Sphera, 2022).

The analysis of the bottling process impacts was separated into line 1 (Glass bottles), line 2 (PET), and line 3 (Bag-in-box). In all of them, the production of packaging materials and their respective transport were considered.

In line 1, the total impact values were 7.10E-07 kg Sb-eq. for ADP category, 2E-03 kg SO_2-eq. for AP; 2.94E-04 kg PO_4-eq. for EP, and 4.25E-01 kg CO_2-eq. for GWP.

Along these same lines, glass stands out as the biggest contributor in all categories, representing around 96% of the impact on ADP (6.82E-07 kg Sb-eq. kg^{-1}), 91% on AP (1.82E-03 kg SO_2-eq. kg^{-1}), and approximately 80% of the impacts in EP and GWP, presenting values of 2.41E-04 kg PO_4-eq. and 3.44E-01 kg CO_2-eq., respectively (Figure 23).

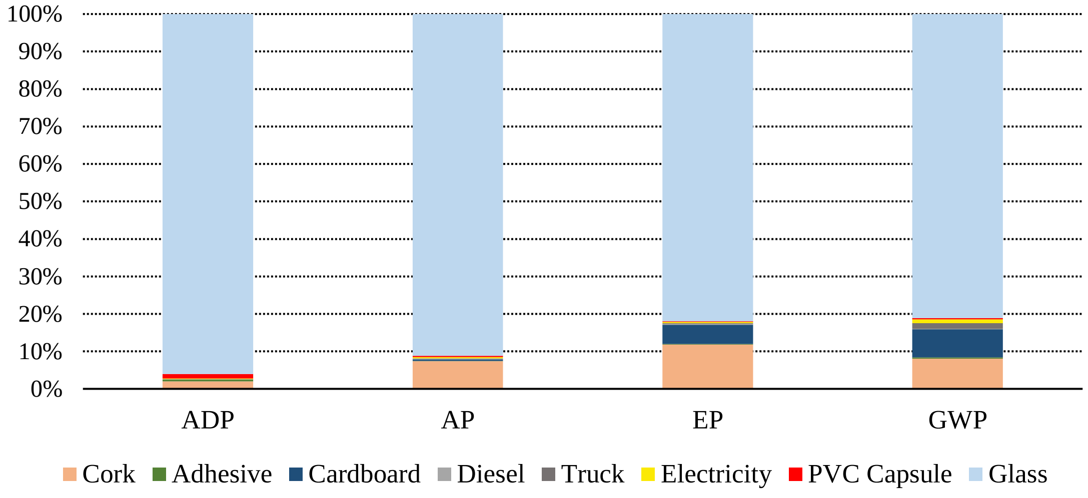

Figure 23: Impacts of bottling line 1 (glass bottle) for all selected categories, per functional unit (0.75 L).

As expected, the glass bottle is the package that most contributes to the impacts caused during the bottling process due to its production incorporating different material, such as soda lime, usually melted in a fossil fuel oven. The main raw materials for melting are glass-forming materials such as cullet and silica sand; intermediate materials such as limestone, feldspar, and soda ash, as well as colouring or bleaching agents such as iron oxide and iron chromite. All these materials are of mineral origin and non-renewable (Sphera, 2022).

With the exception of glass, in the ADP category there are two other materials that vary between 1 and 2% of the total impact, the PVC capsule and cork stopper, respectively. For AP, it is worth noting that cork represents about 7%, with the other materials having lower values. Regarding the EP, cork represents 11% of the impact (3.48E-05 kg PO_4-eq. kg^{-1}) and cardboard 5%. Finally, for the GWP the other biggest contributions were approximately, 8% from cork, 7% from cardboard.

In accordance with Amorim (2019) the impacts of the technical cork stopper are related to the consumption of electricity, natural gas, and the use of silicone elastomer for surface treatment, which is a contributing factor to the ADP category.

For line 2, the total values of impacts for each category were obtained, being 3.98E-06 kg Sb-eq. for ADP; 9.67E-05 kg SO_2-eq. for AP; 4.18E-05 kg PO_4-eq. for EP and 3.33E-02 kg CO_2-eq. for GWP.

The biggest contributor in all impact categories was Polyethylene terephthalate (PET) which is the container material used in this type of packaging. In the ADP categories it represented almost 100% (3.98E-06 kg Sb-eq. kg^{-1}), AP represented 99.4% (9.61E-05 kg SO_2-eq. kg^{-1}), EP represented 99.7% (4.16E-05 kg PO_4-eq. kg^{-1}) and at GWP it represented approximately 98% (3.27E-02 kg CO_2-eq. kg^{-1}). Other impacts correspond to less than 2% in all categories (Figure 24).

