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Evaluation of the carbon footprint of the life cycle of wine production: A review

Luís Pinto da Silva[a,b,*], Joaquim C.G. Esteves da Silva[a,b]

[a] Chemistry Research Unit (CIQUP), Institute of Molecular Sciences (IMS), Department of Geosciences, Environment and Territorial Planning, Faculty of Sciences of University of Porto (FCUP), Rua do Campo Alegre s/n, Porto 4169-007, Portugal

[b] LACOMEPHI, GreenUPorto, Department of Geosciences, Environment and Territorial Planning, Faculty of Sciences of University of Porto (FCUP), Rua do Campo Alegre s/n, Porto 4169-007, Portugal

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ABSTRACT

The accounting and reporting of greenhouse gas emissions associated with wine production have been increasingly pursued by the wine sector, due to increasing interest regarding environmental issues and sustainable development by consumers and organizations. Herein, this report aims to review and evaluate the existent literature regarding the calculation of carbon footprints at various stages of the life cycle of wine production. With this information, this report aims to improve the environmental performance of this sector in terms of greenhouse gas emissions. We have found widely variable carbon footprints between reviewed studies, which included different wine types from major wine producing countries and regions. We were also able to identify the life cycle stages that contribute the most to the overall carbon footprint of wine production, which are bottling and viticulture, while understanding which are the major hotspots at each stage. This allowed us to provide suggestions and recommendations for mitigation of greenhouse gas emissions. Thus, this report can guide future studies aiming to account, report and mitigate the carbon footprint of wine production.

1. Introduction

In past years, consumers have been showing increasing concern about environmental issues, while demanding more information regarding the impacts of purchased products and services. In fact, there has been increasing pressure from both governmental and non-governmental organizations for industries to disclose more information about their associated environmental impacts, while trying to encourage consumers to take that information into account when deciding about desired products/services (Sinisterra-Solís et al., 2020). Given this, stakeholders in different industries have started to take an interest in the identification and dissemination of environmentally relevant topics and information regarding their own industries, to increase their competitivity and consumer satisfaction (Szolnoki, 2013).

One of the sectors that greatly contributes for greenhouse gas (GHG) emissions is that of agriculture, forestry and other land use, which account for about one fifth of total emissions (Chiriacò et al., 2019). Among this sector, the wine industry is among the most relevant. It is estimated that in 2020, the global wine production was of 260 million hectolitres (mhl), with Italy, France, and Spain accounting for 53% of the global production (OIV, 2021). By its turn, the worldwide wine consumption in that year was estimated at 234 mhl (OIV, 2021). The world total surface area planted with vines (associated with production of wine, juices, table grapes and raisins) was also estimated to be 7.3 million hectares (mha) in 2020 (OIV, 2021). Finally, the global export market of wine had a size of 29.6 billion € (OIV, 2021) in 2020.

Given this, identifying and reducing the environmental impacts that arise from the wine industry is a necessity toward mitigating GHG emissions that lead to climate change (Christ and Burritt, 2013), with sustainability needing to become a focus of the wine sector (Forbes et al., 2009). To achieve these goals, it is necessary to possess appropriate procedures to estimate GHG emissions associated with the wine industry (Marras et al., 2015).

One of the possible approaches that can provide this information is Life Cycle Assessment (LCA), which aims to identify and quantify the environmental impacts of a given system during its entire life cycle (from extraction of raw materials to end-of-life, passing by the manufacturing/use stage) (Fernandes et al., 2021; Ramos et al., 2018; Sendão et al., 2020). In fact, LCA approaches provide multiple impact categories in which target products/system can be evaluated (Marras et al., 2015). Given this, LCA-based approaches have been used to evaluate the environmental impacts associated with systems as different as wind farms

* Corresponding author at: Chemistry Research Unit (CIQUP), Institute of Molecular Sciences (IMS), Department of Geosciences, Environment and Territorial Planning, Faculty of Sciences of University of Porto (FCUP), Rua do Campo Alegre s/n, Porto 4169-007, Portugal.

E-mail address: luis.silva@fc.up.pt (L. Pinto da Silva).

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(Bi et al., 2022), dairy products (Kumar et al., 2021), ceramic industry (Monteiro et al., 2022) and even carbon-based nanomaterials (Christé et al., 2020).

