Life cycle assessment of the supply chain of a Portuguese wine: from viticulture to distribution

Belmira Neto · Ana Cláudia Dias · Marina Machado

Abstract

Purpose This paper performs a life cycle assessment study for a white wine produced in the northern part of Portugal, i.e. the white *vinho verde*. The purpose is to identify the environmental impacts occurring along the wine life cycle as well as the stages that mostly contribute to the environmental impact, as well as the associated causes. The stages considered include: (1) viticulture, (2) wine production (vinification to storage), (3) wine distribution and (4) bottles production.

Methods The consumption of materials and energy, as well as the emissions to air, soil and water from the wine campaign of 2008/2009 were reported to the functional unit (0.75 l of white vinho verde). A Portuguese company that produces about 25 % of the current total production of white vinho verde supplied specific life cycle data for the stages of viticulture, wine production and distribution. SimaPro and the Ecoinvent database were used to perform the environmental assessment using CML 2001 impact methodology. A sensitivity analysis for a set of significant parameters was performed.

Results Results show that for viticulture the contribution of each impact category is larger than 50 %. The production of bottles is the second contributor varying from about 4 % (to eutrophication) to 26 % (to acidification). Wine production and distribution are the subsequent contributors. The contribution of wine production varies between 0.6 % (to land competition) and about 13 % (from marine aquatic and sediment ecotoxicity 100a). The contribution of distribution is up to 14 % (to photochemical oxidation). Sensitivity analysis shows that significant changes are calculated for parameters as the nitrate leaching to groundwater, the emission of nitrous oxide from managed soil, and from runoff and leaching. Changes in these parameters are significant for only a few impact categories as eutrophication and global warming.

Conclusions Viticulture is the stage with the largest relative contribution to the overall environmental impact and the bottle production is the subsequent stage. In order to improve the environmental performance of the supply chain for wine, it is necessary to optimise the dosage of fertilisers and phytosanitary products used during viticulture. The sensitivity analysis demonstrates that the most influential parameters relate with the emission of nitrogen compounds associated with the use of fertilisers.

Keywords Distribution · Fertilisers · Life cycle assessment (LCA) · Phytosanitary products · Viticulture · White wine

B. Neto (✉)
CEMUC, Faculty of Engineering, University of Porto,
Rua Dr. Roberto Frias,
4200-465 Porto, Portugal
e-mail: belmira.neto@fe.up.pt

A. C. Dias
Centre for Environmental and Marine Studies (CESAM),
Department of Environment and Planning, University of Aveiro,
Campus Universitário de Santiago,
3810-193 Aveiro, Portugal

M. Machado
Faculty of Engineering, University of Porto,
Rua Dr. Roberto Frias,
4200-465 Porto, Portugal

1 Introduction

This work assesses the environmental impact associated with a wine produced in Portugal (i.e. the white vinho verde) and exported worldwide. This wine is exclusively produced in the northern part of Portugal, in the Demarcated Region of Vinho Verde. The wine sector assumes an important position in Portugal, as the country is among the 12

leading countries for vine plantation (OIV 2010). The white vinho verde is the white wine with the largest production share in Portugal. In 2010–2011, about 50 million litres of white vinho verde were produced in Portugal, of which around 30 % were exported (IVV 2010; CVRVV 2011).

The main stages associated with the wine include activities during viticulture, wine production (from vinification to storage) and distribution (wine commercialisation). However, several other activities also occur. This includes the production and transport of materials used in viticulture (for example phytosanitary products) and during wine production (including wine additives).

Several studies have evaluated the environmental impacts of wine using life cycle assessment (LCA). Environmental product declarations (EPDs) and Product Category Rules (PCRs) have also been published for wine (IEPDS 2011; EPD 2008a, b). These LCA and EPD studies vary on the wine production country, type of wine, production practices (conventional and biological) and, among other aspects, on the life cycle stages considered. Several LCA studies present a cradle to grave approach including wine distribution (Aranda et al. 2005; Gonzalez et al. 2006; Gazulla et al. 2010; Bosco et al. 2011; Point et al. 2012). Other studies perform a cradle to gate approach considering wine distribution (Ardente et al. 2006; Petti et al. 2006). The remainder consider cradle to grave or cradle to gate approaches, however, distribution is not analysed (Notarnicola et al. 2003; Pizzigallo et al. 2008). In summary, the studies demonstrate that the production of glass bottles and viticulture are important stages regarding the impacts of the wine life cycle.

However, a study that analyses a complete set of the relevant inputs and outputs associated with viticulture, wine production and distribution and concerning the life cycle of wine that is sold worldwide is not available in the reviewed literature. We have found that the available studies may not be complete either in the inventory list of materials and energy considered from viticulture (by excluding for instance, the production and the emission resulting from the application of the phytosanitary products) or in the complete assessment for the impacts categories associated with the activities from the main stages of the wine life cycle. Studies that cover a more complete set of environmental impacts lack in the assessment of at least one, of the following impact categories: land competition, ozone depletion, human toxicity, freshwater and marine ecotoxicities (Gazulla et al. 2010; Point et al. 2012; Vázquez-Rowe et al. 2012). Moreover, the studies reviewed lack analysis of the influence of wine distribution (for wines commercialised to several countries for which a long-range transport occurs) in the impact results (Gazulla et al. 2010). This paper aims to cover some of the identified lacks.

The purpose of this study is to perform a LCA of a wine exclusively produced in Portugal, i.e. the white wine designated locally as white vinho verde. This is to identify the environmental impacts occurring along the wine life cycle stages of viticulture, wine production, distribution and glass bottle production. For that purpose, we have made use of data provided by the largest producer of vinho verde in Portugal, Aveleda S.A. In 2008–2009, this company sold about 25 % of the national production of the white vinho verde and exported worldwide around 50 % of its wine. The results obtained for several impact categories are presented for each life cycle stage. A sensitivity analysis is done to identify the parameters that most influence the results of the impact assessment.

2 Methods

2.1 Scope definition

The stages considered include activities taking place during (1) viticulture (grapes growing), (2) wine production (from vinification to wine storage), (3) distribution and (4) bottles production. The data used pertains to the wine produced in the campaign 2008–2009 and refers to 0.75 l of white vinho verde as the functional unit.

The system boundary includes the materials, water and energy used in the activities taking place during viticulture, wine production and the white glass bottle production. Worldwide wine distribution is also included, as well as the transportation of grapes, wine and must and other products used during wine production (Santos 2010; Machado 2011) (Fig. 1).

Some activities were not considered here, as for instance, the transportation of man labour during the grapes harvesting. This is due to the fact that harvesting occurs automatically, i.e. only 4 % of the harvested area uses manual labour. This amount was considered to be negligible. Other activities as the potential impacts regarding the consumption of refrigerated wine were not taken into account. The vinho verde is always refrigerated before consumption and this may occur in the wine shop or at the consumer home. Despite the fact that the potential impact due to refrigeration may be significant, data regarding energy consumption for refrigeration is not readily available and thus this stage was excluded from this study. The same occurs for the consumer transport to purchase wine. This activity was also not considered. Other activity not included is the transportation of wastes as it was considered to be negligible. The transport of phytosanitary products used in the viticulture stage was also excluded due to the lack of data about distances travelled and type of transport. Our study does not consider the capital goods production, maintenance and end of life. Others activities concerning the cork stoppers production as well as the labelling materials used in the bottles were also not considered in the study.