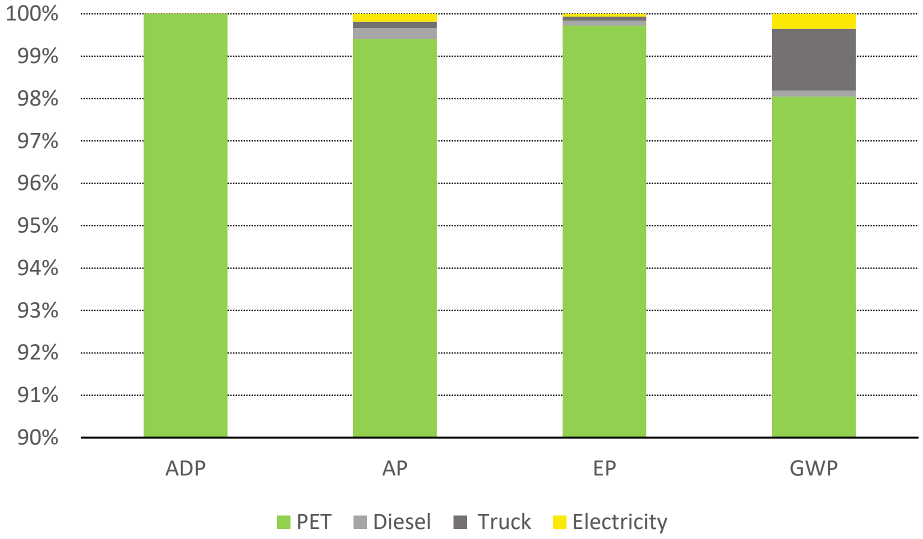

Figure 24: Impacts of bottling line 2 (PET bottle) for all selected categories, per functional unit (0.75 L). Note: To improving the visualization, the scale has been changed.

Line 2 and 3 packaging are plastics, whose manufacture derives from fossil resources. Both PET and low-density polyethylene (LDPE) are among the five most produced plastics globally and are primarily responsible for greenhouse gas emissions. (Meys et al., 2020).

Line 3 presented total impact values of 7.53E-10 kg Sb-eq. for ADP, 7.31E-05 kg SO_2-eq. for AP, 8.09E-05 kg PO_4-eq. for EP and 1.74E-01 kg CO_2-eq. for GWP.In the ADP category, the greatest representation is expressed by Bag with about 70% of the impacts (6.23E-10 kg Sb-eq.), while in the AP category it represents 35% as cardboard contributes around 63%. Cardboard also stands out in the EP and GWP categories, corresponding to 96% (7.89E-05 kg PO_4-eq.) and 92% (1.64E-01 kg CO_2-eq.), respectively (Figure 25).

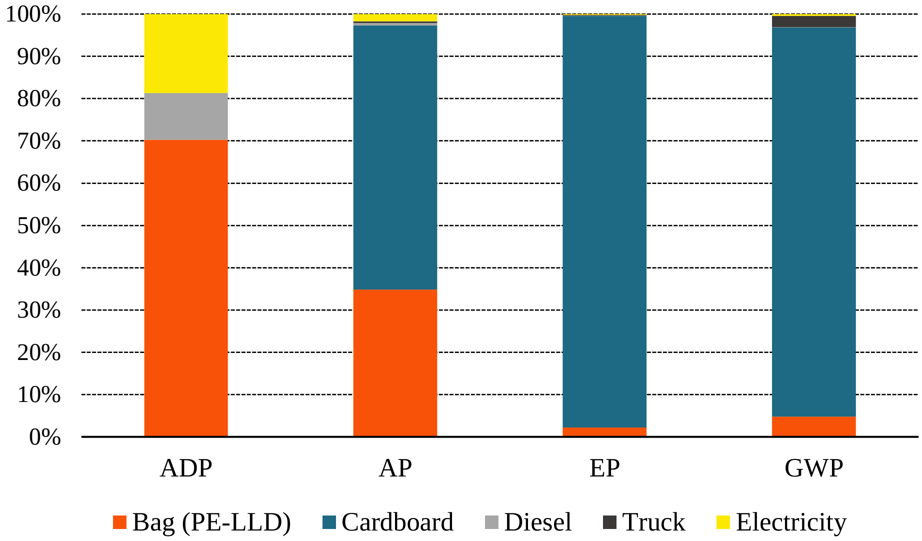

Figure 25: Impacts of bottling line 3 (BIB) for all selected categories, per functional unit (0.75 L).

The manufacture of cardboard has a strong relationship with COD (Chemical Oxygen Demand) discharges into the environment, especially due to the presence of substances that bind its structure, which is even greater in the production of virgin paper than recycled (EEA, 2006), interfering with the eutrophication impact (EP). Acidification and global warming may be related to the use of chemical compounds in their production, especially for the blanket process as well as the burning of biomass that intensifies the emission of SO_2 and CO_2 (Huijbregts et al., 2008; Lin et al., 2022; Sphera, 2022)

Less representative values of impact related to transport, especially in the GWP category, in the three bottling lines can be justified by the distance from the origin to the winery, but also by the difference in density of the materials, which interfere with the truck's payload (e.g., transport of PET is more related to the volume occupied than to its weight).

4.1.2. Product Analysis

When analysing the production process, in a global way, the disproportionality between the stages is verified, where the vinification is tiny when compared to the bottling.

Bottling, in turn, occurs through the diversification of products, which packs the wine produced, and has as a differential the types of materials that were added to it.

The process with the highest impact values is those related to product 1 (glass bottles), especially in the AP, EP and GWP categories (Figure 26). In the ADP category, the opposite situation occurs, not least because the proportion of silica available in the world is higher than that of petroleum and, consequently, the impact of the extraction and manufacture of products derived from this resource will also be. As a result, product 2 (PET) becomes the largest contributor in the ADP category, while product 3 (BIB) has the lowest impact (1.37E-08 kg Sb eq.).

