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Environmental impact analysis of a Chilean organic wine through a life cycle assessment

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ABSTRACT

The food system is responsible for critical environmental problems around the world. The wine industry, having a global scale, is accountable for part of these impacts. Organic wines have been developing fast in the past decade, nevertheless there is still lack of research on this vitiviniculture practice, especially in productive countries outside Europe. Therefore, the purpose of this paper is to explore the impacts of organic vitiviniculture in Chile by utilising the Life Cycle Assessment (LCA) methodology. A cradle-to-market attributional LCA including viticulture, vinification, bottling, and distribution was executed on one of the main wines produced and commercialised by the largest organic winery in the world, representing a reliable recreation of the productive and operative processes involved. The environmental impacts were calculated for all impact and damage categories of the ReCiPe 2016 methodology, using primary data from the company, and modelling it in SimaPro.

Viticulture, bottling, and distribution were identified as the main lifecycle phases contributing to the impacts and damages assessed, contributing 39%, 11.8%, and 42.2% respectively. Fertilisation, the glass bottle, and the long-distance freights were the variables responsible for most of the contribution shares (31.9%, 9.39%, and 33.46% respectively). Energy consumption, especially in the viticulture and vinification phases, was also recognised as an impactful factor to be considered (5.34%, and 6.3% respectively).

Different scenarios were developed to analyse potential actions and the magnitude of their improvements, all being achievable options for the winery. Replacing the glass bottle resulted in the major benefits, reducing environmental impacts between 12.7% and 21.3% depending on the material. The winery should evaluate this alternative further or explore other routes-of-action that allow to decrease the impacts related to the production of glass and their posterior transport to the international markets where the wine is sold.

1. Introduction

The wine industry is directly involved with environmental impacts associated to the food system, particularly contributing with global greenhouse gas (GHG) emissions, terrestrial and freshwater biodiversity loss, freshwater depletion, eutrophication, land use change, soil degradation, and waste generation (Kok and Alkemade, 2014; Ritchie and Roser, 2021; Azoumanidis et al., 2015). In 2018, vineyards represented around 0,15% of the total agricultural land, with almost 60% of their production destined to wine grapes (World Bank, 2021; OIV, 2019), reaching nearly 300 million hectolitres which translated in a significant international trade market with exports of over 100 million hectolitres in volume, and more than €30 billion in value (OIV, 2019). The magnitude reached by this industry has raised awareness about its environmental impacts (Lamastra et al., 2016), which is proved by the weight different national trade unions give to sustainability. Several certifications can be found around the world, with special focus on vitiviniculture practices such as organic and biodynamic, and social aspects (Moscovic and Reed, 2018; Puckette, 2021; Sabbado, 2018). “Organic”, “sustainably produced”, “fairtrade”, and “environmentally friendly” have been identified as the four main growth opportunity categories for wine producers (Wine Intelligence, 2020), being reinforced by the following statistics (IWSR, 2019):

Organic still wine’s global consumption.

- o 2012–2017: +14.1%.
- o 2017–2022: +9.2% (forecast).

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Organic vineyards' global area.

- o 2007–2017: +234%.
- o 2017–2022: +27.5% (forecast)

In Chile, wine production and commercialisation started growing exponentially on the early 1980s (WoC, 2021). Let alone, wine represents more than 11% of the country's forestry, crop and livestock farming sector exports (Domínguez et al., 2019), and nearly 6% of the national exports without counting the mining sector, reaching 0.5% of Chile's GDP (WoC, 2021), and positioning it as the 6th biggest wine producer and the 4th exporter market globally (OIV, 2019). The rapid development experienced by the this industry has been accompanied by an evident pressure on renewable natural resources across the country due to modern intensive viticulture practices, characterised by increasing water depletion and soil erosion (Donia et al., 2018), which boosted measures and regulations resulting in Wines of Chile's (WoC) Sustainability Code and Certification, and the promotion of diverse vitiviniculture practices. In 2018, the total agricultural surface certified as organic reached just above 67,800 Ha, of which nearly 7% corresponded to organic vineyards, growing 25% since 2014 (Domínguez et al., 2019).

Popularity gained by "greener" viticulture practices does not mean these are necessarily more environmentally friendly (Renaud-Gentié et al., 2020; Nicoletti et al., 2001; Seufert et al., 2012; Tuomisto et al., 2012), and is even less clear when considering the whole life cycle of a wine bottle. For this reason, the application of LCA has notoriously increased in the wine sector during the last decade, with special focus in Europe, but it is still on an early stage. Two systematic literature reviews (Azoumanidis et al., 2015; Ferrara and De Feo, 2018) analysed 34 and 81 studies respectively (with a match of 17), concluding similar ideas and recommendations. Even though most of the documents conducted assessments on 0.75 L of bottled wine, following a cradle-to-grave approach, the reviews identified over 10 functional unit (FU) definitions based on 15 system boundaries. These boundaries covered life cycle phases such as vine planting, grape growing, vinification, packaging production, bottling, distribution, consumption, waste disposal, and end-of-life scenarios, translating in other common approaches like cradle-to-farm gate, cradle-to-market, cradle-to-retailer, and cradle-to-consumer.

Within the almost 100 studies revised in both papers, less than 23% were related to organic wines, suggesting a research gap that was reinforced by a direct search in Web of Science (WoS) and Scopus utilising the concepts "life cycle assessment", "wine", and "organic". Only 35 results were obtained, between 2007 and 2021, 10 of which were covered by the cited systematic reviews. Of the remaining 25, only 13 are relevant for the topic in discussion. Furthermore, adding the word "Chile" to the search brought the results to zero. Looking in other search engines, international journals, and local sources, only an undergraduate thesis (Piña, 2016) and the "environmental calculator" Ecobase (FCH, 2021) were found publicly available, which assessed wines produced under conventional viticulture practices. Although environmental assessments in general have developed positively during the last decade in Chile, in line with the Sustainable Consumption and Production Programme launched by the Ministry of the Environment in 2014 (Biggs et al., 2015), LCA is still considered as a young environmental assessment methodology across a variety of economic sectors in the country (Iriarte, 2018; Capozza, 2016), being the wine industry no exception. Hence, the methodology and its application are undeveloped in the local industry, and require further research, especially with regards to organic vitiviniculture.

It is complex to generalise, compare, and justify the results of particular studies on the basis of different agricultural practices, because there are several factors affecting the lifecycle phases of a bottle of wine (Azoumanidis et al., 2015; Notarnicola et al., 2003). The wide range of grape varieties and vine's clones, geographic and topographic characteristics, yearly changing climatic conditions, viticultural practices, oenological inputs and practices, infrastructure and technologies available directly influence the environmental performance of the different wines analysed (Marras et al., 2015; Vázquez-Rowe et al., 2013; Vendrame et al., 2018). Moreover, results and conclusions fluctuate heavily due to the goal and scope of each study, which is evidenced by the amount of FUs and system boundaries that have been identified, hence recommendations of best practices for this productive sector to advance on a more environmentally friendly path also vary significantly from case to case. These are the reasons why it is important to conduct localised LCA research within the wine industry.

Acknowledging the growth that organic vitiviniculture is experimenting, and the lack of environmental studies on non-European wines, this study will focus on the evaluation of different environmental impacts caused by an organic wine by conducting a life cycle assessment of a Chilean wine. The world's largest organic winery (Brandl, 2021; Emiliana, 2019), which manages almost 1000 Ha of vineyards in Chile and sells over 8,760,000 bottles (Emiliana, 2021) will act as a case study providing primary operational and technical data, with the aim of identify and quantify the environmental impacts of one of the main organic wines in the world (in volume) through an attributional LCA. This is important novel research, tackling the almost inexistent assessments within the Chilean wine sector, and being the first one conducted over an organic Chilean wine, setting the first step for further progression on this field, and contributing to a sustainable development of a growing and relevant industry in the country.

2. Methodology

2.1. Life cycle assessment

2.1.1. Goal and scope definition

This definition is considered the most important stage in any LCA, being fundamental for a correct interpretation of the results (JRC-IES, 2010). This study was born from the identification of a literature and industrial practice gap, and the interest of a large organic winery to work in collaboration. The aim is to identify hotspots within the different lifecycle phases and impact categories included and simulate different scenarios helping to recognise operational best practices.

The system to be studied is the lifecycle of a wine produced by a well-established winery in Chile, with over two decades of experience producing organic and biodynamic wines. In this case, just a fraction of the overall system will be assessed, conducting a cradle-to-market LCA following an attributional modelling framework (Goedkoop et al., 2016).

2.1.1.1. Functional unit. The FU quantifies the functions of the product analysed, providing reference of the related inputs and outputs, necessary for comparison and normalisation purposes (BSI, 2018; BSI, 2020). For this study the FU was a 0.75 L of glass bottled Reserva Rosé 2020 wine, accounting for almost 12% of the winery's sales during 2020 (Emiliana, 2020a, 2020b, 2021).