Fig. 1 Life cycle of the white vinho verde. The *dashed line* identifies the stages not included in the analysis
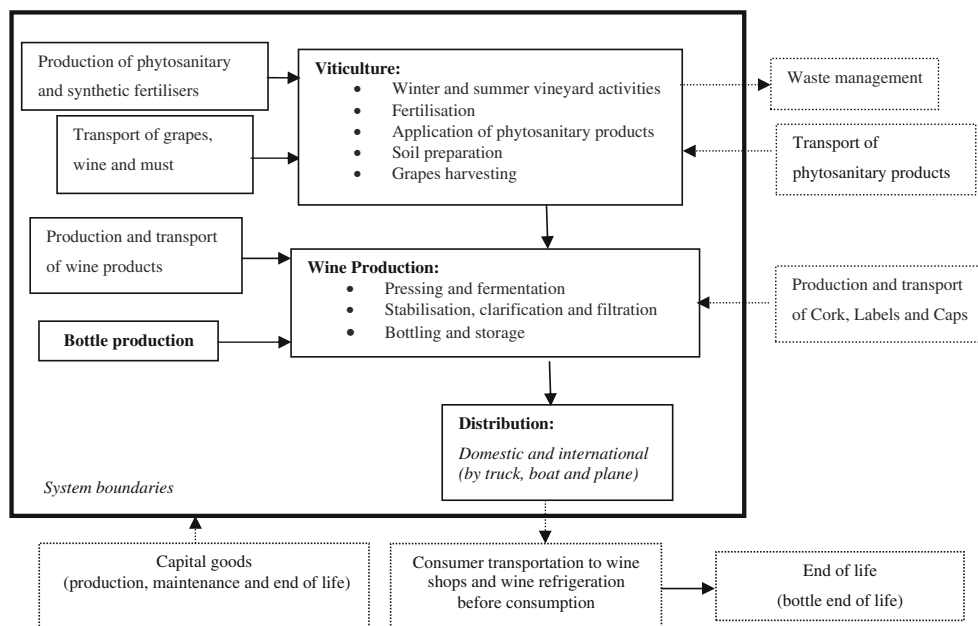
2.2 Inventory

The analysis was performed by using SimaPro software (SimaPro 2011). The Ecoinvent database (Ecoinvent 2011) was employed as the principal source of background data. Table 1 shows the activities and its duration associated with the viticulture, wine production and distribution stages for Aveleda S.A. wine campaign of 2008–2009.

The inventory data from viticulture were supplied by the case company or estimated using activity data from the company and emission factors from literature. Aveleda S.A. is the largest producer of white vinho verde and despite owning vineyards it purchases around 90 % of grapes and about

Table 1 Time frame associated to each life cycle stage for the wine campaign 2008–2009

Life cycle stages	Time frame considered for the inventory
Viticulture	November 2007 to October 2008
Winter and summer vineyard activities	
Fertilisation	
Application of phytosanitary products	
Soil preparation	
Grapes harvesting	
Wine production	September 2008 to November 2009
Pressing and fermentation	September to October 2008
Stabilisation, clarification and filtration	September 2008 to August 2009
Bottling and storage	December 2008 to November 2009
Distribution	January to December 2009

40 % of must and wine used to produce wine. Grapes and must are produced by other local producers within the Demarcated Region of Vinho Verde. For the purpose of the analysis, we have considered that the practices of other producers are similar to Aveleda's. The grape vines are not irrigated.

Table 2 lists the inventory for viticulture calculated based on data supplied by Aveleda S.A. about the vine area, grapes and wine production and productivity, materials, water and energy used as well as the wastes produced. Background data associated with the production of materials used in viticulture is estimated using Ecoinvent (2011).

The emissions resulting from the application of phytosanitary products, fertilisers and from diesel consumption in viticulture were estimated. The emissions associated with the use of phytosanitary products are, according to many authors, mainly released to soil (Audsley 1997; Hauschild 2000; Margni et al. 2002; Milà i Canals 2003; EMEP/EEA 2009). This study considers that 75 % of the emissions of the active chemical are released to soil. The remaining is emitted to air. This approach was considered to occur for all phytosanitary products used. The value 75 % is not explicitly recommend to use in the literature, thus we have performed a sensitivity analysis, regarding the amount of the active chemicals released to air and soil, as result of the application of the phytosanitary products.

The emissions of nitrogen compounds to air such as nitrous oxide (N_2O), nitrogen oxides (NO_x) and ammonia (NH_3) and the emission of nitrate (NO_3^-) to water, were estimated based on the methodology described in Intergovernmental Panel on Climate Change (IPCC 2006a). Nitrogen compounds are emitted to air and water as a result of the use of fertilisers (synthetic and solid manure). The emissions of N_2O to air (i.e. the N_2O direct emissions from managed

Table 2 Direct inputs and outputs from viticulture

Viticulture inputs	Amount	Unit reported to FU
Water	7.26E-04	m^3
Land occupation	1.08E-04	ha
Electricity	2.59E-01	kWh
Diesel (agricultural machinery)	2.34E-01	kg
Phytosanitary products:		
Dithiocarbamate compounds		
Metiram	1.03E-03	kg
Thiocarbamate compounds		
Cymoxanil	1.51E-04	kg
Iprovalicarb	2.14E-04	kg
Acetamide-aniline compounds		
Phenexamid	9.4E-04	kg
Cyclic–N compounds		
Tebuconazol	1.25E-04	kg
Penconazole	4.40E-05	kg
Phtalamide compounds		
Folpet	5.97E-03	kg
Organophosphorus compounds		
Fosetyl-Al	7.54E-03	kg
Glyphosate	3.96E-03	kg
Unspecified		
Sulphur	2.98E-2	kg
Copper	1.72E-3	kg
Pyraclostrobin	1.94E-4	kg
Synthetic fertilisers:		
Ammonia nitrate	7.80E-03	kg
Ammonia sulphate	6.48E-02	kg
Urea ammonia nitrate	6.28E-02	kg
Solid manure	1.26	kg
Transport of grapes	1.86E-02	t.km
Transport of wine and must	1.09E-02	t.km
Viticulture outputs:		
Grapes	1	kg
Emissions to air (due to fertilisers use):		
Ammonia	1.88E-05	kg
Nitrous oxide	8.59E-04	kg
Nitrogen oxides	2.00E-04	kg
Carbon dioxide (fossil)	1.97E-02	kg
Emissions to air (due to phytosanitary products):		
Dithiocarbamate compounds		
Metiram	2.58E-04	kg
Thiocarbamate compounds		
Cymoxanil	3.77E-05	kg
Iprovalicarb	7.30E-05	kg
Acetamide-aniline compounds		
Phenexamid	2.35E-04	kg
Cyclic–N compounds		
Tebuconazol	3.14E-05	kg
Penconazole	1.10E-05	kg
Phtalamide compounds		
Folpet	1.49E-03	kg

Table 2 (continued)