Among available environmental impact categories in LCA-based methodologies, carbon footprint is the most suitable indicator for assessing the GHG emissions resulting from the wine industry (Pattara et al., 2022). The carbon footprint indicator, within a LCA approach, quantifies the direct and indirect GHG emissions (CO_2, CH_4, N_2O, among others) during the life cycle of a given product/service/activity (Weidema et al., 2008). This indicator is typically expressed in kg of CO_2 equivalent (eq.), which is a metric that allows comparing the emissions of GHG on terms of their global warming potential and, consequently, climate change contribution.

Herein, the objective of this report is to review and evaluate existent literature regarding the calculation of carbon footprints for the wine industry. With this work, we intend to identify and characterize main hotspots that contribute to the carbon footprint of the various stages of the wine production process. This information is essential for identifying points of improvement for wine companies in terms of their sustainability, to help them monitor and evaluate their environmental performance. Upon identification of relevant sources of GHG emissions, suggestions, and recommendations for mitigating these emissions will be provided. Thus, this report can help to guide future efforts that aim to calculate and reduce the carbon footprint of wine production.

2. Existent guidelines for calculating carbon footprints in the wine industry

The overall carbon footprint of wine products should result from its entire life cycle: from vine planting to final disposal or recycling (Martins et al., 2018). Nevertheless, in terms of evaluating the environmental performance of wine production, the life cycle stages typically considered are viticulture, winemaking, bottling and distribution (Martins et al., 2018; Neto et al., 2013). While other life cycle stages should also provide some contribution to carbon footprint of wine, they are typically excluded from carbon footprint analysis, as it is difficult to obtain reliable data for these stages (Martins et al., 2018; Point et al., 2012). It is also doubtful how useful could be the inclusion of these stages (such as retail and consumer use) towards monitoring and improving the environmental performance of wine by producers/stakeholders, as the environmental impacts of these life cycle stages are generally outside their control.

Viticulture is the life cycle stage that takes place at vineyards, and typically consists in the cultivation and harvesting of grapes (Jradi et al., 2018). In this stage are typically included winter (as pre-prunning and pruning) and summer vineyard activities, vine planting, soil preparation, fertilization, application of phytosanitary products, use of agricultural machinery, harvesting of grapes and their transportation to wineries (Neto et al., 2013).

Winemaking (also known as vinification) is the production of wine from grapes in wineries, through fermentation (Pretorius, 2000). This stage includes inventory such as electricity required for wine production, storage and refrigeration, yeasts and enzymes, wine additives and enologic products, waste management and sanitation products (Bosco et al., 2011; Martins et al., 2018; Neto et al., 2013).

Bottling (and packaging) is the life cycle stage where the produced wine is stored and bottled/packed, after which is stored in bottles and shipped depending on distributor/consumer demands (Martins et al., 2019). Typical inputs for this stage include the glass wine bottles, closures, packaging and storing materials, water, and electricity requirements (Benedetto, 2013; Bosco et al., 2011; Martins et al., 2018; Martins et al., 2019).

Finally, distribution refers to the transport of finished bottled wine to the first point of sale, and typically includes transportation by several means (as boat, train, and truck) (Bosco et al., 2011; Neto et al., 2013).

Over the years there has been increasing efforts made by organizations of different sectors to develop guidelines and approaches for accounting and reporting carbon footprints at the corporate level, with the wine industry not being an exception. For instance, FIVS provides guidelines for reporting and accounting GHG emissions by the wine industry internationally (FIVS, 2018). These guidelines recommend that organisational boundaries are set by taking operational control in mind, which means to ensure that the company has the power to reduce GHG emissions from specific operations. Upon defining operational boundaries, FIVS guidelines (FIVS, 2018) recommend that GHG emissions to be divided into three scopes or types:

- Scope 1 corresponds to the direct emissions that result from items controlled by the reporting company. Namely, direct emission from the generation of heat or steam, combustion of fuel used in stationary and mobile equipment, and fugitive emissions.
- Scope 2 corresponds to indirect carbon emissions from electricity consumption.
- Scope 3 is typically related with indirect carbon emissions associated with the use of inventory included in viticulture (as phytosanitary products, winemaking (as enologic products and cleaning agents), bottling (packaging materials), and distribution (transportation).