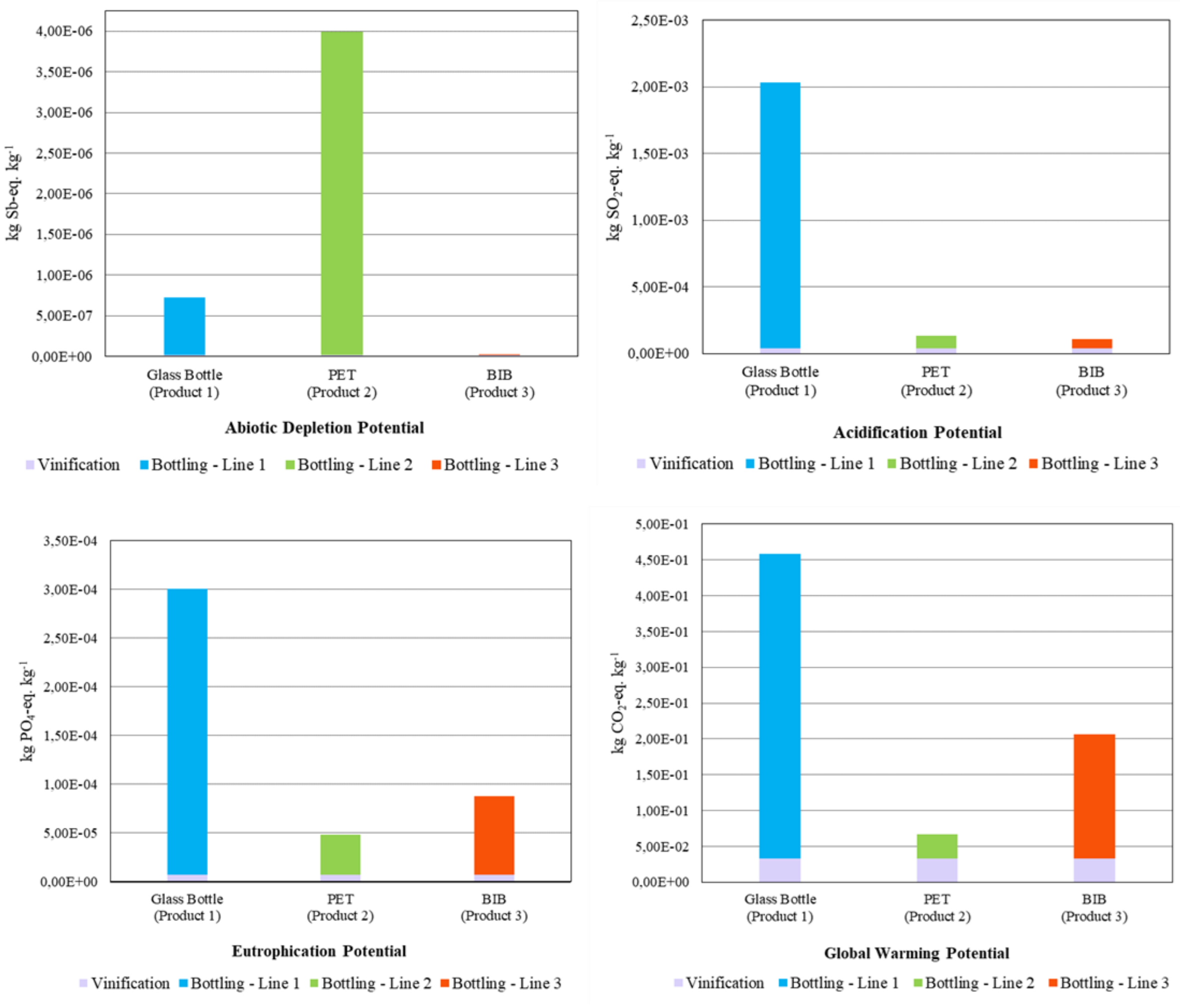

Figure 26: Global results for all impact categories, in FU (0.75 L).
Note: Between the categories, there is a difference in the scales.

The product 1 stands out as having the greatest potential for impact (2.03E-03 kg SO_2 eq.). in the AP category. Differently, product 2, represents 1.33E-04 kg SO_2 eq. and product 3 which has 1.10E-04 kg SO_2 eq. of representation in this category.

A similar situation occurs in the EP category, where product 1 still has the highest value, however, product 3 has a slightly higher value (8.74E-05 kg PO_4 eq.) than product 2 (4.83E-05 kg PO_4 eq.).

Analysing the GWP category, it can be inferred that it is the category where winemaking has the greatest contribution in relation to bottling. The product 1 has contribute with 4.58E-01 kg CO_2 eq., and similar values (approximately 6E-01 kg CO_2 eq.) were presented by Amienyo et al. (2014) and Rugani et al. (2013). Overall, this is where product 3 stands out the most, representing about 2.07E-01 kg CO_2 eq. It is the most significant negative difference when compared to product 2 (6.66E-02 kg CO_2 eq.), being that this factor can be explained using cardboard in the BIB, which, as mentioned above, has a greater proportion of impact in this category.

When comparing the environmental impact of beer production and its bottling in a glass bottle (Amienyo & Azapagic, 2016) and the wine production and glass bottling of this study (product 1), it is noted that the results obtained for beer are more representative, for while wine generates 4.58E-01 kg CO_2 eq. in GWP, the beer generates about 1.22 kg CO_2 eq. in the same category. Amienyo & Azapagic, (2016) also compared three different types of beer packaging, namely glass bottle, aluminum can and steel can, and as shown in product 1 of this study, bottling in glass is the one that generates the greatest environmental impact.

For most categories, it appears that the glass product is the one that causes the greatest impact among the three analysed, being PET and the intermediary. However, the BIB remained with the lowest values and the lowest variation in all categories, proving to be the most viable. The same can be observed in the study of Ferrara & de Feo (2020).