Viticulture inputs	Amount	Unit reported to FU
Organophosphorus compounds		
Fosetyl-Al	1.89E-03	kg
Glyphosate	9.90E-04	kg
Unspecified		
Pyraclostrobin	2.35E-05	kg
Emissions to air (from diesel combustion):		
Carbon dioxide (fossil)	7.39E-01	kg
Carbon monoxide (fossil)	1.39E-03	kg
Methane	4.45E-06	kg
Nitrous oxide	3.23E-05	kg
Ammonia	1.87E-06	kg
NMVOC	2.74E-04	kg
Nitrogen oxides	4.82E-03	kg
Particulates	1.47E-04	kg
Emissions to water (due to fertilisers):		
Nitrate	5.76E-02	kg
Emissions to soil (due to phytosanitary products):		
Dithiocarbamate compounds		
Metiram	7.75E-04	kg
Thiocarbamate compounds		
Cymoxanil	1.13E-04	kg
Iprovalicarb	2.19E-04	kg
Acetamide–aniline compounds		
Phenexamid	7.05E-04	kg
Cyclic–N compounds		
Tebuconazol	9.43E-05	kg
Penconazole	3.30E-05	kg
Phtalamide compounds		
Folpet	4.48E-03	kg
Organophosphorus compounds		
Fosetyl-Al	5.66E-03	kg
Glyphosate	2.97E-03	kg
Unspecified		
Sulphur	2.24E-02	kg
Copper	9.90E-04	kg
Pyraclostrobin	1.46E-04	kg
Wood wastes from vineyard	8.80E-01	kg
Packaging wastes	9.67E-04	kg
Other wastes (including wasted oil and other materials from equipment maintenance)	2.62E-02	kg

The inventory data reports to the functional unit (FU)=0.75 l of vinho verde

soils and N$_2$O indirect emissions from volatilisation and from runoff and leaching) were estimated based on emission factors taken from IPCC (2006a). Besides, the calculated N$_2$O indirect emissions from volatilisation considered also emission factors specific for the chemical compounds occurring in the synthetic fertilisers, i.e. the ammonium nitrate, ammonium sulphate and the urea ammonium nitrate. These

emission factors, that were also used to estimate NH_3 emissions, were collected from Nemecek and Kägi (2007). We have assumed that the N_2O indirect emissions are all volatilised as NH_3. Emission factors for NO_3^- are from IPCC (2006a). Although not often included in the inventory of wine-related studies, the emissions of NO_x were estimated as being 0.21 times the total emissions of N_2O (Nemecek and Kägi 2007). This equation, valid for non-irrigated systems (as stated in Nemecek and Kägi 2007), was used in order to cover a wide number of pollutants associated with viticulture.

The emissions of fossil carbon dioxide (CO_2) resulting from urea application were calculated according to IPCC (2006a). Air emissions from diesel combustion during the use of agricultural machinery were estimated based on the emission factors from the European Monitoring and Evaluation Programme/European Environment Agency (EMEP/EEA 2009) by using the tier2 approach.

Must and wine purchased by Aveleda S.A. come from local producers. About 85 % of the must and wine travel between 9 and 46 km and the remaining 15 % travel between 35 and 60 km. During the campaign 2008–2009, grapes were purchased from about 40 producers. About 83 % of the grapes travelled to Aveleda less than 60 km, around 15 % travelled between 61 and 110 km and the remaining grapes travelled between 110 and 374 km. Table 2 lists the t.km associated with grapes, wine and must transportation from local producers to Aveleda. Grapes are transported in a tractor and trailer and wine and must in lorries >32 t.

The inventory data from wine production was mainly supplied by the case company (Table 3). This specifically refers to materials, water and energy used as well as water emissions and solid wastes produced.

Air emissions associated with fermentation and liquefied petroleum gas (LPG) use were estimated based on activity data from Aveleda S.A. and emission factors from literature. During fermentation, biogenic CO_2 and nonmethane volatile organic compounds (NMVOC) are released. The emission factor for CO_2 was taken from Peynaud (1981) and Soares (1998) and the emissions of NMVOC were calculated from EMEP/EEA (2009). The emissions released during LPG consumption in wine production (LPG is used to generate vapour used to sterilise the empty wine bottles) were estimated using emission factors from IPCC (2006b) and EMEP/EEA (2009).

The materials used during wine production, the enologic products, the filtration and cleaning agents and the other wine additives, are transported by truck to the company. Most of the products are purchased from a national retailer and transported at a distance less than 50 km. Exceptions are the sulphur dioxide (SO_2) and a few cleaning agents, for which the supplier is located at a distance of about 350 km. Table 3 lists the t.km associated with the transportation of wine products as the additives, disinfectants, enologic

Table 3 Direct inputs and outputs from wine production

Wine production inputs	Amount	Unit reported to FU
Grapes	1	kg
Water	1.68E-03	m³
Electricity	2.91E-01	kWh
LPG for bottles sterilization	8.68E-03	kg
White glass bottle	5.30E-01	kg
Wine additives:		
Sodium hydroxide	1.35E-03	kg
Tallow	9.20E-07	kg
Cleaning agents and disinfectants:		
Isopropanol	3.68E-06	kg
Peracetic acid	3.68E-06	kg
Hydrogen peroxide	3.68E-06	kg
Ammonium chloride	2.76E-05	kg
EDTA (ethylenediaminetetraacetic acid)	1.12E-04	kg
Sodium hydroxide	7.04E-04	kg
Potassium hydroxide	7.45E-06	kg
Sodium hypochlorite	5.04E-06	kg
Phosphoric acid	5.80E-05	kg
Enologic products:		
Nitrogen liquid	7.40E-04	kg
Carbon dioxide liquid	2.61E-04	kg
Oxygen liquid	1.05E-06	kg
Sulphur dioxide liquid	1.38E-04	kg
Bentonite	6.28E-04	kg
Potassium carbonate	1.68E-04	kg
Potassium metabisulphite	6.32E-05	kg
Whey (enzymes)	1.01E-04	kg
Yeast	1.53E-04	kg
DAP (diammonium phosphate)	1.10E-04	kg
Silica gel	3.45E-04	kg
Gelatine	1.04E-04	kg
Flor-stop agent	3.31E-08	kg
PVPP (polyvinyl polypyrrolidone) granulate	9.78E-05	kg
Filtering materials:		
Corrugated board	1.45E-04	kg
Perlite	2.57E-03	kg
Silica sand	3.84E-04	kg
Kraft paper	3.59E-04	kg
Transport of wine products:		
Transport of additives	5.30E-05	t.km
Transport of disinfectants	6.53E-04	t.km
Transport of enologic products	4.26E-04	t.km
Transport of filtering materials	1.32E-04	t.km
Wine production outputs:		
Wine	0.75	l
Air emissions from fermentation:		
Carbon dioxide (biogenic)	5.20E-02	kg

Table 3 (continued)