2.1.1.2. System boundaries, details, and limitations. The unit processes considered in this study are detailed in Fig. 1, including inputs, outputs, and a clear division between the background and foreground systems assessed. The total production of the wine analysed raised up to 750,250 L, divided in four different blends involving 12 wine grapes producers (including the winery assessed), grapes harvested in 2018, 2019, and 2020, and 10 grape varieties. These blends were either bottled in Chile, shipped as bulk to be bottled in international markets such as Denmark, France, Sweden, and USA, or both, reflecting the complexities behind wine production (Emiliana, 2020a; Emiliana, 2020b; Emiliana, 1027a; Emiliana, 1027b; Emiliana, 1027c; Emiliana, 1027d). Due to lack of data from grape suppliers, a blend accounting for 200,000 L vinified by the

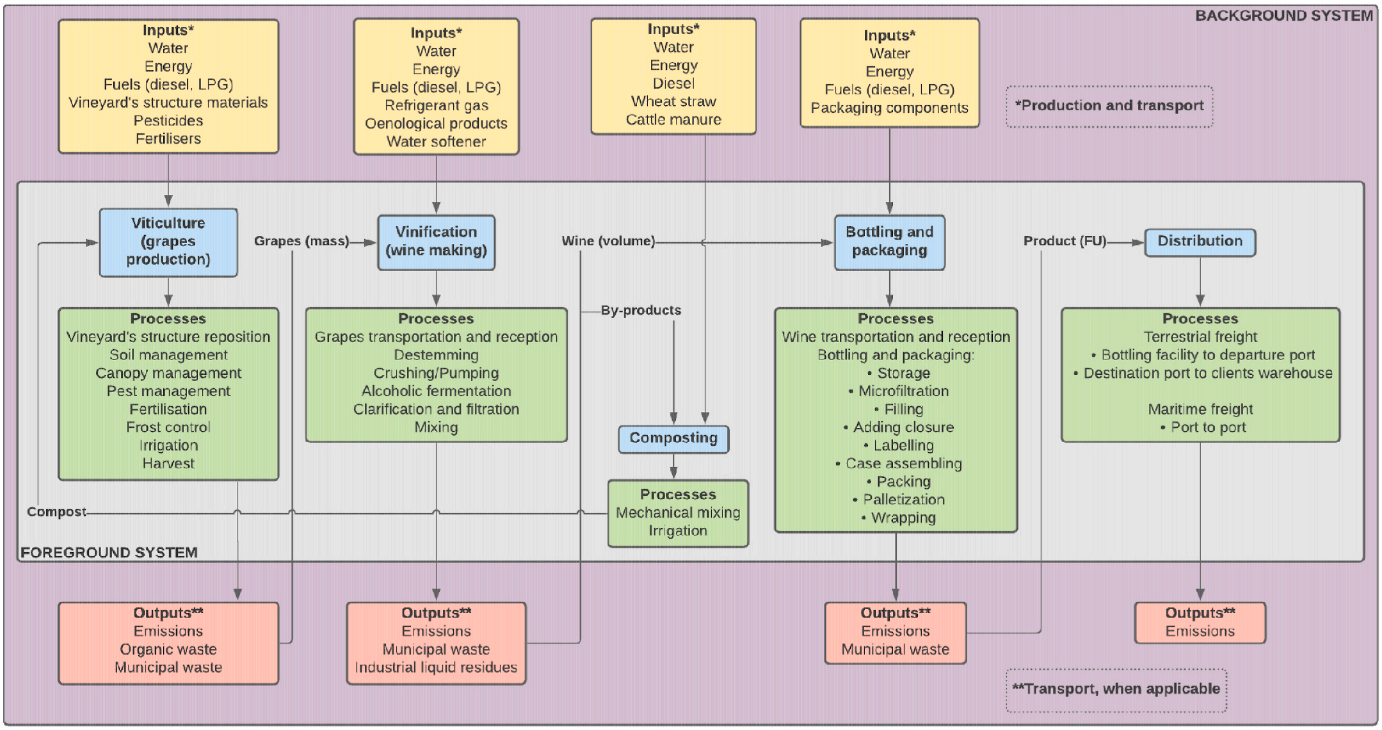

Fig. 1. System boundaries defined for this project.

winery, from 2020 vintage grapes grown by the same company, was analysed, considered the most representative of the winery's reality. The blend was renamed as "Nº1", and Fig. 2 shows further detail on its origins and movements.

Some phases of the lifecycle were left aside from the assessment as follows. In the distribution phase, only the terrestrial transportation between the bottling facilities and the port, the maritime transportation, and the terrestrial transportation from the port to the clients' warehouses were included, not considering the transportation within the markets to get to the different points of sale, due to lack of data. In addition, the whole retail and consumption phases, which implies transportation to purchase the product and refrigeration, among other processes, and the end-of-life phase of the bottles were marginated mainly because of lack of data, and the level of generalisation on the assumptions needed to model them, probably altering the results of the evaluation. Although this could be declared as a limitation, to maximise the amount of primary data and keep the results as realistic as possible, it was considered the best way to proceed. Refer to (Letamendi, 2021) for the full list of background and foreground data and processes left aside.

2.1.1.3. Allocation. In the case of wine production, it does not make sense to divide the vinification phase in different sub-phases, as the different by-products (i.e., grape pomace, stalks, lees) are impossible to be produced separately (Azoumanidis et al., 2015). Specifically with regards to Nº1, all pruning residues (wood and shoots) generated during the viticulture phase were left in the vineyards and incorporated back to the soil, and 100% of the grape pomace, stalks, and dry lees generated during the vinification phase were used as input for their internal composting, which is a generalised practice for all the winery's wines (Emiliana, 2021). Besides these by-products, and the wine, around 700 L of liquid lees were also obtained, which were sold as input to produce other generic and varietal wines. This by-product represented less than 0.3% of the vinification outputs (in mass), hence it was assumed as negligible and not considered in the assessment results, treating the wine as the only marketable product of the system. Therefore, no allocation was performed, following a similar approach than (Notarnicola et al., 2003; Rallo, 2011; Vázquez-Rowe et al., 2012a).

2.1.1.4. Data requirements[1]. This project involved not publicly available primary data collection from the world's largest organic winery, for each of the inputs and outputs related to all lifecycle phases and unit processes within the system boundaries defined. Accurate data collection was ensured through frequent calls and meetings with the winery's Sustainability Director and Environmental Manager, and a rigorous questionnaire.

Considering some of the limitations on data availability mentioned in section 2.1.1.2, the Ecoinvent 3 database (particularly its "at point of substitution" unit datasets) was used as supplement when needed. Even though diverse assumptions and limitations underlie this database, which can potentially affect the results of this particular study, its trajectory, international recognition, completeness, transparency, precision, compliance with international standards, and extensive use not only at a general LCA level, but also in particular within wine LCA studies, makes it a very useful resource in an attributional LCA like this one (Ferrara and De Feo, 2018; JRC-IES, 2010; Goedkoop et al., 2016; PR é, 2021). SimaPro 9.1.1.7 version was used for the calculations.

2.1.2. Life cycle inventory analysis

This analysis is an iterative process, derived from the goal and scope definition, to quantify all applicable inputs and outputs of the system assessed. All processes within the system boundaries were modelled as described in Fig. 1, inventorying the amount of each input and output based on the FU. The four main lifecycle phases (viticulture, vinification, bottling & packaging, and distribution), together with the composting process, were defined as sub-assemblies of the principal assembly, one bottle of Reserva Rosé (2020), each containing either supporting processes, or sub-assemblies as well.[2] Assumptions, missing data, and the

[1] For further details on the questionnaire and disaggregated foreground data refer to (Letamendi, 2021).

[2] A supporting process accounting the general waste generated along the productive chain of the wine was also included as part of the main assembly.