4.2. SENSITIVITY ANALYSIS

The choice of the set of parameters for this analysis had the main objective of encompassing the most uncertain data from the inventory, to verify how much each of them would be able to change the proportions of the impact for each of the categories: ADP, AP, EP and GWP (Neto et al., 2013). Thus, the most sensitive parameters of this work are identified, being the ones that present a greater range of variation. The less sensitive ones were also identified, being the ones that present a variation closer to 0%.

The results were obtained using the standard deviation, indicating a variation of ± (plus or minor) for each category, corresponding to the change in the parameter (Table 13).

Table 13: Sensitivity analysis results based on selected impact parameters and categories.

	Standard deviation values (±)							
Parameters	**ADP**		**AP**		**EP**		**GWP**	
	(-)	**(+)**	**(-)**	**(+)**	**(-)**	**(+)**	**(-)**	**(+)**
Electricity	0%	0%	-2.10%	2.94%	-1.88%	2.63%	-1.61%	2.25%
Grape	0%	0%	0.32%	-0.43%	0.28%	-0.39%	0.25%	-0.33%
Glass bottle	0%	0%	-27.8%	9.25%	-27%	8.99%	-24.50%	8.16%

A variation of 0% was obtained in the ADP category for all parameters, noting that this category is not susceptible to such changes.

The electricity, which was estimated with a variation of -5% and +7%, leads to small changes in the categories acidification (-2.1%; +2.9%), eutrophication (-1.9%; +2.6%) and global warming (-1.6%; 2.3%), demonstrating that when the values of this input are lower, there will be a reduction in the impact, as well as for higher values of electrical consumption, there will be an increase in the impacts.

Despite being a small percentage, it is inferred that this factor is relatively sensitive since electricity is a variable component over the years and its impacts are linked to different sources due to the Portuguese electrical mix.

The same comparison can be observed for the glass bottle parameter, since the relationship between this parameter and the categories turn out to be corresponding. It means that, the greater the parameters deviation, the greater the categories impact, even if in different proportions.

The abovementioned can be observed since for a reduction of -30% in glass bottle weight, there was a decrease of almost -28% in the AP category, -27% in EP and 24.5% in GWP, while for an increase of +10% in glass bottle weight, the increase in the AP, EP and GWP categories were 9.25%, 9% and 8.16%, respectively. Even though it was the parameter that established the highest percentage of change in the methodology, the results had the highest amplitude, almost proportionally, demonstrating that the weight of glass bottles is an extremely sensitive parameter.

The opposite occurs with the yield of grapes, because the higher this yield, the impact tends to be lower. In the same way that a lower yield causes an increase in impact. For all categories, the change in grape yield was less than ±1%, making it a parameter with very low variation, and consequent low sensitivity (Laca et al., 2021).

5. CONCLUSION

In this study, the LCA methodology was used to quantify the environmental impacts associated with the production of *vinho verde* in the Minho region, being one of the few works in the topic dedicated to this specific wine reported in the literature so far. It is possible to observe from the global analysis that the winemaking represents a small value compared to the bottling process in all lines in the winery.

The use of glass bottle (line) in the bottling process was the greatest contributor of environmental impacts, followed by the pet bottle (line 2). It is worth mentioning that in ADP category the PET bottle surpasses the potential impacts of the glass bottle, situation that occurs only once in this study. On the other hand, in the other categories PET bottle presented low potential impacts compared to glass bottle and BIB (line 3). The BIB, in turn, remained at low and medium values for all analysed categories, being, therefore, suggested the one with the lower environmental impact potential, among the three ones evaluated.

Still regarding the bottling, the cardboard materials (used in lines 1 and 3) and technical cork (used in line 1) are the ones that presented the most significant impacts. It is worth mentioning that in most cases cork is not considered as a potential cause of impact in the literature, since that natural cork are generally considered. However, this study found that in case of technical cork there are potential significant impacts related to this material, which suggests that natural corks are more environmentally friendly materials.

The electricity, diesel and truck are also processes that influence the environmental impact from both winemaking and bottling. Its use is linked to indirect production processes, which are related to the electricity and diesel production processes, as well as the use of the truck in materials transportation.

In vinification, the process that most contributes to the ADP, AP and GWP categories is alcoholic fermentation, due to the use of oenological products. Even though this process is still representative in the EP category, the stabilization and fining process is more representative to this category since it is where most NaClO and NaOH are spent on equipment cleaning.

Finally, in the sensitivity analysis for the three parameters used, the one that presented greater variation in relation to the results was glass bottle weight, becoming the most sensitive factor for the represented system. Electricity is also relatively sensitive, while grape yields are not very sensitive to variations.

In future studies it should be considered that:

- It is essential to acquire a database that contains a set of data linked to the wine sector, which are available at high costs and need to be previously evaluated. It is recommended to find companies that can provide primary data and/or encourage others to perform periodic self-assessments to acquire trustworthy data.
- Expand the system boundary to the “cradle to grave” type considering the life cycle stages not included in this work, such as vineyards, distribution, consumption, waste treatment and end-of-life options for packaging.