Wine production inputs	Amount	Unit reported to FU
Non-methane volatile organic compounds	2.63E-04	kg
Air emissions from LPG combustion:		
Carbon dioxide (fossil)	2.54E-02	kg
Methane	4.02E-04	kg
Nitrous oxide	4.02E-05	kg
Nitrogen oxides	4.02E-05	kg
Carbon monoxide (fossil)	1.61E-05	kg
NMVOC (non-methane volatile organic compounds)	4.02E-06	kg
Sulphur oxides	5.63E-05	kg
Particulates	1.11E-05	kg
PM< 10 um	8.65E-06	kg
PM< 2.5 um	6.63E-06	kg
Lead	6.43E-09	kg
Cadmium	1.21E-10	kg
Mercury	4.02E-11	kg
Arsenic	4.02E-10	kg
Chromium	5.14E-09	kg
Copper	2.89E-09	kg
Nickel	1.04E-07	kg
Zinc	3.22E-09	kg
Polychlorinated dioxins and furans (PCDD/F)	4.02E-15	kg
Benzo(*a*)pyrene	2.09E-09	kg
Benzo(*b*)fluoranthene	2.49E-09	kg
Benzo(*b*, *j*, *k*)fluoranthene	1.61E-09	kg
Indeno(1,2,3-cd)pyrene	8.84E-10	kg
Water emissions:		
COD	2.23E-03	kg
BOD$_5$	5.59E-04	kg
TSS	7.70E-04	kg
Phosphorus (total)	5.39E-05	kg
Nitrogen (total)	7.51E-05	kg
Solid wastes:		
Stalk	3.13E-02	kg
Bagasse	7.46E-02	kg
Organic waste	2.04E-02	kg
Urban wastes	1.85E-02	kg

The inventory data reports to the functional unit (FU)=0.75 l of vinho verde

products and filtering materials to Aveleda. These are transported in vans <3.5 t.

White glass bottles were assumed to be manufactured out of about 61 % recycled glass. This value was retrieved from the ecoinvent database (version 2.2) for white packaging glass (Ecoinvent 2011).

In respect to the distribution, in 2009, about 50 % of the total wine produced by Aveleda S.A. was sold in Portugal. The remaining wine was exported to several countries. Nearly 40 % of the total exportation was delivered by truck, boat and plane, to six countries, namely USA, Germany, France, Angola, Canada and Brazil.

Information regarding the sales destination countries, amount transported and type of transport (truck, boat and plane) was also made available by Aveleda S.A. The company sells in 38 countries, from which 20 are located in Europe, seven in America, six in Africa, four in Asia and one in Oceania. The road transport (about two thirds of the transportations) is mainly done by 16–32 t lorries. However, transoceanic tankers and flight freights are also used. Around one third of the transportations occur by boat and the flights represent a small amount. Emissions were estimated for lorries, transoceanic tankers and flight freights by using the Ecoinvent (2011) database. Table 4 expresses in t.km the amount of wine transported in Distribution.

2.3 Impact assessment

SimaPro (version 7.3.2) was used to model the life cycle of wine using midpoint indicators of environmental impact (CML 2001 impact assessment method). Results are obtained for the characterisation step. This widely accepted method was chosen also to allow the comparison of our results with a large number of related studies on wine impact assessment.

The amount of biogenic CO_2 sequestered from the atmosphere during vine and grape growth was assumed to be equal to the amount of CO_2 that is released back to the atmosphere due to the oxidation of the carbon contained in the pruning wastes, as well as due to oxidation of the carbon contained in the grapes along the downstream life cycle stages. Data taken from Ecoinvent also assumes neutrality for biogenic CO_2. Therefore, biogenic CO_2 was not considered in the global warming impact category.

2.4 Sensitivity analysis

A set of parameters, considered to be the most uncertain, were changed in order to assess its influence in the environmental impact results (Table 5). In viticulture, the parameters include those associated with the emission to air and water of nitrogen compounds (NO_3^-, NH_3, N_2O (direct and indirect)) caused by application of fertilisers. We also changed the NO_x emission between a minimum and a maximum as a function of the total emission of N_2O. We changed the amount of manure used in fertilisation by ±20 % and the CO_2 emission as result of the urea application by lowering it by 50 % relative to the reference case. Finally, for viticulture, we also changed the emissions to soil and air associated with

Table 4 Inventory data for the distribution of vinho verde

Distribution country	Units (t.km) reported to UF		
	Truck	Boat	Plane
USA	–	1.2E+00	4.3E-05
Angola	–	2.8E-01	–
Canada	–	2.1E-01	2.3E-05
Brazil	–	1.6E-01	4.2E-05
Germany	1.6E-01	4.3E-03	–
Portugal	1.2E-01	1.7E-02[a]	1.9E-06
France	8.2E-02	–	–
China	–	4.3E-02	–
South Africa	–	3.6E-02	–
Sweden	–	2.8E-02	2.2E-06
Japan	–	2.7E-02	–
Denmark	2.3E-03	2.0E-02	1.7E-06
Finland	5.0E-03	2.0E-02	6.2E-06
Switzerland	1.8E-02	–	–
Australia	–	1.4E-02	–
Cape Verde	–	1.3E-02	–
Norway	1.3E-02	–	1.9E-06
Luxembourg	1.1E-02	–	–
Belgium	9.8E-03	–	–
Venezuela	–	9.6E-03	–
Mozambique	–	8.3E-03	–
Namibia	–	7.4E-03	–
Paraguay	–	5.7E-03	–
UK	5.6E-03	–	2.6E-06
Russian Federation	5.0E-03	–	–
Mayotte	–	9.3E-04	–
Estonia	8.9E-04	–	–
Uruguay	–	7.9E-04	–
Spain	7.8E-04	–	–
Poland	7.5E-04	–	–
Andorra	6.3E-04	–	–
India	–	4.9E-04	–
Netherlands	4.2E-04	–	–
Costa Rica	–	3.5E-04	–
Ireland	3.2E-04	–	–
Austria	1.1E-04	–	–
Singapore	–	1.1E-04	–
Czech Republic	8.0E-05	–	–

[a] Includes the transportation by boat to Madeira and Azores islands

the use of the active chemical of the 12 phytosanitary compounds (listed in Table 2).

For wine production, factors changed were the emission factors of CO_2, methane (CH_4) and N_2O associated to the use of LPG in the sterilisation of bottles occurring in the production line. These were changed between a minimum and a

maximum within a range defined in EMEP/EEA (2009). The results are obtained by considering simultaneously, in one hand all minimum values of emission factors and, on the other hand, all maximum values.

The amount of recycled glass used in bottle production is also a source of uncertainty. The Portuguese situation, in 2009, is that 55 % of the glass packaging has been recycled (APA 2011).

However, the amount of white packaging glass being recycled for wine bottle production purposes is not available. Moreover, no inventory data is readily available concerning the production of white glass in Portugal. Also, no data is available in respect to the materials and energy needs as a function of the amount of cullets used to produce white glass for packaging. For these reasons, the execution of a sensitivity analysis on the percentage of recycled glass incorporated in the production of white packaging glass, although important, is left outside the scope of this paper. More research is needed on this topic and this must be done with the cooperation of the glass production industry.

In the distribution, the sensitivity analysis focused on changing the distance travelled. The distances changed by ±30 % for all the 38 countries and for each transportation mode (truck, boat and plane).

3 Results

Results show that the viticulture is the life cycle stage that mostly contributes to all impact categories. The contribution to each category is larger than 50 % (Table 6).

Bottles production is the second contributor. The contribution varies from about 4 % (eutrophication) to 26 % (acidification). Wine production and distribution are the subsequent contributors. The contribution of wine production varies between 0.6 % (to land competition) and about 13 % (from marine aquatic and sediment ecotoxicity 100a). The contribution of distribution ranges from 0 % (to land competition) to 14 % (to photochemical oxidation).