These guidelines consider the best reporting practices to include at least scope 1 and scope 2 emissions in the inventory (FIVS, 2018). Nevertheless, emission sources included in scope 3 can also contribute greatly to carbon footprint of wine production, and so, they should be included to better understand and monitor the environmental performance of these processes.

FIVS guidelines (FIVS, 2018) also indicate which should be the primary contributors to the carbon footprint of the different stages of wine production, while indicating contributions that can be excluded. For example, it considers that the primary contributors for viticulture are the emissions from combustion of fossil fuels, and field emissions (with focus on N_2O) from application of synthetic fertilizers and management practices. By its turn, CO_2 fluxes related to short-term carbon cycle are excluded and assumed to be net zero (FIVS, 2018). As for the winemaking stage (FIVS, 2018), the primary contributors are electricity consumption and combustion of fossil fuels, with additional emissions resulting from onsite waste disposal, CO_2 used during winemaking and gas recharge of cooling systems. Meanwhile, CO_2 generated from fermentation is not reported (FIVS, 2018). As for bottling/packaging (FIVS, 2018), are considered emissions from glass, fibre, and alternative (as wine bags) packaging. Meanwhile, both closures and pallets are excluded on the grounds that they should be not relevant contributors to the carbon footprint of the reporting company (FIVS, 2018). Distribution is considered within these guidelines due to the expected relevancy toward the carbon footprint of the global industry (FIVS, 2018). Finally, it should be noted that both the use and product disposal stages are excluded from these guidelines (FIVS, 2018). For the former stage, there is both lack of information and great variability, making it quite difficult to account for associated carbon emissions. As for the latter stage, its impact is quite low toward the overall carbon footprint.

Another relevant organization related to the wine industry, the International Organisation of Vine and Wine (OIV), also provided recommendations for accounting and reporting GHG emissions in wine production (OIV, 2017). According to these guidelines (OIV, 2017), the system boundaries should cover the entire life cycle of the product, and should be chosen according to one of two protocols:

- The enterprise protocol, which covers viticulture, winemaking, and bottling/packaging.
- The product protocol, which goes from viticulture to end-of-life (including use, disposal, and recycling).

Within the enterprise protocol, the OIV guidelines (OIV, 2017) consider the same three scopes than of the FIVS protocol (FIVS, 2018). Also as indicated by FIVS guidelines (FIVS, 2018), OIV recommends that while emissions included in scope 3 are not mandatory, they should still be included (depending on data availability) given their important contributions to the carbon footprint (OIV, 2017). The OIV guidelines (OIV, 2017) provide also important recommendations for what is to be included in the inventory of emissions and sequestration at various stages and scopes, while providing examples of calculations and benchmark values (OIV, 2017).

National organizations have also developed their own guidelines and carbon footprint calculators, based on international guidelines. For instance, the Australian Grape & Wine, the South Australian Wine Industry Association and the Winegrape Council of South Australian developed the Australian Wine Carbon Calculator (AWCC 2022), which can be used by wine industry members to calculate carbon footprints at the vineyard, winery, and packaging/distribution levels, with emissions divided into scopes 1 to 3. The national associations for the English and Welsh wine Industry (WineGB) also developed a similar carbon footprint calculator (WineGB 2022): WineGB Farm Carbon Calculator. By its turn, the California Sustainable Winegrowing Alliance developed the California Code of Sustainable Winegrowing Workbook, as part of the Sustainable Winegrowing Program (CSWP 2022). In it, different indicators are employed to assist wine producers in monitoring their environmental standard, among which are included GHG emissions at the vineyard and winery levels.

Given this, the wine sector is attempting to improve its accounting and reporting strategies regarding the carbon footprint of wine production.

3. Reviewing calculated carbon footprints for wine production

In this section will be reported and discussed the available literature regarding the determination of carbon footprints for wine production, based on LCA approaches. As the reviewed studies considered different system boundaries, this section will be sub-divided considering the main life cycle stages included in each reviewed study: 2.1. Viticulture; 2.2. Viticulture and Winemaking; 2.3. Winemaking and Bottling; 2.4. Viticulture, Winemaking and Bottling; 2.5. Viticulture, Winemaking, Bottling and Distribution. Twenty-six studies were reviewed, which included various wine types (red, rosé, white, and sparkling) from both different countries (Spain, Italy, France, Portugal, Australia, Germany, US, Luxembourg, Canada, and Cyprus) and within different regions from the same country. Focus was given to studies published from the 2010s onward. The wide variety of wine types and countries/regions, as well as the focus on different life cycle stages considered by each study, allows us to provide a more complete description of the global wine industry.