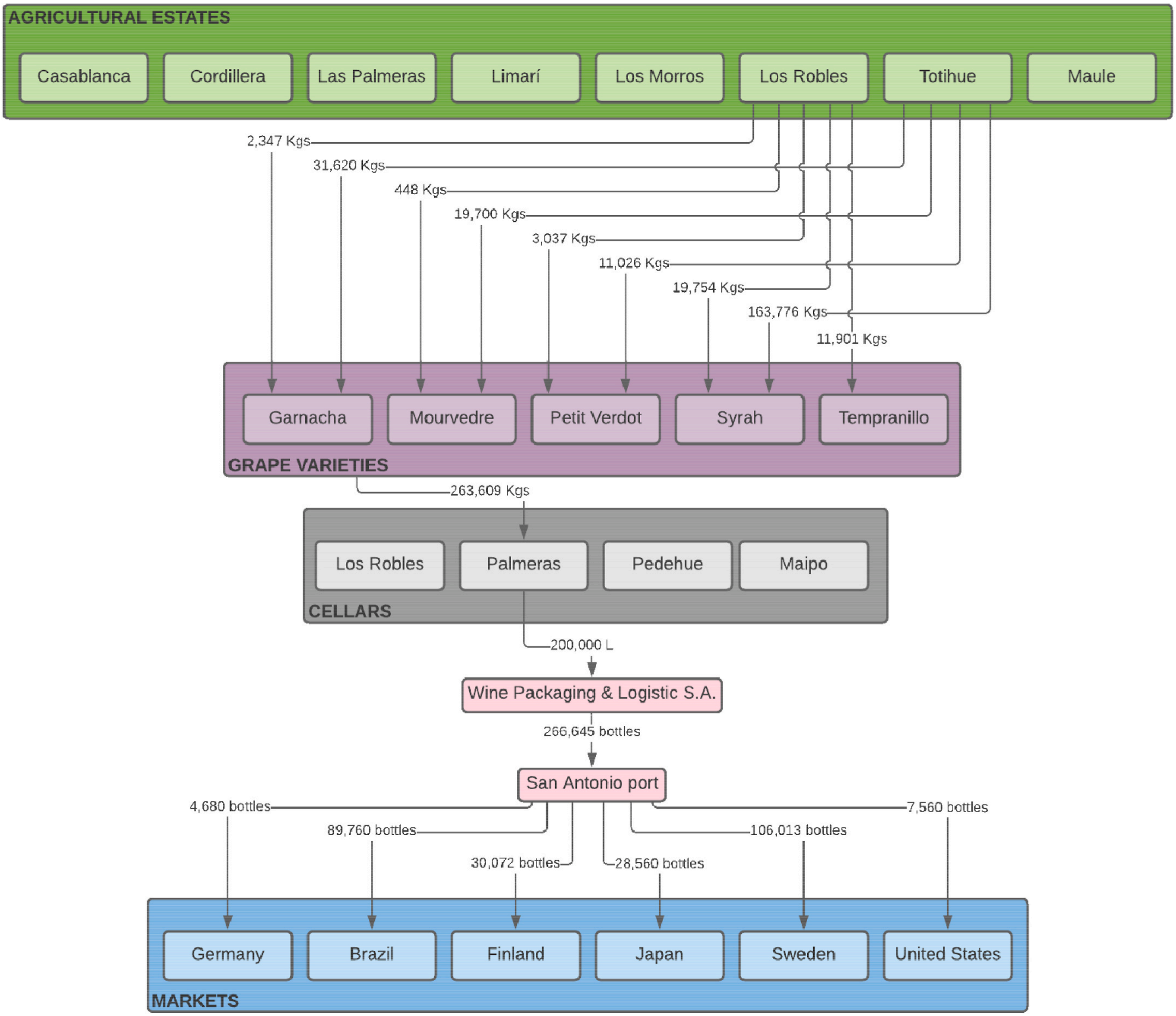

Fig. 2. Cradle-to-market flow chart of N°1, from vines to final destinations.

methodologies used for calculating pesticides and fertilizers field-level emissions, and fugitive emissions from fermentation can be found in the supplementary information section of this document, and further details can be found in (Letamendi, 2021).

An aggregated summary of the foreground specific data collected and utilised in this assessment its showcased in Table 1.

2.1.3. Life cycle impact assessment (LCIA)

The purpose of the impact assessment stage is to use the LCI results to appraise the magnitude of potential environmental impacts generated by the product system analysed (JRC-IES, 2010; BSI, 2020). Currently there is no consensus on what impact assessment method is better than the rest (Goedkoop et al., 2016), and for this study ReCiPe 2016[3] was chosen as it:

- Has a global scale, being more appropriate for the Chilean context than methodologies focused on Europe or North America.
- Is well-established and counts with international reputation.
- Includes 18 impact categories at a midpoint level (i.e., individual categories, problem oriented), and 3 categories at an endpoint level (i.e., aggregated impact categories, damage oriented), allowing for a broader understanding of the environmental issues behind wine production.
- Provides normalisation and weighting steps, which helps to simplify the interpretation stage.
- Is the successor of the Eco-Indicator99 and CML-IA methods, which were the ones used by the majority of the studies analysed by (Azoumanidis et al., 2015; Ferrara and De Feo, 2018).
- Provides a hierarchist perspective following a consensus model based on the most common policy principles.

2.2. Sensitivity analyses

Reliability and robustness evaluation is not a common practice within wine LCAs (Azoumanidis et al., 2015). Nevertheless, in this case sensitivity analyses were defined as a specific objective of the study, aiming to better understand the environmental impacts associated to

[3] Refer to (Huijbregts et al., 2017) for further detail.

Table 1
Foreground specific data collected and calculated per FU (0.75 L of glass bottled Reserva Rosé, 2020 wine)[a].

Inputs	Amount per FU	Unit	Outputs	Amount per FU	Unit
Vineyard's structure materials	1.56E-03	kg	Grapes	9.89E-01	kg
Diesel	4.80E-03	kg	Pesticides field-level emissions	5.37E-03	kg
Liquefied petroleum gas	2.14E-02	kg	Fertilizers field-level emissions	3.01E-02	kg
Electricity	3.65E-01	kWh	Pruning residues	3.89E-01	kg
Water	8.86E-02	m3	Municipal waste	3.89E-03	kg
Pesticides components	9.93E-03	kg	Recyclables	1.13E-03	kg
Fertilizers components	8.99E-03	kg	Hazardous waste	3.49E-04	kg
Compost	8.46E-03	kg	Bulk wine	7.50E-01	litres
Cattle manure	8.40E-01	kg	Fermentation's fugitive emissions	2.35E-04	kg
Grapes	9.89E-01	kg	Vinification by-products	1.92E-01	kg
Oenological products and compounds	1.32E-03	kg	Industrial liquid residues	6.30E-03	kg
Refrigerant gas	8.56E-06	kg	Compost	6.29E-02	kg
Water softener	1.50E-04	kg	Bottled wine	7.50E-01	litres
Vinification by-products	1.92E-01	kg			
Wheat straw	9.15E-04	kg	**Transport**	**Amount per FU**	**Unit**
Bulk wine	7.50E-01	litres	Road transport of inputs and outputs	3.33E+00	tkm
Packaging components	4.57E-01	kg	Maritime transport of bottled wine	1.08E+02	tkm
Bottled wine	7.50E-01	litres			

[a] The compost considered as input is different than the one considered as output, and it was modelled accordingly in SimaPro. The input compost was produced in Los Robles estate and applied, in part, to some of the vineyards' blocks analysed in this assessment. The output compost was produced in Las Palmeras estate, using the vinification by-products of N°1.

N°1 by exploring how changing the inputs related to the most relevant issues identified in the LCI and LCIA may change the results. This assessment is a trustworthy recreation of the real productive and operational processes behind N°1, not involving unrealistic assumptions, or calculations misaligned with the winery's own analyses, therefore the sensitivity analyses in this case will be conducted to evaluate environmental performance improvements rather than model uncertainties generated by subjective choices or assumptions. These analyses will be explored further in the following chapter, and consist in:

- Terrestrial freight to Brazil replaced by air freight.
- Primary packaging (glass bottle) replaced by three alternatives (can, board container, and PET).
- Potassium fertilizer replaced by compost, in 15% and 30%.
- Manure application reduction, in 15% and 30%.
- Photovoltaic energy use replacing the normal grid supply, in 25% and 50%.
- A combined scenario including some of the above (air freight to Brazil, PET bottle, 15% replacement of potassium, 15% manure reduction, and 25% photovoltaic energy coverage).

3. Results

3.1. Inventory results

Inventory results are a collection of all inputs and outputs within the system boundaries described in Fig. 2, including raw materials involved, residues generated, emissions into air, soil, and water, and non-material emissions. These results are usually tedious to analyse and interpret, nonetheless it is important to revise their content to get an idea of the numbers before they undergo characterisation. Table 2 presents the top ten substances of each compartment included in the study (raw materials, material emissions, and final waste flows). Substances of the main lifecycle phases analysed are presented in the supplementary information section, and (Letamendi, 2021) contains additional detail.

3.2. Inventory impact assessment

3.2.1. Characterisation and damage assessment

The absolute amounts of each impact and damage category indicator resulting from the FU are contained in Tables 3 and 4 (Letamendi, 2021). shows disaggregated data per lifecycle phases and processes assessed, and further details of each of the categories involved. All results include long-term emissions and infrastructure processes calculations.

Impact and damage categories can also be represented as showcased in Fig. 3, each one in relation to the contribution of the lifecycle phases and processes involved in the production of one bottle of Reserva Rosé (2020), always delimited by the system boundaries defined, and the inputs and outputs included. Although the values detailed in Tables 3 and 4 clearly differ between categories, this is a good exercise to get an idea of the relative importance of each phase and process in the different impacts and damages evaluated. Delving into this contribution analysis (Zampori et al., 2016), propose some rules to undertake a hotspots analysis whereby inputs responsible for more than 50% of the environmental impact of a category, or when two inputs combined generate over 80% of the impacts, are recognised as hotspots. Table 5 exhibits the hotspots identified in this case, based on lifecycle phases and processes rather than inputs alone. The contribution distribution of each category per lifecycle phases and processes assessed, along with complementary analysis can be found in (Letamendi, 2021).