Viticulture has a large contribution to the majority of the environmental problems. We identify below the pollutants responsible for about two thirds of the overall contribution of viticulture to each impact category.

Eutrophication is caused by the emissions of NO_3^- (to water) due to the use of fertilisers. Land competition is caused by the soil area needed for grapes growing. The ozone depletion problem is related to the emission of CFC and halon occurring, respectively, during the production of a phytosanitary compound (the acetamide aniline compound, phenexamid) and the production of diesel. Terrestrial ecotoxicity is due to the emission of glyphosate (to soil) and vanadium (to air). Glyphosate emission to soil is due to the phytosanitary application and the emission of vanadium occurs during the production of fertilisers.

Table 5 List of parameters and respective changes considered in the sensitivity analysis

Life cycle stage	Parameter description	Variation
Viticulture	NO_3^- leaching to groundwater	The fraction of all N added to soils in regions where leaching/runoff occurs that is lost through leaching and runoff changed between 0.1 and 0.8 (NH_3+NO_x−N)/kgN (IPCC 2006a)
Viticulture	N_2O direct emissions from managed soils	Emission factor for N_2O changed between 0.003 and 0.03 N_2O-N/kgN (IPCC 2006a)
Viticulture	N_2O indirect emission from volatilisation	The fraction of applied organic N fertiliser that volatilises as NH_3 and NOx, changed between 0.05 and 0.5 kg (NH_3+NO_x−N)/kgN (IPCC 2006a)
		The fraction of applied synthetic N fertiliser that volatilises as NH_3 and NOx, changed between 0.03 and 0.3 kg (NH_3+NO_x−N)/kgN (IPCC 2006a)
		The emission factor for N_2O changed between 0.002 and 0.05 kg N_2O−N/ (NH_3+NO_x−N) (IPCC 2006a)
Viticulture	N_2O indirect emission from runoff and leaching	The fraction of all N added to/mineralised in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff changed between 0.1 and 0.8 kgN/kgN (IPCC 2006a)
		The emission factor for N_2O changed between 0.0005 and 0.025 kg N_2O−N/kg N (IPCC 2006a)
Viticulture	NO_x emission	Considered to vary as function of the previous calculated total (direct and indirect) minimum and maximum emission of N_2O (the minimum is 4.39E-05 and the maximum is 7.82E-04) (IPCC 2006a)
Viticulture	NH_3 emissions	The fraction of applied organic N fertiliser that volatilises as NH_3 and NOx, changed between 0.05 and 0.5 kg (NH_3+NO_x−N)/kgN (IPCC 2006a)
		The fraction of applied synthetic N fertiliser that volatilises as NH_3 and NOx, changed between 0.03 and 0.3 kg (NH_3+NO_x−N)/kgN (IPCC 2006a)
		The emission factor for N_2O changed between 0.002 and 0.05 kg N_2O-N/ (NH_3+NO_X−N) (IPCC 2006a)
Viticulture	Amount manure used	Considered that the amount of manure used varies by ±20 % (Aveleda 2011, personal communication)
Viticulture	CO_2 emission from urea	Considered the minimum value as −50 % of the reference value (IPCC 2006a)
Viticulture	Emissions to air associated to the use of the 12 phytosanitary compounds	Considered that the active chemical is emitted to air in an amount varying between 10 % and 50 % (EMEP/EEA 2009)
Viticulture	Emissions to soil associated to the use of the 12 phytosanitary compounds	Considered that the active chemical is emitted to soil with a maximum value of 85 % (EMEP/EEA 2009)
Wine production	Emission factors for CO_2, CH_4 and N_2O associated to the use of LPG for bottles sterilisation	The emission factors were changed accordingly (EMEP/EEA 2009): EF $CO_{2(min)}$=61.6 kg/GJ; EF $CO_{2(max)}$=65.6 kg/GJ EF $CH_{4(min)}$=0.3 kg/GJ; EF $CH_{4(max)}$=3 kg/GJ EF $N_2O_{(min)}$=0.03 kg/GJ; EF $N_2O_{(max)}$=0.3 kg/GJ
Distribution	Distances travelled for distribution (all countries and transportation modes)	Travelled distances were considered to change by ±30 %

Global warming problems are essentially due to the emission of CO_2 and N_2O. CO_2 emissions are mainly associated with the combustion of diesel, used in the agricultural machinery, and the CO_2 emitted during application of urea. The emission of N_2O is essentially occurring due to the application and production of fertilisers.

The problems of fresh water and sediment ecotoxicity are due to emission of glyphosate (to air) and barium, formaldehyde, polyaromatic hydrocarbons (PAHs) and zinc (to water). The emission of glyphosate occurs during the application of this phytosanitary product. Barium and PAH are emitted during the production of diesel. Formaldehyde results

from the production of glyphosate and zinc occurs during the production of a phytosanitary compound (i.e. the dithiocarbamate compound, metiram).

Human toxicity is associated with the emission of heavy metals to air (as nickel and arsenic), benzene (to water) and PAH to both water and air. Nickel and arsenic are associated with the production of fertilisers, electricity and diesel. The emission of benzene to water occurs mainly during the production of phytosanitary compounds (as the acetamide aniline compound, phenexamid and other unspecified). The emission of benzene to air is also due to the production of phytosanitary compounds (as the acetamide aniline

Table 6 Results (expressed in absolute values and in percentage of contribution) from the characterisation step presented for each impact category and for all the life cycle stages considered

Impact category	Viticulture	%	Bottle production	%	Wine production	%	Distribution		
							Domestic	Worldwide	%
Eutrophication (kg PO_4^{3-} eq)	7.3E-03	89.9	2.9E-04	3.6	3.7E-04	4.5	1.2E-04	4.5E-05	2.0
Land competition (m^2a)	1.1E+00	88.7	1.3E-01	10.7	7.4E-03	0.6	1.6E-05	2.0E-05	0.0
Ozone layer depletion steady state (kg CFC-11 eq)	3.3E-07	77.3	4.8E-08	11.1	1.5E-08	3.6	2.7E-08	7.6E-09	8.0
Terrestrial ecotoxicity 100a (kg 1.4-dB eq)	6.8E-04	70.0	1.9E-04	19.7	7.3E-05	7.5	2.4E-05	3.0E-06	2.8
Global warming 100a (kg CO_2 eq)	2.0E+00	68.6	4.4E-01	15.3	2.4E-01	8.1	1.8E-01	5.2E-02	8.0
Freshwater aquatic ecotoxicity 100a (kg 1.4-dB eq)	1.4E-02	67.4	4.4E-03	21.5	9.5E-04	4.7	1.0E-03	2.9E-04	6.4
Human toxicity 100a (kg 1.4-dB eq)	2.0E-01	65.5	5.4E-02	17.4	3.3E-02	10.4	1.2E-02	8.4E-03	6.7
Marine sediment ecotoxicity 100a (kg 1.4-dB eq)	2.6E-01	65.2	4.7E-02	11.9	5.2E-02	13.2	1.7E-02	2.2E-02	9.7
Freshwater sediment ecotoxicity 100a (kg 1.4-dB eq)	2.4E-02	64.1	8.5E-03	22.5	2.1E-03	5.6	2.3E-03	7.3E-04	7.8
Abiotic depletion (kg Sb eq)	1.1E-02	63.7	3.3E-03	18.9	1.6E-03	9.0	1.1E-03	3.3E-04	8.4
Marine aquatic ecotoxicity 100a (kg 1.4-dB eq)	2.3E-01	63.3	5.7E-02	15.6	4.7E-02	13.0	1.4E-02	1.6E-02	8.1
Acidification (kg SO_2 eq)	8.3E-03	55.1	4.0E-03	26.4	1.8E-03	11.9	6.1E-04	3.9E-04	6.6
Photochemical oxidation (kg C_2H_4 eq)	3.1E-04	50.6	1.4E-04	23.7	7.0E-05	11.7	7.1E-05	1.3E-05	14.0

compound, phenexamid) but also to the production of diesel. The emission of PAH to air occurs during the production of fertilisers and electricity. The emission of PAH to water occurs during diesel production.