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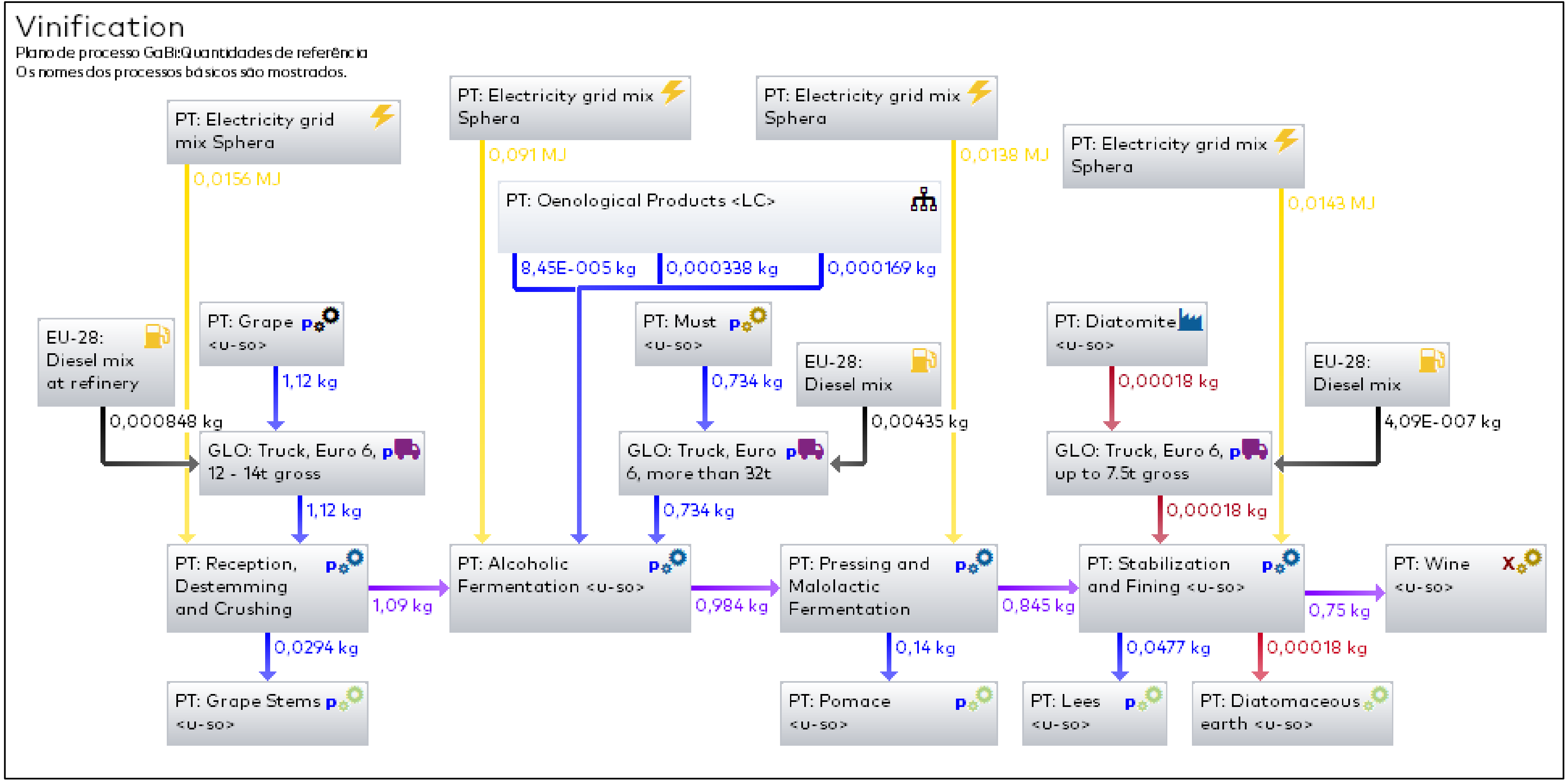
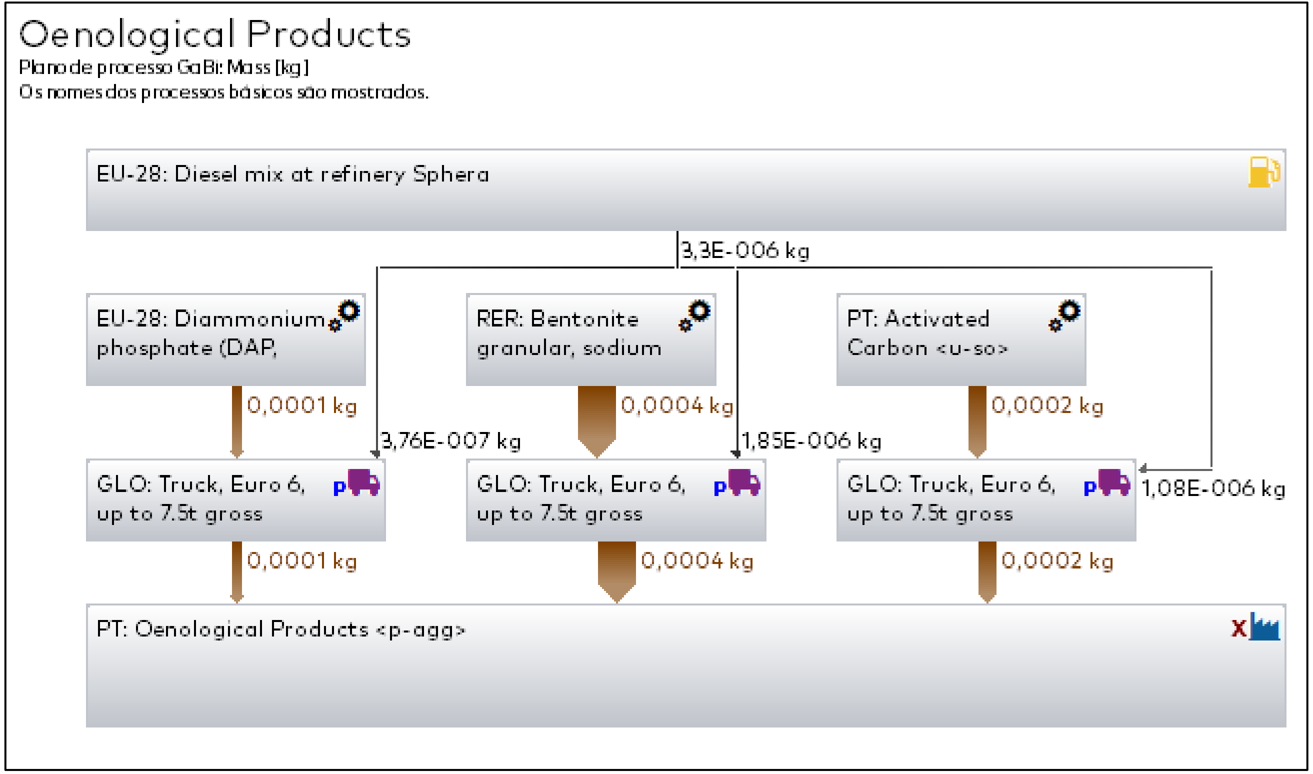
LIST OF ANNEXES