Focusing on the categories which present a hotspot, a deeper exploration of the results is needed to understand better where those contribution shares come from. First, the distribution leads 2 damage categories (Human Health and Resources) and 6 impact categories (GW, OFHH, PM, OFTE, TA, FRS) due to the maritime freight and 1 impact category (TE) due to the long-distance terrestrial freight between WPL and Brazil (39.2%). Let alone, the long-distance freight to Brazil is very notorious, contributing 16.1%, 6.75%, 4.26%, 6.81%, 3.46%, 19.2%, 7.75%, and 20.3% respectively,[4] and having a larger contribution than each individual maritime freight in all categories analysed. The model accounts for all the fuels used (along with their production and distribution), lorries and vessels' production and maintenance, and all the inputs needed for these purposes (using global averages), among other inputs and processes.

Second, the viticulture leads 4 impact categories and 1 damage category. In the case of SOD and MEu the viticulture contribution comes from the fertilisation assembly associated to this lifecycle phase, in an 86.1% and 94.4%, respectively. Fertilisation in these cases is explained by the field-level emissions estimated, in an 83.5% and 92.9% respectively, which in turn are directly related to the amount of manure applied.[5] In the case of LU and Ecosystems, the viticulture contribution comes also from the fertilisation assembly in a 94.6% and 83.3% respectively. But in these cases, fertilisation is explained by the fertilisers applied which contain potassium, in a 73.5% and 62.7% respectively. This agricultural input is related to the global market for compost, which

[4] TE is not considered in this list of percentages.

[5] On the 44.04 Ha analysed, 8861.51 Kg of fertilisers, 24,050 Kg of compost, and 393,480 Kg of manure were applied. Field-level emissions were estimated for fertilisers containing nitrogen and phosphate, and manure, being directly related to the amount used in each case.

Table 2
Main substances in the LCI using ReCiPe 2016 Midpoint H method.

	Raw materials			Emissions to air			Emissions to soil		
No	Substance	Amount	Unit	Substance	Amount	Unit	Substance	Amount	Unit
1	Occupation, urban, green areas	1.90E+01	m2a	Carbon dioxide, fossil	2,49E+03	g	Heat, waste	4.33E-03	MJ
2	Water, turbine use, unspecified natural origin, CL	5.59E+00	m3	Carbon dioxide, biogenic	1,37E+02	g	Sulfur	3.81E-03	kg
3	Energy, gross calorific value, in biomass	2.21E+00	MJ	Carbon dioxide, land transformation	3,37E+01	g	Oils, unspecified	2.01E-03	kg
4	Water, turbine use, unspecified natural origin, RoW	1.37E+00	m3	Nitrogen oxides	2,72E+01	g	Mineral oil	7.83E-04	kg
5	Energy, potential (in hydropower reservoir), converted	8.51E-01	MJ	Sulfur dioxide	1,78E+01	g	Carbon	2.83E-04	kg
6	Water, turbine use, unspecified natural origin, CN	6.28E-01	m3	Ammonia	6,05E+00	g	Carbon dioxide	2.44E-04	kg
7	Oil, crude	6.03E-01	kg	Particulates, < 2.5 um	4,61E+00	g	Calcium	1.16E-04	kg
8	Gravel	6.02E-01	kg	Carbon monoxide, fossil	4,11E+00	g	Iron	9.62E-05	kg
9	Occupation, forest, intensive	2.91E-01	m2a	Methane, fossil	2,17E+00	g	Chloride	7.91E-05	kg
10	Coal, hard	2.34E-01	kg	Particulates, > 10 um	2,28E+00	g	Silicon	5.54E-05	kg

	Emissions to water			Waste generated		
No	Substance	Amount	Unit	Substance	Amount	Unit
1	Chloride	3,03E+01	g	Waste, organic	5.81E-01	kg
2	Sulfate	2,91E+01	g	Sludge	6.32E-03	kg
3	Nitrate	2,30E+01	g	Municipal waste, unspecified	3.89E-03	kg
4	COD, Chemical Oxygen Demand	1,65E+01	g	Cardboard waste	9.85E-04	kg
5	Sodium	1,45E+01	g	Hazardous waste, unspecified treatment	3.49E-04	kg
6	Silicon	1,28E+01	g	Polyethylene waste	7.58E-05	kg
7	Suspended solids, unspecified	1,02E+01	g	Glass waste	5.85E-05	kg
8	Calcium	9,91E+00	g	Plastic waste	6.06E-06	kg
9	BOD5, Biological Oxygen Demand	5,49E+00	g	Packaging waste, paper, and board	4.96E-06	kg
10	Iron	5,48E+00	g	Polystyrene waste	2.93E-08	kg

Table 3
Total absolute values of each impact category indicator, by FU.

Impact category	Abbreviation	Unit	Total
Global warming	GW	kg CO2 eq	2.94E+00
Stratospheric ozone depletion	SOD	kg CFC11 eq	1.19E-05
Ionizing radiation	IR	kBq Co-60 eq	5.50E-02
Ozone formation, Human health	OFHH	kg NOx eq	2.92E-02
Fine particulate matter formation	PM	kg PM2.5 eq	1.37E-02
Ozone formation, Terrestrial ecosystems	OFTE	kg NOx eq	2.95E-02
Terrestrial acidification	TA	kg SO2 eq	4.01E-02
Freshwater eutrophication	FEu	kg P eq	7.58E-04
Marine eutrophication	MEu	kg N eq	1.58E-03
Terrestrial ecotoxicity	TE	kg 1,4-DCB	1.70E+01
Freshwater ecotoxicity	FEc	kg 1,4-DCB	8.43E-02
Marine ecotoxicity	MEc	kg 1,4-DCB	1.17E-01
Human carcinogenic toxicity	HCT	kg 1,4-DCB	8.79E-02
Human non-carcinogenic toxicity	HNCT	kg 1,4-DCB	1.78E+00
Land use	LU	m2a crop eq	1.41E+01
Mineral resource scarcity	MRS	kg Cu eq	1.30E-02
Fossil resource scarcity	FRS	kg oil eq	8.17E-01
Water consumption	WC	m3	9.92E-02

Table 4
Total absolute values of each damage category indicator, by FU.

Damage category	Unit	Total
Human health	DALY	1.21E-05
Ecosystems	species.yr	1.47E-07
Resources	USD2013	3.25E-01

in turn is highly associated to the home and industrial treatment of biowaste, as modelled by Ecoinvent 3. Worth mentioning that, to a lesser extent, fertilisers containing nitrogen also stand out as part of the fertilisation contribution (15.3% and 13.1%, respectively). In the case of WC, the viticulture contribution comes from the irrigation process associated to this lifecycle phase, in an 84%.

Finally, bottling and distribution leads IR and MRS. In both cases the bottling phase's contribution is explained by the white glass bottle used as primary packaging component, in a 41.2% and 43.4% respectively. The bottle production is the main contributing variable (39.38% and 42.5%, respectively), which was modelled using global averages contained in Ecoinvent 3 for the production of white glass packaging. The distribution phase contribution comes from the combination of maritime freights (19.58% and 19.02%, respectively), but as a single contributing variable the one leading is the long-distance terrestrial freight to Brazil (15.6% and 16%, respectively).

3.2.2. Normalisation, weighting, and single scores

Normalisation helps to simplify the results' interpretation by showing how relatively high or low each impact category indicator is when compared to a baseline, measuring all categories under the same unit measure (Goedkoop et al., 2016). Weighting is not permitted by ISO if the results of an assessment will be used for public comparisons (BSI, 2018), but it is extensively used for internal decision making (Goedkoop et al., 2016), which is essentially what the winery wants to do with the results of the present study. Therefore, both elements were incorporated to the assessment, based on global average factors used by ReCiPe (2016) Endpoint H/A method.

Single scores are basically an aggregation of the impact and damage categories evaluated by ReCiPe, where these categories are normalized and then weighted. Individual impact categories' results, like the ones presented in section 3.2.1, serve for more detailed analysis, and single