The problems of marine aquatic and sediment ecotoxicity are caused by the emission of vanadium, and nickel (to air) and tributyltin (to water). Tributyltin is a biocide used to prevent the growth of marine organisms on the hulls of large ships to water during barge tanks transport. Vanadium and nickel are associated with the production of fertilisers and electricity and tributyltin is mainly due to the production of diesel. Abiotic depletion is due to the consumption of fossil-based energy resources as oil crude, natural gas and coal. Acidification is mostly associated with the emission of SO_2 and NO_x to air. The emission of SO_2 is mainly caused during the production of electricity and diesel. NO_x is essentially associated with the diesel combustion is the agricultural machinery. Finally, the photochemical oxidation results from emission of SO_2 and CO. SO_2 emission is mainly due to the production of electricity and diesel and CO emission is mainly associated with the combustion of diesel used during the operations of agricultural machinery.

The main environmental problems associated with glass bottle production are acidification (26 %), photochemical oxidation (24 %), freshwater sediment ecotoxicity (23 %), freshwater aquatic ecotoxicity (22 %), terrestrial ecotoxicity (20 %) and abiotic depletion (19 %). Acidification and photochemical oxidation are mainly caused by the emission

of SO_2 to air. Freshwater aquatic and sediment ecotoxicity are due to the emission of heavy metals (mainly selenium (emitted to air), nickel and barium emitted to water). Finally, abiotic depletion results mostly from the use of natural gas and crude oil.

Wine production problems relate mainly to marine aquatic and sediment ecotoxicity (both contributing to 13 %), acidification and photochemical oxidation (contribution of about 12 %) and human toxicity (contribution of 10 %). Ecotoxicity is due to the release of heavy metals to air (mainly vanadium). Photochemical oxidation is mainly associated with the emission of SO_2 and the human toxicity are due to the release of heavy metals (as nickel and arsenic) and PAH to air.

The environmental problems caused during distribution include photochemical oxidation (contribution of 14 %), and marine sediment ecotoxicity (contribution of 10 %). Photochemical oxidation is mainly caused by the emission of CO and SO_2 associated with diesel combustion during truck transport. The problem of marine sediment ecotoxicity 100a relate to the use of biocides (i.e. tributyltin) used to prevent the growth of marine organisms on the hulls of large ships to water during barge tanks transport.

The results of the sensitivity analysis show that changing some parameters does not influence the impact assessment results for the variation range analysed. This is valid for a number of parameters analysed including the amount of manure used, the emissions of CO_2 associated with the urea

use and the emissions to air associated with the use of the 12 phytosanitary products. Other parameters, not influencing the results, include the distances travelled during wine distribution for a large number of countries.

However, some parameters influence significantly the calculated impact categories. Table 7 shows the parameters for which the changes in the characterisation results are equal or larger than 1 % for at least one impact category, when compared to the results obtained for the reference case. Significant changes are calculated for parameters SA1 (NO_3^- leaching to groundwater), SA2 (N_2O direct emission from managed soil) and SA4 (N_2O indirect emission from runoff and leaching) (see Table 7).

We observed that these changes are significant for only a few impact categories. SA1 leads to changes in eutrophication due to changes in NO_3^- emissions. SA2, SA3 and SA4 lead to changes in global warming 100a due to the variation on the emission of N_2O which has a large global warming potential.

Others parameters influence, by a comparatively small amount, multiple categories (see Table 7). This is the case for SA5 (NO_x emissions from fertilisers use), SA6 (NH_3 emissions), SA7 (emissions to soil from the use of phytosanitary compounds), SA8 (emission factors for CO_2, CH_4 and N_2O from LPG used for bottles sterilisation during wine

production), SA9 (distance travelled by truck in Portugal) and SA10 (distance travelled by boat to USA).

SA5 leads to small changes in the categories acidification (−1, +2 %) and eutrophication (0, +1 %). SA6 caused changes in acidification (0, +2 %) and eutrophication (0, +1 %). SA7 affects freshwater aquatic ecotoxicity 100a (+2 %), terrestrial ecotoxicity 100a (+4 %) and freshwater sediment ecotoxicity 100a (+1 %). The parameter SA8 leads to a change in global warming 100a (±1 %) and photochemical oxidation (+1 %). The parameter SA9 leads to changes in a large number of environmental problems, varying from ±1 % (acidification, human toxicity, marine aquatic and sediment ecotoxicity 100a and terrestrial ecotoxicity) to ±4 % (photochemical oxidation). SA10 leads to small changes for the categories of marine aquatic and sediment ecotoxicity 100a (± 1 %).

4 Discussion and conclusions

Viticulture is the life cycle stage with the largest relative contribution to the overall environmental impact. This stage contributes by more than 50 % to all environmental problems. Bottle production appears as the second stage due essentially to the fossil fuels used during glass bottles

Table 7 Sensitivity analysis results, calculated for the characterisation step, expressing the changes for each impact category related to the reference case

Impact Categories:	Sensitivity parameters									
	SA1 (%)	SA2 (%)	SA3 (%)	SA4 (%)	SA5 (%)	SA6 (%)	SA7 (%)	SA8 (%)	SA9 (%)	SA10 (%)
Abiotic depletion (kg Sb eq)	0	0	0	0	0	0	0	0	±2	0
Acidification (kg SO_2 eq)	0	0	0	0	−1, +2	0, +2	0	0	±1	0
Eutrophication (kg $PO4^{3-}$ eq)	−47, +118	0	0	0	0, +1	0, +1	0	0	0	0
Global warming 100a (kg CO_2 eq)	0	−5, +14	0, +3	−2, +12	0	0	0	−1, +1	±2	0
Ozone layer depletion steady state (kg CFC-11 eq)	0	0	0	0	0	0	0	0	±2	0
Human toxicity 100a (kg 1.4-dB eq)	0	0	0	0	0	0	0	0	±1	0
Freshwater aquatic ecotoxicity 100a (kg 1.4-dB eq)	0	0	0	0	0	0	+2	0	±2	0
Marine aquatic ecotoxicity 100a (kg 1.4-dB eq)	0	0	0	0	0	0	0	0	±1	±1
Terrestrial ecotoxicity 100a (kg 1.4-dB eq)	0	0	0	0	0	0	+4	0	±1	0
Marine sediment ecotoxicity 100a (kg 1.4-dB eq)	0	0	0	0	0	0	0	0	±1	±1
Freshwater sediment ecotoxicity 100a (kg 1.4-dB eq)	0	0	0	0	0	0	+1	0	±2	0
Land competition (m^2 a)	0	0	0	0	0	0	0	0	0	0
Photochemical oxidation (kg C_2H_4 eq)	0	0	0	0	0	0	0	0, +1	±4	0