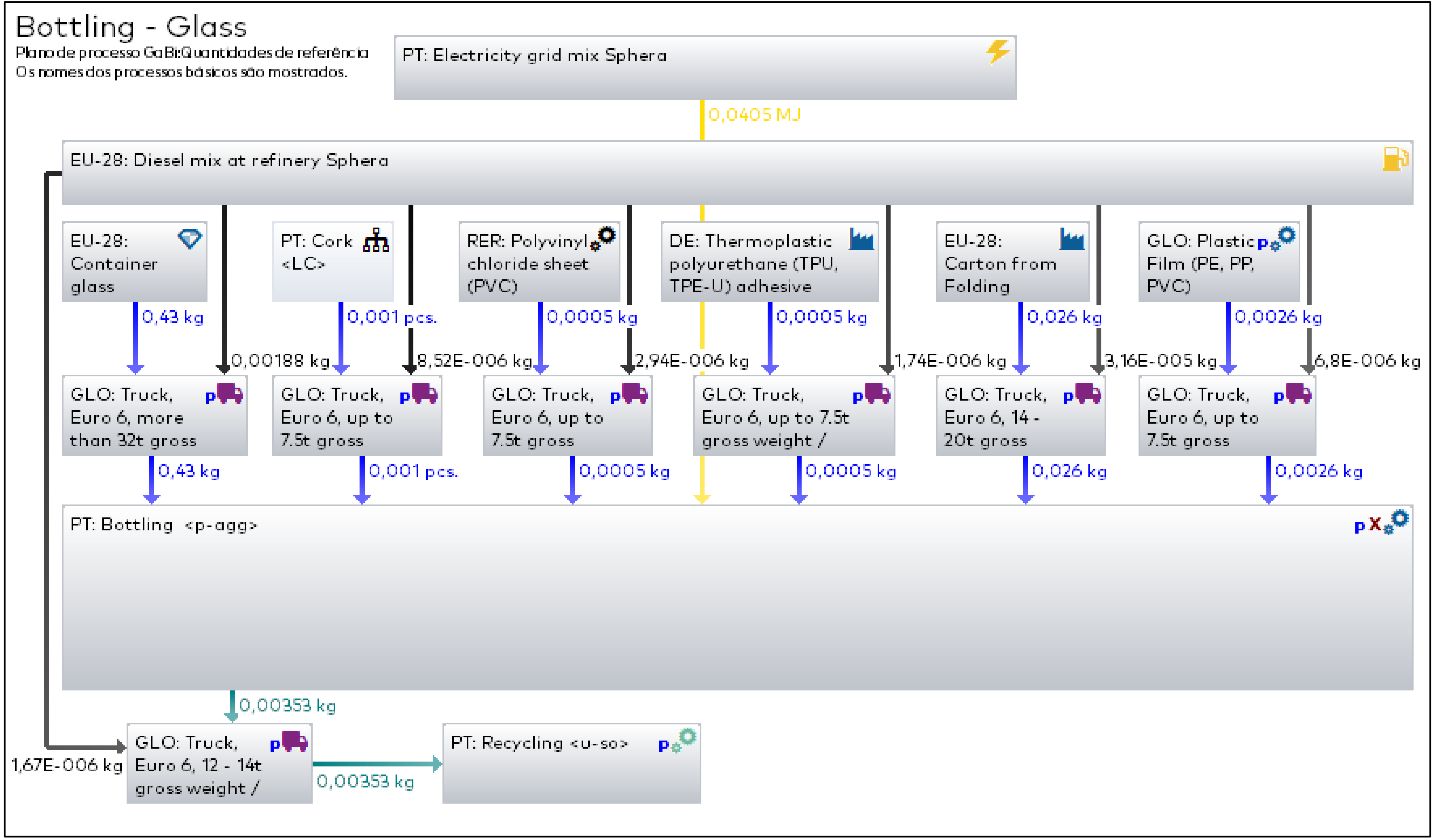
ANNEX I. Flowchart of the winemaking/vinification process inserted in the GaBi software version 10.6.