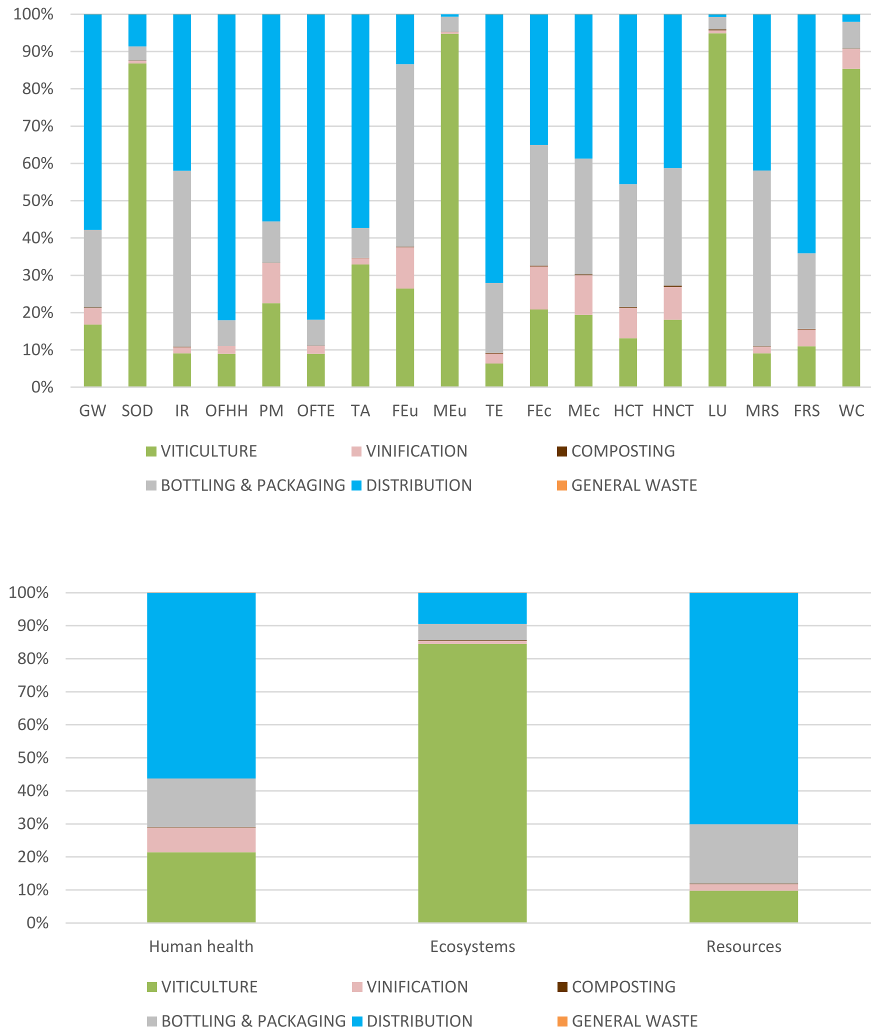

Fig. 3. Contribution of different lifecycle phases and processes to the environmental impact indicators related to the FU, using ReCiPe 2016 Midpoint H (above) and Endpoint H/A (below).

scores are a useful complement to understand overall environmental performance of products, and to make informed design or operational decisions (PR é Sustainability, 2020). Fig. 4 illustrates how each lifecycle phase and process assessed[6] is composed by the different impact and damage categories included in the methodology. "Pt" refers to eco-indicator points, and the unit measure "mPt" means millipoints. Its absolute values are not very important as the intention is to compare relative differences between the relevant phases and processes (MHSPE, 2000).

After normalising and weighting the standard results, distribution is the phase contributing the most to the overall environmental impacts generated by the production of one bottle of Nº1 (42.2%), mainly impacting in terms of PM and GW, and damaging human health. Of this share, 33.46% corresponds to maritime freights, and 6.47% corresponds only to the terrestrial freight to Brazil. Viticulture is the second largest contributing phase, accounting for 39% of the impact and damages assessed, mainly with regards to LU, PM, GW, and Ecosystems. Of this share, 31.9% corresponds to fertilisation and 5.34% to electricity production and consumption. Fertilisation's contribution, aligned with the details presented in section 3.2.1, is mainly explained by the amount of potassium and nitrogen applied (18% and 3.8%, respectively) and the field-level emissions calculated (7.95%). In third place stands the bottling & packaging phase, specially impacting to PM, GW, and Human Health, and contributing with 11.8% of which 9.39% is generated by the production of the glass bottle utilised. Vinification represents only 6.83%, nonetheless it worth considering that 6.3% of this share is directly caused by the production, transmission, and consumption of electricity during the processes involved.

3.3. *Sensitivity analyses*[7]

3.3.1. *Freights and primary packaging replacement*

Altogether, maritime freights are the main contributing variable in several of the impact and damage categories analysed, however it is complex to modify this element as exports need to take place to keep the winery's business alive, and air freights are limited by cost, considering the distances to be covered and the amount of wine cases needing to be

[6] The supporting process "General Waste" modelled in SimaPro is not showcased in Fig. 4 due to its minimal contribution to the overall environmental impact.

[7] (Letamendi, 2021) contains information regarding the associated absolute values, a comparison based on single score calculations, assumptions, and calculations made for the different changes applied, for all sensitivity analyses conducted.

Table 5
Hotspot analysis of impact and damage categories.

Impact Category	Hotspot	Contribution
GW	Distribution	57.8%
SOD	Viticulture	86.8%
IR	Bottling & Packaging + Distribution	89.1% (47.1% + 42%)
OFHH	Distribution	82%
PM	Distribution	55.5%
OFTE	Distribution	81.9%
TA	Distribution	57.3%
FEu	No hotspot	–
MEu	Viticulture	94.8%
TE	Distribution	72.0%
FEc	No hotspot	–
MEc	No hotspot	–
HCT	No hotspot	–
HNCT	No hotspot	–
LU	Viticulture	94.4%
MRS	Bottling & Packaging + Distribution	89% (47.1% + 41.9%)
FRS	Distribution	64.1%
WC	Viticulture	85.4%
Damage Category	**Hotspot**	**Contribution**
Human Health	Distribution	55.2%
Ecosystems	Viticulture	84.3%
Resources	Distribution	69.7%

transported (World Bank, 2009). The terrestrial freight associated to Brazil's exports was also identified as an individual process responsible for a significant share of impacts and damages, therefore it was selected as an example and replaced by an air freight to analyse the resulting effects. Fig. 5 details the changes generated when compared with the baseline model, per impact and damage category. In line with the results presented in section 3.2.1, the categories most positively affected were TE, FEc, MEc, HCT, HNCT, and MRS, indicating the potential that a change of transport mode has, even just considering one destination and trip.

Sections 3.2.1 and 3.2.2 revealed that the glass bottle significantly influenced the environmental impacts behind the production and commercialisation of this wine. The bottle represented 86.52% of the overall packaging components' weight included in the model, hence it was replaced by three different materials to analyse the resulting effects,[8] cans, a liquid packaging board container, and a PET bottle. Fig. 6 details the changes generated when compared with the baseline model (packaging end-of-life not included), showing the substantial reductions in almost all categories (especially in IR, FEu, TE, and Resources), which are explained by the influence of these changes not only over the bottling & packaging phase, but the distribution phase as well (all transports are measured in tkm, with the weight of the load and the distance to be covered as the main variables involved). It is important to notice the critical effect of cans on HCT, which is directly related to the production of aluminium, process classified as carcinogenic by the International Agency for Research on Cancer (Krewiski et al., 2011). This issue may be mitigated by partnering with a can's supplier with high recyclability rates.

3.3.2. Potassium replacement and manure reduction

Potassium is the most demanded nutrient by the vines, performing critical functions related to plant physiology and biochemistry, and having the potential to affect yields, grapes' quality and resistance to pests, or the acidity level of wines (FAO, 2002). Hence, determining how much to apply requires localised soil and vines analysis, and reducing or replacing its quantities is not a straight-forward decision (Gispert, 2021), even less in presence of soils with low or moderate potassium content, as in Los Robles and Totihue (Agrolaba; Agrolabb). Considering that potassium is removed when harvesting the grapes, mostly ending up in the grape pomace generated during the vinification phase (Longbottom, 2010; Antonic et al., 2020), and that the winery use all of their pomace to produce compost that then is applied as a fertilization supplement, in this case two scenarios were modelled, one replacing 15% of the total amount of potassium applied with compost, and other replacing 30%. In both scenarios, besides reducing the amount of potassium and increasing the amount of compost of the assembly, the transport processes related to the fertilisers containing potassium were also modified, reducing their weights. Fig. 7 details the changes that each scenario generates when compared with the baseline model, and (Letamendi, 2021) contains further details on how these calculations were made. In line with the results presented in section 3.2.1, the categories positively affected were LU and Ecosystems. How and in which magnitude these productive alterations will affect the grapes growth and finally the wine production is suggested to be considered in future research.

Manure is the main input (in mass) utilised in the viticulture phase, as presented in section 2.1.1.4, and reinforced in section 3.2.1. The field-level emissions estimated are directly influenced by the quantity of fertilisers and manure applied, thus manure was responsible for over 80% of each nitrogen-related emission accounted in the model (ammonia, dinitrogen monoxide, and nitrogen monoxide to air, and nitrate to water). To analyse possible improvements, two scenarios were modelled, one reducing 15% of the total amount of manure as fertiliser, and other reducing 30%. In both scenarios, besides reducing the amount of manure, the transport of the manure, the process representing its loading and spreading on the vineyards, and the field-level emissions were also modified accordingly. Fig. 8 details the changes that each scenario generates when compared with the baseline model. In line with the results presented in section 3.2.1, the main categories positively affected were SOD and MEu, but it also generated an interesting reduction on TA.

3.3.3. Electricity mix modification

The winery is about to launch a photovoltaic energy project to supply clean electricity to their operations in Casablanca estate. Considering a hypothetical case where this project expands to Los Robles and Totihue estates, and Palmeras cellar, two scenarios were modelled, one accounting for 25% of photovoltaic energy produced in-house (for consumption in both, the viticulture and vinification phases), and other accounting for 50%. The differences (75% and 50%, respectively) were covered by the same low voltage country mix electricity used in the baseline model. As a proxy, mono silicon panels with slanted-roof installation in Chile were chosen (as modelled by Ecoinvent 3), due to its efficiency, purity, resistance to high temperatures, and longevity (Bagher et al., 2015). Fig. 9 details the changes that each scenario generates when compared with the baseline model, showing some variability. Although reductions resulted especially in PM, FEu, and Human Health, minor increases were experienced in IR, TE, and MRS, which are associated to the metal and fossil resources extraction needed to produce the panels (Rashedi and Khanam, 2020).