SA1 NO_3^- leaching to groundwater, *SA2* N_2O direct emission from managed soil, *SA3* N_2O indirect emission from volatilisation, *SA4* N_2O indirect emission from runoff and leaching, *SA5* NO_x emissions from fertilisers use, *SA6* NH_3 emissions from manure, *SA7* emissions to soil from the use of phytosanitary compounds, *SA8* emission factors for CO_2, CH_4 and N_2O from LPG used for bottles sterilisation during wine production, *SA9* distance travelled by truck in Portugal, *SA10* distance travelled by boat to USA

production. We have found that these two stages have a larger contribution to the impact when compared to wine production and distribution. This is also valid for a number of reviewed wine studies (e.g. Gazulla et al. 2010; Point et al. 2012). Furthermore, the environmental problems for wine production are, alike for the bottle production stage, associated with the fossil fuels used during wine production.

We observed that despite the fact that 50 % of the wine is being distributed to 37 countries located worldwide, distribution has a relatively lower impact when compared to viticulture and bottle production. Environmental problems caused by distribution are mainly associated with the emission of gases from diesel combustion and use of biocides associated with the maritime transportation. Based on these results, we may then conclude that wine distribution, for this specific case in which a long-range transportation occurs, does not influence significantly the overall environmental problems associated with the wine life cycle.

The comparison with other recent published wine-related LCA studies shows that the impact assessment results may differ. A significant difference occurs for global warming. We summarise here the differences found for the viticulture and distribution stages, which are the stages for which major variations occur. The values found for viticulture expressed in kilograms CO_2 eq. per FU (0.75 l of wine) are the following: 0.33 (Bosco et al. 2011), 0.50 (Gazulla et al. 2010), 0.80 (Point et al. 2012) and 2.5 (Vázquez-Rowe et al. 2012). The value we calculated for white vinho verde is equal to 2.0 kg CO_2 eq./FU. These differences may occur due both to different degrees of mechanisation in the agricultural procedures and to different amounts and composition of the fertilisers used (manure and synthetic). The methods used to estimate the emissions may also be the cause. Thus, further investigation is needed to understand these differences.

For the distribution stage, the study from Bosco et al. (2011) calculates 0.44 kg CO_2 eq./FU referring to a wine distributed from the winery gate in Tuscany to a wine platform located 1,600 km away. The study from Gazulla et al. (2010) calculates 0.076 kg CO_2 eq./FU for domestic distribution within Spain and 0.085 kg CO_2 eq./FU for distribution to UK. Our study calculates 0.18 kg CO_2 eq./FU for the distribution in Portugal and 0.052 kg CO_2 eq./FU for the worldwide distribution. That is to say that about 78 % of the GWP value is due to the domestic distribution. We conclude that indicators for global warming potential vary largely even among wines produced and commercialised within Europe. Therefore, more research is needed to better understand the differences in the magnitude among these values.

A complete assessment of the environmental problems allows a more supported decision on how to reduce the overall impact associated with the wine life cycle. This study shows the importance of using a more complete set of inventory data concerning specifically the life cycle of phytosanitary products and their consequent impacts in air, soil and water. In fact, by considering the production of phytosanitary products it was possible to draw important conclusions associated with the toxicity (human, terrestrial, freshwater and sediment ecotoxicities) related to the production and use of these products. In the wine campaign of 2008–2009, the number of phytosanitary interventions was comparatively large by comparison to other years. This was to avoid the reduction of grapes productivity caused by the mildew disease that could affect in this specific campaign largely the vineyard. For this specific situation, the most significant results indicate that the acetamide–aniline compounds (more specifically the phenexamid) are responsible for the emission of substances contributing to human toxicity. The use of glyphosate is contributing to terrestrial, freshwater and sediment ecotoxicities. Also, the production of the dithiocarbamate compound (more specifically the metirame) is causing freshwater and sediment ecotoxicities. The comparison among the toxicity categories (human, terrestrial, freshwater and marine aquatic and sediment ecotoxicities) also allows to conclude that the magnitude of the indicators for human toxicity (3.1E-01 kg 1.4-dB eq./UF), marine aquatic (3.7E-01 kg 1.4-dB eq./UF) and marine sediment (4.0E-01 kg 1.4-dB eq./UF) are relatively large when compared to the other toxicity categories. Therefore, human toxicity, marine aquatic and sediment seem to be the larger contributors to toxicity problems. This is true for all the life cycle stages considered.

We conclude that viticulture is also the stage where large sensitivities are found. Changes in the sensitivity parameters lead to comparatively large effect for few impact categories as eutrophication and global warming. Results show that the most influential parameters relate to the emission of nitrogen compounds resulting from the use of manure and synthetic fertilisers. Changes in these parameters (SA1, SA2 and SA4) affect eutrophication and global warming.

The other parameters do not influence significantly the impact categories analysed. Changes in the parameter SA3 leads to changes in the global warming potential. Changes in SA5 and SA6 change the acidification and eutrophication categories. Changes in the parameters associated with the emission of phytosanitary compounds to soil (parameter SA7) affect some of the toxicity related categories and changes in the emission factors specific for LPG (parameter SA8) result in small changes for global warming and photochemical oxidation. The changes in the distance travelled in Portugal by truck (parameter SA9) influence by small amount (from ±1 to ±4 %) several categories. Finally, the distance travelled to USA by barge tank (parameter SA10) show to affect only by a small amount the maritime toxicity problems.

A limitation of this study relates with the exclusion of some activities, namely waste management activities; the transportation of phytosanitary products, production and transport of cork, labels and caps; the consumer transportation to wine shops, wine refrigeration before consumption and the bottle end of life. This is due to two reasons: (1) data were not readily available at Aveleda, S.A. and estimation may result very uncertain and (2) these activities were considered by others as relatively less important when compared to the main stages here considered (as in Gazulla et al. 2010 and Point et al. 2012). However, we refer, in line with the study from Point et al. (2012) that among the above-mentioned activities, the consumer transportation to purchase wine might be a relatively important stage and thus should not be neglected. In summary, the different results obtained indicate that a more complete study, covering more wine life cycle stages, is needed in order to reveal the relative importance of them.

Finally and from the review made, we conclude that for the few available wine-related LCA studies, the impact categories results are not easily comparable. This may be due to different methodological options as, for instance, the inventory parameters considered, the methods used to estimate emissions and the impact assessment methods. This also highlights the need of developing harmonised PCRs to allow the comparison among the results of LCA studies for wine.

Another possible reason relates to distinct procedures used to produce wine. Concerning future studies, it is important for the decision making on reducing wine impacts that the studies performed made available a more transparent list of inventory data associated with all stages from the wine life cycle covering also a large number of problems such as the toxicity related impacts.