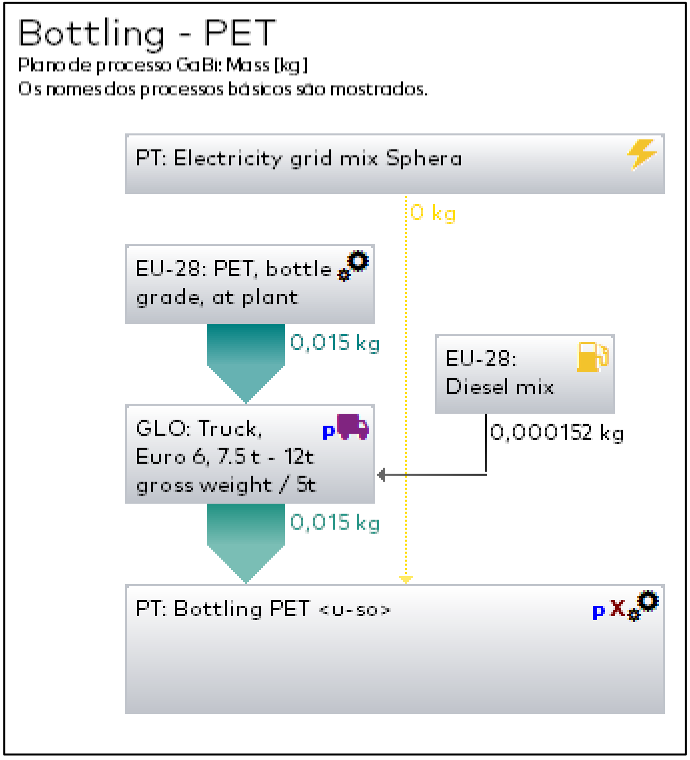
ANNEX II. Flowchart of the oenological products present in the GaBi software version 10.6.



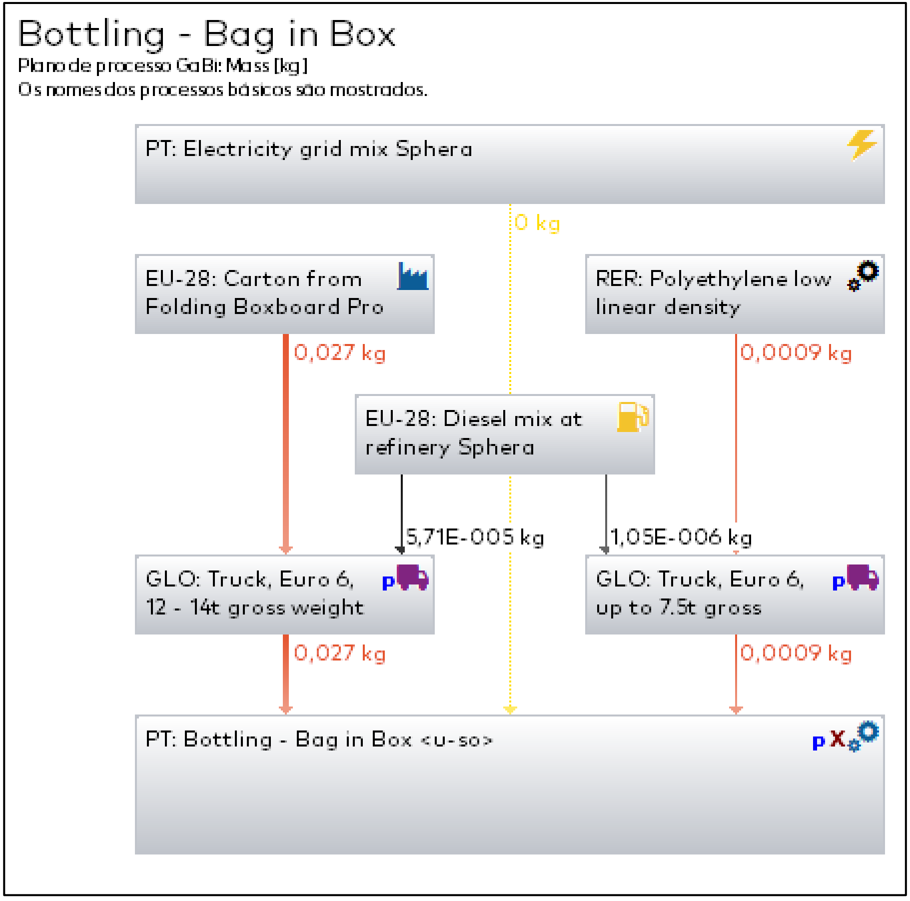
ANNEX III. Flowchart of wine bottling in glass bottle inserted in the GaBi software version 10.6.