3.3.4. All in one

In addition to all these sensitivity analyses, a final exercise was executed where different scenarios were combined to get an idea of the potential aggregated improvements resulting from diverse actions taken at the same time. The 15% replacement of potassium, 15% manure reduction, 25% photovoltaic energy coverage, air freight to Brazil, and PET bottle were chosen as an example. Fig. 10 details the changes generated when compared with the baseline model, showing large improvements in almost all categories (especially IR, FEu, TE, and MRS), and reaching a single score reduction of 28.29%.

[8] A fourth scenario utilising a lighter bottle was not considered as the winery already use the most eco-friendly and lightest bottle provided by its supplier ("eco-glass", 0.365 Kg).

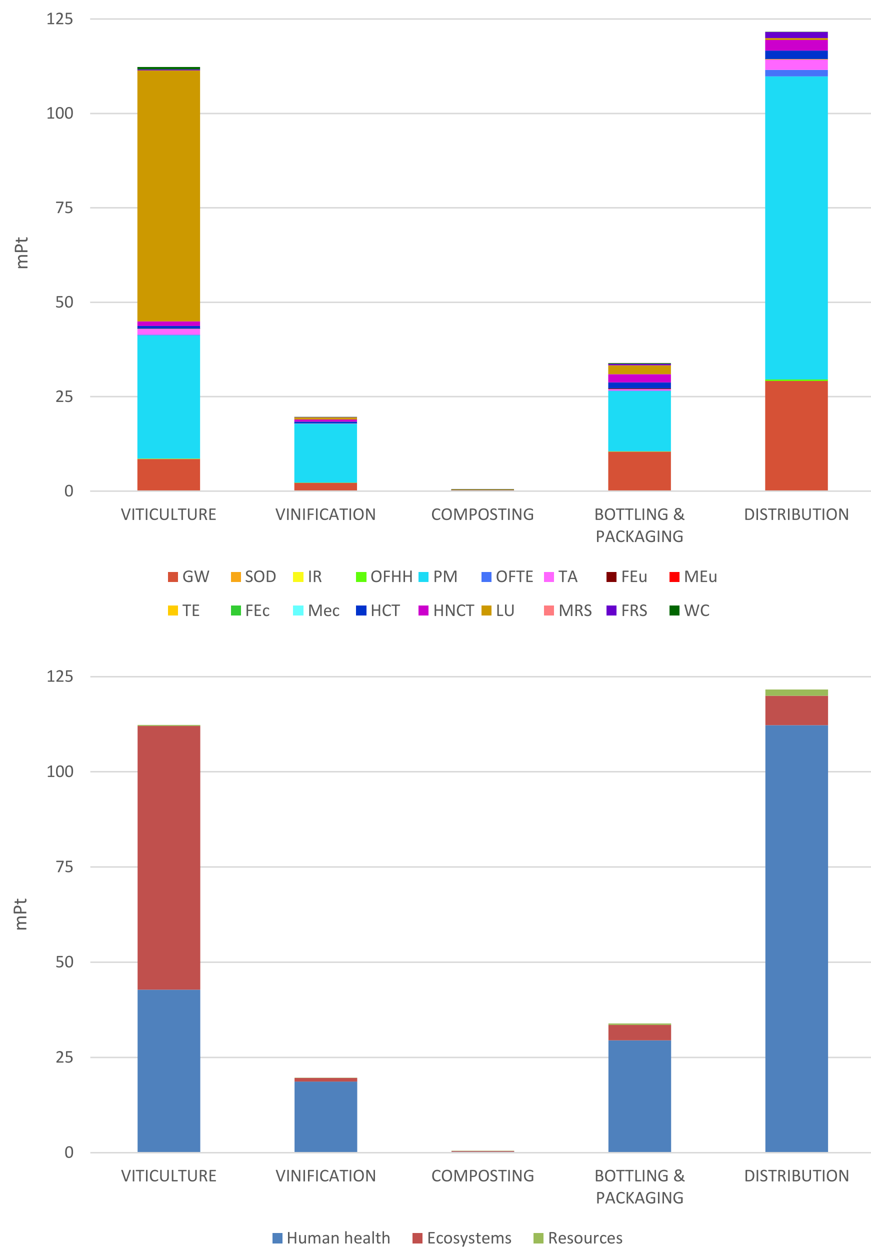

Fig. 4. Single scores of each impact (above) and damage (below) category in the different lifecycle phases and processes assessed, using ReCiPe 2016 Endpoint H/A.

4. Discussion

4.1. Environmental issues and hotspots

Distribution was the lifecycle phase identified as hotspot for 7 of the impact categories and 2 of the damage categories assessed, particularly with regards to its contribution to climate change. Surprisingly, it contributed more than viticulture, normally recognised as the most impactful phase within wine LCAs (Azoumanidis et al., 2015; Christ and Burritt, 2013). This can be explained by the number of international markets included in this assessment and the distances involved, which are larger than in almost all the studies reviewed, usually accounting for international transport within Europe and not overseas.

Viticulture was identified as the second phase contributing the most to the overall environmental load, being hotspot for 4 impact categories and 1 damage category and having almost the same contribution share than the distribution phase when evaluated from a single score perspective. This is completely lined up with what some authors have concluded regarding acidification and eutrophication risks (Arzoumanidis et al., 2013), land use (Marras et al., 2015; Ferrari et al., 2018), ecosystems damage, and high water demand (Azoumanidis et al., 2015; Christ and Burritt, 2013). Delving into this phase, the literature shows that the fertilisation process have also been reported as a main variable responsible for the contribution of viticulture practices on global warming and eutrophication, particularly its associated field-level emissions (Gazulla et al., 2010; Litskas et al., 2020; Neto et al., 2013; Point et al., 2012). A novelty in these results are the impacts associated to the potassium content of fertilisers, which have not been reported as an issue within the papers, reports, and case studies revised.

The contribution from bottling was led by the production of the glass bottle used, placing this lifecycle phase in third place as a combined hotspot of 2 impact categories, which was also reported as a major issue in the systematic reviews conducted by (Azoumanidis et al., 2015; Ferrara and De Feo, 2018). A considerable number of those studies

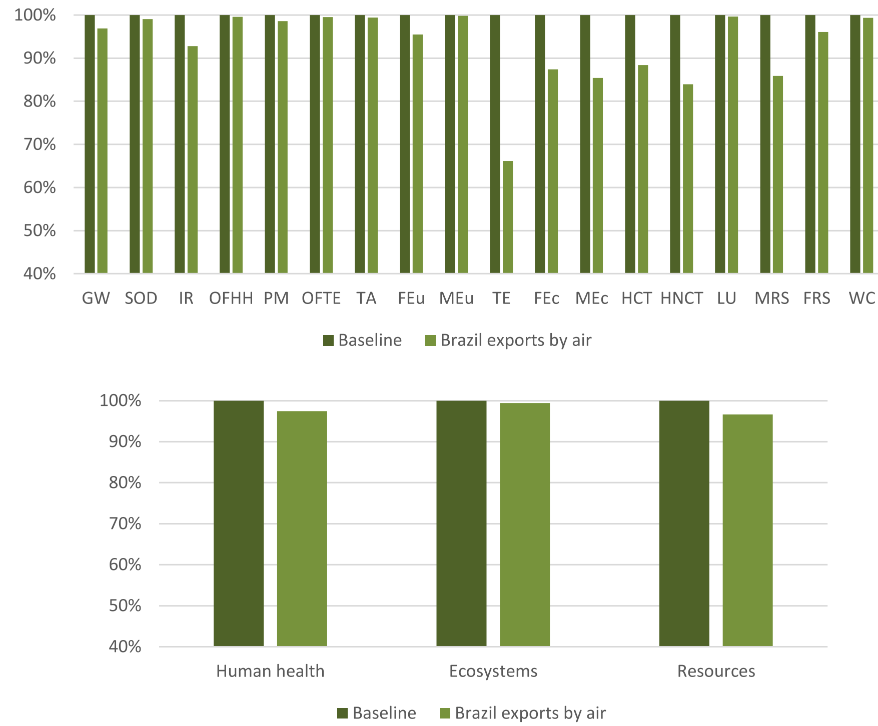

Fig. 5. Comparison between baseline and modified distribution scenario.