References

APA (Agência Portuguesa do Ambiente) (2011) Embalagens e Resíduos de embalagens. Situação de referência 2004–2010 (in Portuguese) Departamento de Fluxos Especiais e Mercado de Resíduos. Divisão de Entidade Gestoras e Mercado de Resíduos Available in http://www.apambiente.pt/_zdata/Politicas/Residuos/FluxosEspecificosResiduos/ERE/SituacaoReferenciaERE.pdf. Accessed Sep 2012

Aranda A, Scarpellini S, Zabalza I (2005) Economic and environmental analysis of the wine bottle production in Spain by

means of life cycle assessment. Int J Agric Resour Gov Ecol 4(2):178–191

Ardente F, Beccali G, Cellura M, Marvuglia A (2006) POEMS: a case study of an Italian wine-producing firm. Environ Manag 38 (3):350–364

Audsley E (1997) Harmonization of environmental life cycle assessment for agriculture. European Commission DG VI Agriculture. Silsoe Research Institute, Silsoe

Bosco S, Di Bene C, Galli M, Remorini D, Massai R, Bonari E (2011) Greenhouse gas emissions in the agricultural phase of wine production in the Maremma rural district in Tuscany, Italy. Ital J Agron 6(e15):93–100

CVRVV (Comissão de Viticultura da Região dos Vinhos Verdes) (2011) Statistics of production and exportation of vinho verde. Available in http://www.vinhoverde.pt/en/. Accessed Jan 2012

Ecoinvent (2011) Ecoinvent (database ecoinvent data v.2.2) available in http://www.ecoinvent.ch/

EMEP/EEA (2009) 4.G—Agriculture other (use of pesticides and limestone). In Air pollutant emission inventory guidebook 2009—technical report no 9/2009. European Environment Agency: Copenhagen

EPD (2008a) Environmental product declaration. Bottled red sparkling wine. "Grasparossa Righi, validated environmental product declaration No S-P-00109. Available in http://gryphon.environdec.com/data/files/6/7505/EPD%20S-P-00109%20ingl-2008-def.pdf. Accessed Sep 2012

EPD (2008b) Environmental product declaration. Bottled organic Lambrusco Grasparossa red sparkling wine "Fratello Sole". Available in http://gryphon.environdec.com/data/files/6/7521/EPD_Fratello%20Sole_english%202008-def.pdf. Validated environmental product declaration No S-P-00119. Accessed Sep 2012

Gazulla C, Raugei M, Fullana-i-Palmer P (2010) Taking a life cycle look at crianza wine production in Spain: where are the bottlenecks? Int J Life Cycle Assess 15:330–337

Gonzalez A, Klimchuck A, Martin M (2006) Life cycle assessment of wine production process: finding relevant process efficiency and comparison to eco-wine production. Environmental Engineering and Sustainable Infrastructure. Life Cycle Assessment Course (1 N1800). Stockholm, KTH-Royal Institute of Technology

Hauschild M (2000) Estimating pesticide emissions for LCA of agricultural products. In: Weidema BP, Meeusen MJG (eds) Agricultural data for life cycle assessments, volume 1. Agricultural Economics Research Institute (LEI), The Hague

IEPDS (The International Environmental Product Declaration System) (2011) Product category rules. CPC Subclass 24212. Wine of fresh grapes, except sparkling; grape must. PCR 2010:02, version 1.01. Available in http://www.environdec.com/en/Product-Category-Rules/Detail/?Pcr=5850. Accessed Sep 2012

IPCC (Intergovernmental Panel on Climate Change) (2006a) In 2006 IPCC Guidelines for National Greenhouse Inventories. Vol.4: Agriculture, forestry and other land use, chapter 11: N_2O emissions from managed soils, and co_2 emissions from lime and urea. Prepared by the National Greenhouse Gas Inventories Programme. In: Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K (eds) N_2O Emissions from managed soils and CO_2 emissions from lime and urea application. Published by the Institute for Global Environmental Strategies (IGES), Hayama

IPCC (Intergovernmental Panel on Climate Change) (2006b) In 2006 IPCC Guidelines for National Greenhouse Inventories. Vol.2: Energy. Prepared by the National Greenhouse Gas Inventories Programme. In: Eggleston HS, Buendia L, Miwa K, Ngara T,

Tanabe K (eds) Stationary combustion. Published by the Institute for Global Environmental Strategies (IGES), Hayama

IVV (Instituto da Vinha e do Vinho) (2010) Portuguese statistics for wine production and exportation. Available in http://www.ivv.min-agricultura.pt/np4/home.html. Accessed Sep 2011

Machado M (2011) Modelling the life cycle of vinho verde and wine cork stoppers through the use of several impact assessment methods (in Portuguese). Master thesis dissertation in Environmental Engineering, Faculty of Engineering, Porto University, Porto

Margni M, Rossier D, Crettaz P, Jolliet O (2002) Life cycle impact assessment of pesticides on human health and ecosystems. Agric Ecosyst Environ 93:379–392

Milà i Canals L (2003) Contributions to LCA methodology for agricultural systems. Site-dependency and soil degradation impact assessment. PhD thesis in Environmental Sciences, Universitat Autònoma de Barcelona, Barcelona. Available in http://www.tesisenxarxa.net/TDX-1222103-154811/. Accessed Oct 2011

Nemecek T, Kägi T (2007) Life cycle inventories of agricultural production systems. Ecoinvent report no. 15. ART Zurich, Switzerland

Notarnicola B, Tassielli G, Nicolett M (2003) Life cycle assessment (LCA) of wine production. In: Mattson B, Sonesson U (eds) Environmentally friendly food processing. Woodhead, Cambridge, pp 306–326

OIV (International Organisation of Vine and Wine) (2010) Statistics of production and exportation. Available in http://www.oiv.int/oiv/cms/index. Accessed Sep 2011

Petti L, Raggi A, Camillis C, Matteucci P, Sára B, Pagliuca G (2006) Life cycle approach in organic wine-making firm: an Italian case study. 5th Australian Conference on Life Cycle Assessment. Australian Life Cycle Assessment Society. Melbourne

Peynaud E (1981) Conhecer e trabalhar o vinho (in Portuguese). Biblioteca Agrícola Litexa, Lisboa

Pizzigallo A, Granai C, Borsa S (2008) The joint use of LCA and emergy evaluation for the analysis of two Italian wine farms. J Environ Manag 86(2):396–406

Point E, Tyedmers P, Naugler C (2012) Life cycle environmental impacts of wine production and consumption in Nova Scotia, Canada. J Clean Prod 27:11–20

Santos AM (2010) Life Cycle Assessment of vinho verde (in Portuguese). Master thesis dissertation in Environmental Engineering, Faculty of Engineering, Porto University, Porto

SimaPro software (2011) website at http://www.pre.nl

Soares M (1998) Implementação e estudo de vários métodos de determinação do CO_2 dissolvido em vinhos (in Portuguese). Licenciatura em Enologia. Universidade de Trás-os-Montes, Vila Real

Vázquez-Rowe IP, Villanueva-Rey P, Moreira MT, Feijoo G (2012) Environmental analysis of Ribeiro wine from a timeline perspective: harvest year matters when reporting environmental impacts. J Environ Manag 98:73–83