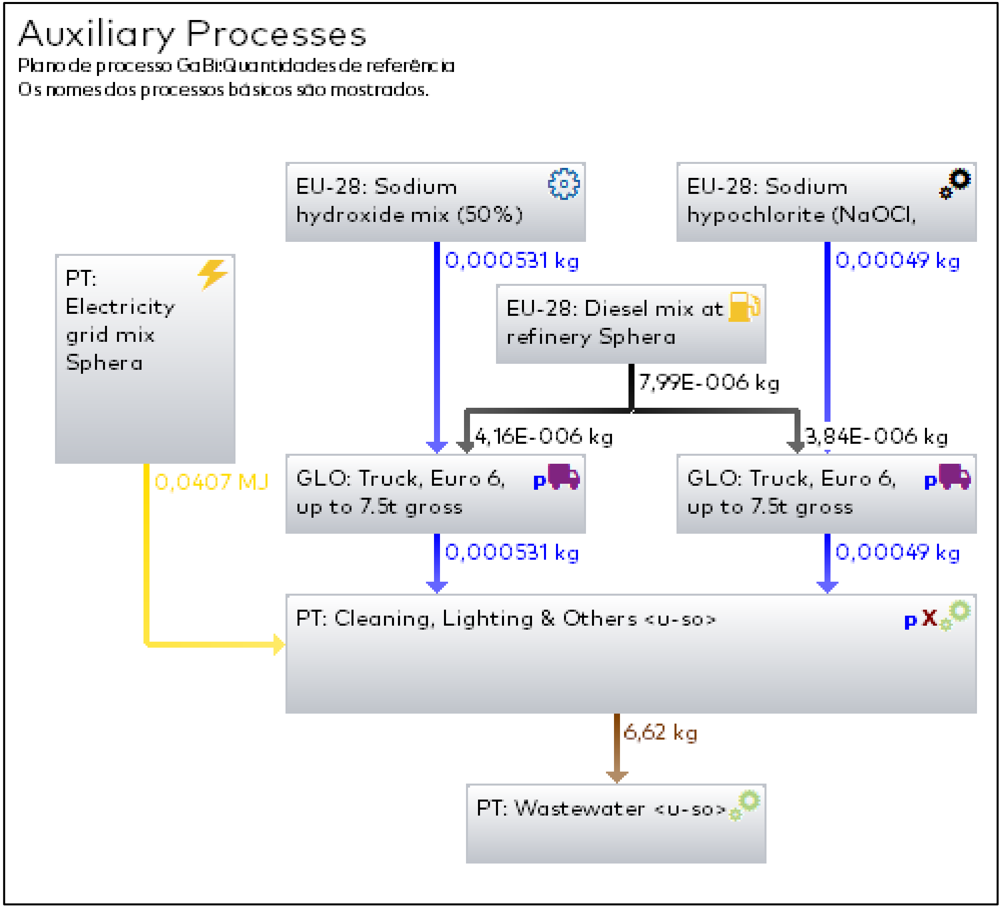
ANNEX IV. Flowchart of wine bottling in PET bottle inserted in the GaBi software version 10.6.



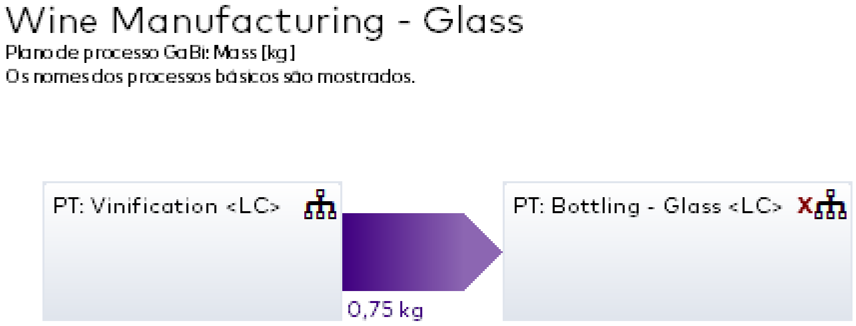
ANNEX V. Flowchart of wine bottling in Bag-in-Box (BIB) inserted in the GaBi software version 10.6.



ANNEX VI. Flowchart of auxiliary processes inserted in the GaBi software version 10.6.



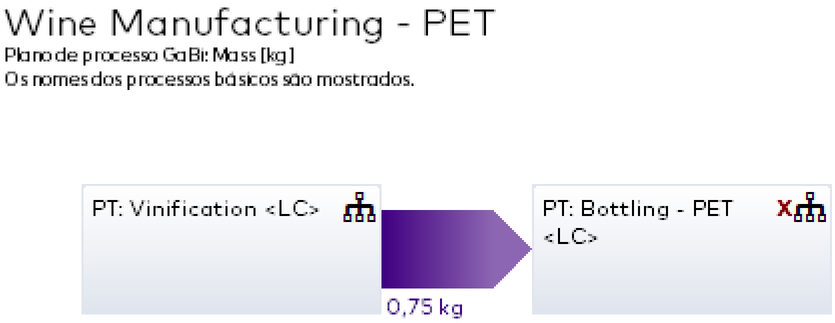
ANNEX VII. Flowchart of wine production in each type of packaging in the functional unit, inserted in the GaBi software version 10.6.



Wine Manufacturing - Glass

Plano de processo GaBi: Mass [kg]

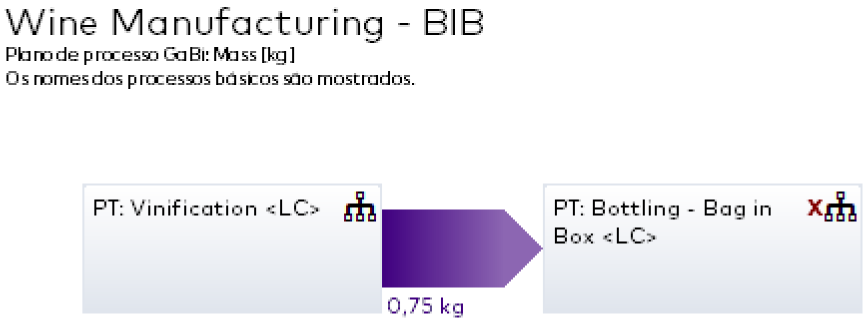
Os nomes dos processos básicos são mostrados.



Wine Manufacturing - PET

Plano de processo GaBi: Mass [kg]

Os nomes dos processos básicos são mostrados.



Wine Manufacturing - BIB

Plano de processo GaBi: Mass [kg]

Os nomes dos processos básicos são mostrados.