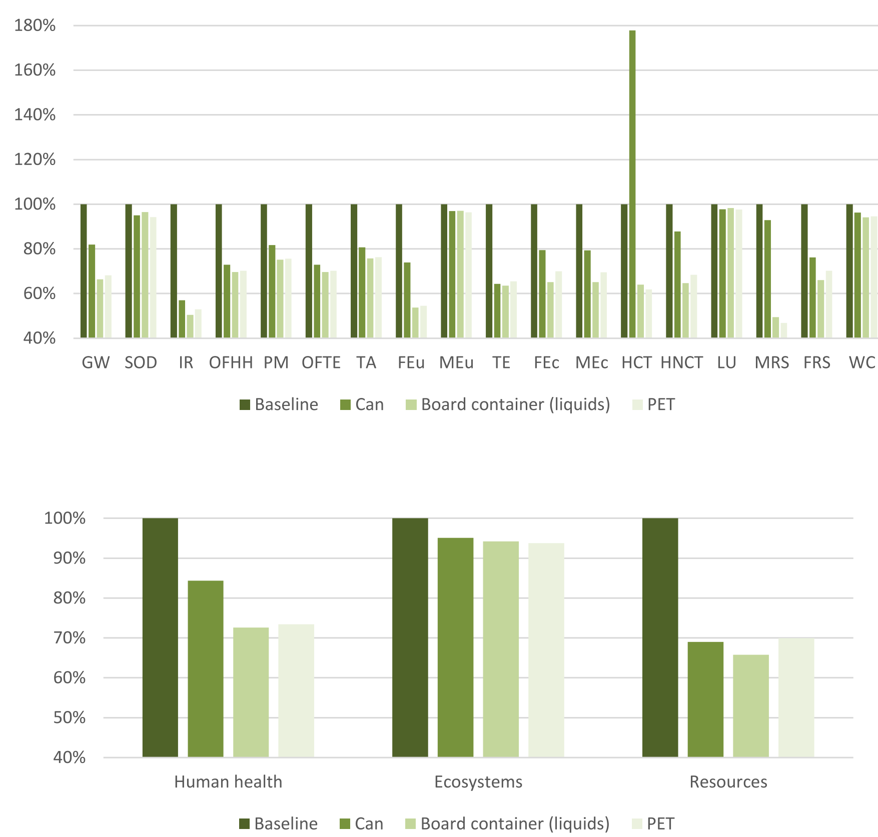

Fig. 6. Comparison between baseline and modified packaging scenarios.

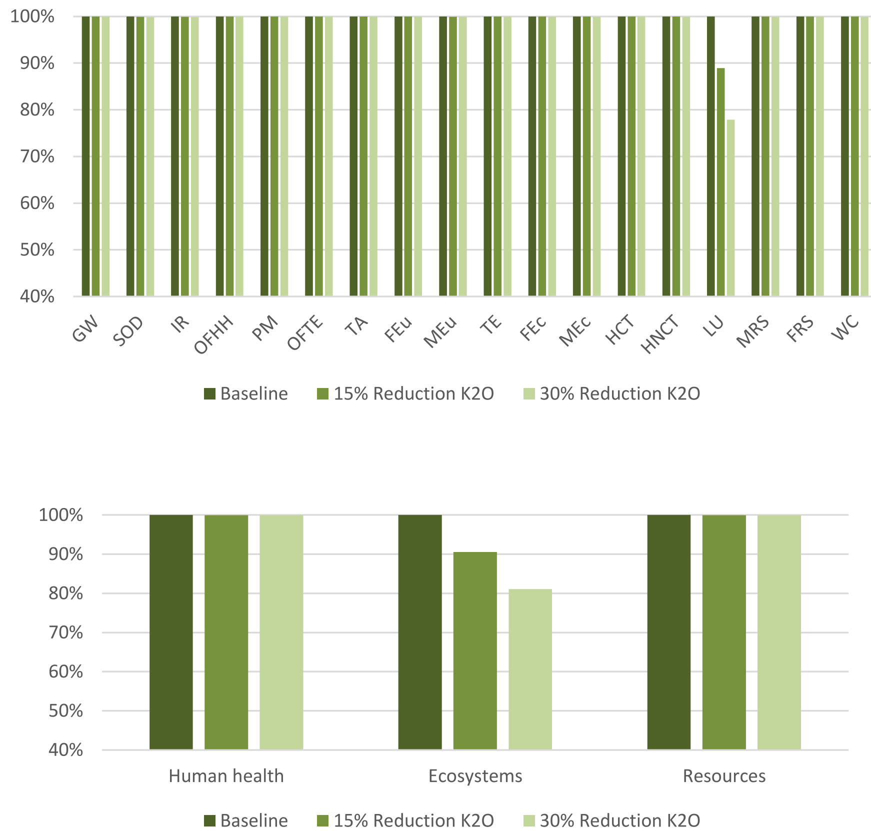

Fig. 7. Comparison between baseline and modified potassium scenarios.

identified the bottle as the main overall contributing variable, not being the case in this project, possibly due to the differences on system boundaries, software, and LCI databases utilised. Nonetheless, the reported impacts' interpretations are alike to the one in this study, with a focus on global warming, resources depletion, and eco and human toxicities (Ardente et al., 2006).

Publications that conducted wine LCAs with the same FU and similar system boundaries than the present assessment got coinciding overall results to the ones of this study (Amienyo et al., 2014). recognised the viticulture and distribution phases as the main hotspots, contributing more than 70% to the environmental impacts they considered (Harb et al., 2021). identified the grape production, primary packaging production, and wine distribution as the main relevant stages, contributing 39%, 34%, and 19% to the impact categories considered, respectively (Piña, 2016). reported that the main contributors to the environmental impacts were the glass bottle (26%), irrigation (21%), wine distribution (18%), and fertilisers and pesticides used (14%). Additionally, vinification is usually considered as less impactful than the rest of the lifecycle phases, being the energy consumption the most relevant contributing variable (Vázquez-Rowe et al., 2012b; Iannone et al., 2016)., which is also the case in this study. Therefore, it is possible to state that in this case the results obtained support and are reinforced by the existent literature.

4.2. Sensitivity analyses and recommendations

Scholars who performed sensitivity analyses had found that actions related to fertilisers use, opting for lower-weight glass bottles, and the management and logistics of the wine distribution are the areas showing higher potential to maximise environmental performance improvements (Cleary, 2013; Jiménez et al., 2014; Rugani et al., 2013). This is completely aligned with the analyses conducted in this study, strengthening the argument proposed in section 4.1.

In terms of distribution, three alternatives can be recommended to the winery. One is to evaluate the use of air freights instead of maritime freights, being an unlikely route-of-action considering how the industry works and the associated economic costs of such a change. Analysing this alternative for intracontinental terrestrial freights (e.g., Brazil) may be worth the time and effort, since it can have significant improvements on 6 impact categories (specially TE). The second alternative is to analyse different packaging options, either looking for a supplier that can provide lighter glass bottles or exploring other primary packaging materials. As showed in Fig. 6, this option generates the most substantial improvements between all the scenarios revised, and in almost all categories analysed. However, this alternative represents a complex decision for wineries, due to marketing and prestige issues (Barber et al., 2006), and the existent controversy between who defend the glass bottle as a requirement for keeping the wine's quality, and studies showing no significant differences when sensory and oenological analyses are applied to wines packed in containers made of different materials (Ghidossi et al., 2012). The third alternative is to evaluate exporting bulk wine, bottle it in the markets of destination (where feasible), and then distribute it accordingly. It is expected that this alternative should bring improvements considering the reduction in weight during the distribution phase, nevertheless it will only generate positive net benefits if the bottling & packaging phase in the different markets is less impactful than WPL's current operations, and if the impacts related to the posterior wine distribution are lower than the ones generated by the current terrestrial distribution in Chile and abroad. Furthermore, aluminium, cardboard and PET containers weight less and contribute less than glass in several of the categories evaluated, suggesting that a comparative LCA between the baseline model developed in this study and this third alternative might be useful for internal decision making. Finally, waste management systems vary between the different markets

Fig. 8. Comparison between baseline and modified manure scenarios.

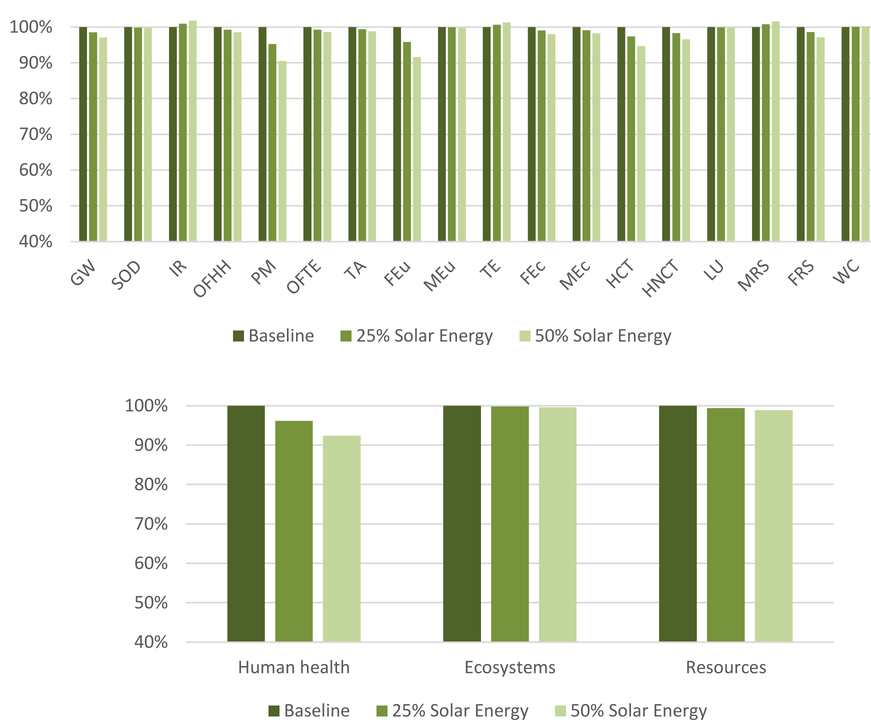

Fig. 9. Comparison between baseline and modified energy mix scenarios.

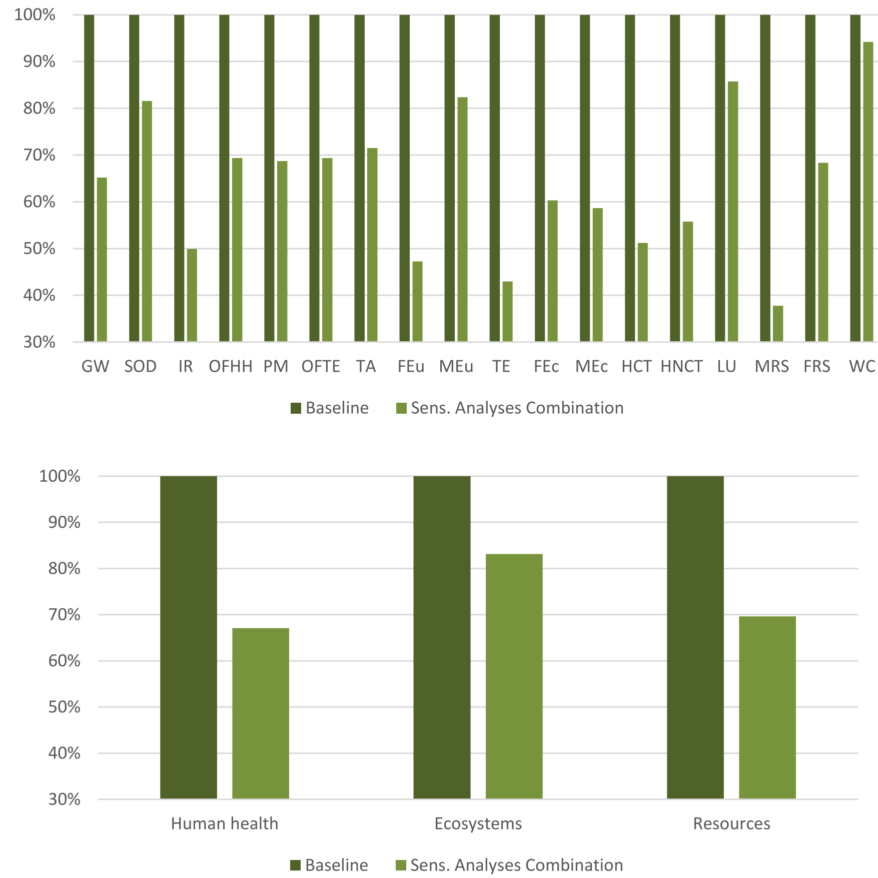

Fig. 10. Comparison between baseline and combined sensitivity analyses scenarios.

where the wine is sold, and the materials analysed. Adding this lifecycle phase to the assessment might lead to different results and conclusions that worth attention and deeper analysis.

In terms of nutrient management, replacing potassium with compost generates significant improvements on LU and Ecosystems impacts. Additionally, manure's reduction can result in a notable improvement for SOD and MEu impacts. Vineyards nutrition is critical for healthy and commercially viable grape production, being inputs' replacement or reduction not always possible. Hence, a sensitive recommendation for the winery would be to permanently conduct a combination of soil and plant tissue (petiole) analyses, and visual assessments of foliage helping to optimise the quantities of fertilisers and manure to be applied yearly (Gispert, 2021; Schaller, 2008).

The locally produced photovoltaic energy scenarios analysed showed that developing new installations can provide improvements in some categories and deterioration in others, Reaching a higher energy coverage than the scenarios presented might result in intensified environmental improvements and should be an alternative for the winery to explore, but it is important to acknowledge that a net benefit will only occur if the positive impacts on some categories exceed the negative impacts on other categories, which will ultimately depend on the priorities of the winery. Other option would be to generate electricity through biogas, processing their vinification by-products, however this alternative requires deeper analysis as these by-products are an essential component of their internal composting, which in turn is a vital fertilisation supplement. Feasibility evaluations must be conducted on renewable energy alternatives along with the modification of bottling and distribution practices, in operational and financial terms, ensuring their economic sustainability. For the moment, the environmental improvements of these alternatives indicate that the winery should not let pass these complementary evaluations.

5. Conclusions

5.1. Limitations

Representing a recreation of reality, this study results in several limitations and recommendations for future research.

- Wine production has a heterogeneous nature, implying that meaningful comparisons even within the winery's products may lose practical use. Furthermore, the FU, system boundaries, assumptions, inputs, outputs, and processes included and left aside, complicates the comparison with other studies.
- It is a very specific project, accounting for just 1 of 4 blends that compose the total production of Reserva Rosé (2020). Although N°1 was selected for its representativeness of the internal winery's operations, modelling and results of the other blends might differ substantially. Thus, assessing all blends would allow to get a full picture of the reality.
- The use of primary data was maximised, but several global averages were also utilised based on LCA databases, potentially leading to large standard deviations. For example, two of the main hotspots identified (glass bottles and fertilisers) were modelled using Ecoinvent 3 data. Collecting and including specific operational and technical data from inputs' producers would be beneficial.
- Only 1 LCIA method was applied for calculating the results, which can narrow the interpretation. Using 2 or 3 LCIA methodologies would allow to compare and evaluate the consistency of the results. Furthermore, conducting uncertainty analyses such as Monte Carlo

simulations can improve the reliability of the results, and enrich the temporal and geographical variability of the study.

- Default ReCiPe 2016 normalisation and weighting factors were used. Using bespoke factors might be helpful for better decision making, based on internal priorities and strategies, and the country's specific environmental situation and planning.
- Fertilisers' application timing, soil characteristics, and climatic conditions during application were not considered for field-level emissions calculations. Furthermore, it was not possible to differentiate in Ecoinvent 3 between synthetic and natural origin fertilisers and pesticides used, which might change the results obtained, especially altering the estimation of field-level emissions. More work is needed to develop databases containing a broader range of organic and natural origin agricultural inputs, and to articulate economic and environmental indicators accounting for benefits associated to natural and organic approaches to vitiviniculture.

5.2. Wider implications

The environmental issues related to the wine industry are complex. On one hand, they vary in scope and scale depending on the reality in which each grape producer and winery is immersed. On the other hand, they are innately interrelated and are shared by several studies. Therefore, individual environmental approaches and strategies are needed, which together will make possible a social, environmental, and economically sustainable industry.

The winery assessed is a good example of a company with a clear environmental sustainability strategy that goes well beyond the immediate scope of this LCA. Its organic and biodynamic vitiviniculture practices do not permit synthetic pesticides or fertilisers, promote biodiversity within their vineyards through the development of biological corridors and intercropping, and are complemented by a Breeding and Nursery Programme. Moreover, developing a circular economy approach on 100% of its vinification by-products, using light bottles eco-glass 2, having installed recycling points in all facilities, and being a member of the Science Based Targets Initiative (SBTi) are just some initiatives that characterise the company's commitments for responsible production (Emiliana, 2021). Although some of these were included as part of the LCA, the majority were out of the scope of the project. An assessment involving all these actions along with the social initiatives developed by the winery such as organic agriculture education, community gardens, and recreational centres (Emiliana, 2021) would possibly alter the results, reducing the impacts reported for Reserva Rosé 2020 by extending the scope of the assessment towards additional sustainability dimensions, integrating an LCA with a S-LCA (Hauschild et al., 2018).

Extended assessments like the example above would nurture the industry of valuable insights, enhancing better practices for the people, the planet, and wineries' financial results, trespassing the immediate borders of vineyards and wineries' doors. Even though it is unlikely that this technique expands fast and broadly, due to the resources related to comprehensive LCAs (namely time and money) (Ardente et al., 2006), there are options for producers to optimise their supply chains and support the wider industry. In the case of the winery assessed, keeping the research and development work done in alliance with WoC, Corfo, and ANID its crucial (Emiliana, 2021), and can be leveraged by adding projects with a lifecycle perspective over their products and supplies, either working together with the same organisations, or generating new partnerships. An example could be work in collaboration with the Ministry of the Environment, under the framework of its Sustainable Consumption and Production Programme, like the successful case experienced by Yalumba and the Australian Environmental Protection Authority (EPA, 2004).

Research and assessments comprising a lifecycle and holistic approach have the potential to not only improve the functioning of supply chains, but their environmental and social impacts as well. Progress on this matter will never be reached without, first, the will of grape producers and wineries, and second, the support and prioritisation of trade unions, government agencies, and policy makers, especially in terms of funding and regulatory frameworks.

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CRediT authorship contribution statement

Javier Letamendi: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Eva Sevigne-Itoiz:** Conceptualization, Resources, Writing – review & editing, Visualization, Supervision. **Onesmus Mwabonje:** Conceptualization, Resources, Writing – review & editing, Visualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.133368.

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