3.1. Viticulture

The carbon footprint of the viticulture stage of wine production was evaluated by Steenwerth et al. (2015) for wine grape production in two regions (Napa and Lodi) of the US state of California. This study assessed the annual cycle for wine grape production, starting at raw material extraction for fabricating inputs required on the vineyard and ended at the transportation of grapes to the winery. This study used a functional unit for the evaluation of grape production of one metric ton (t) of wine grapes, with the life cycle model being area-based (0.4 ha) (Steenwerth et al., 2015). The hotspots in carbon emissions were pesticide manufacturing, on-farm truck use and associated fuel requirements, and field N_2O emissions associated with N-fixing legumes in cover crop mixes. As for the last point, it should be elaborated that the use of N-fixing legumes leads to higher field N_2O emissions because a commensurate reduction in synthetic N does not occur, resulting in a net N addition to the system (Steenwerth et al., 2015). Interestingly, the regional productivity differences between the regions of Napa and Lodi did affect carbon emissions per amount of wine grapes, having a relevant effect in the carbon footprint of resulting wine bottles. Finally, the carbon footprint of the viticulture stage for California-based wine grapes varied between 87 and 584 kg CO_2 eq. per t of wine grape (Steenwerth et al., 2015).

The sole impact of viticulture in terms of carbon footprint was also evaluated by Marras et al. (2015). More specifically, they determined the carbon footprint of a mature vineyard, located in the South of Sardinia (Italy), during grape production. A functional unit of 1 kg of grape produced was employed, and the study included only the viticulture stage. The authors calculated a carbon footprint of 0.39 kg CO_2 eq. per 1 kg of grape, which was attributed mainly to use of fossil fuels and soil management.

Further assessment of the viticulture stage was performed by Litskas et al. (2017), which compared Indigenous and introduced grape varieties in the island of Cyprus, by using ninety vineyards as case study. The determined carbon footprint was of 0.85 kg CO_2 eq. per kg of grape for the Mediterranean table grape variety Soultanina, while Cabernet Sauvignon presented a carbon footprint of 0.56 kg CO_2 eq. per kg of grape and the indigenous white variety Xynisteri values of 0.28 kg CO_2 eq. per kg of grape. As consistent with other studies here reviewed, the obtained carbon footprints were mainly explained by fertilizers and field energy use (Fig. 1). Interestingly, the authors performed modeling studies in which they found that application of local animal manure and reducing tillage frequency were effective carbon footprint mitigation strategies (decrease of 40–67%). In fact, with those mitigation strategies, the carbon footprint of the Indigenous Xynisteri grape variety could reach values close to zero. However, it is still not clear if these mitigation strategies would not have negative impacts on grape production yield.

Bartocci et al. (2017) evaluated the life cycle of aged vinegar in Italy, which resulted from Sagrantino and Grechetto gapes. These grapes are transformed in wineries, from which the wine is transported to the farm to produce vinegar. Despite the ultimate goal being evaluating aged vinegar, these authors did provide carbon footprints of 0.311 (Grechetto grapes) and 0.470 (Sagrantino) kg CO_2 eq. per kg of grapes (Bartocci et al., 2017), which are quite in line with previous values described above.

An interesting study was performed by Gierling and Blanke (2021a), which aimed to understand the difference between steep and flat terrains in vineyards in terms of carbon footprint. The main difference between these terrains is that while fertilizers and phytosanitary products are similar, the usage of farm vehicles and manual labour differ between flat and steep terrain. This study was performed with data from a local winery in the Rhine valley (Germany) that produces Riesling grapes on both flat and steep slopes. The authors found lower carbon footprints for steep slopes (2990 kg CO_2 per hectare) than for flat terrain (4046 kg CO_2 per hectare). This relevant difference results from the fact that the use of farm vehicles is limited on steep slopes, in which manual labour is preferentially used, which further highlights the impact of fossil fuels in the carbon footprint of the viticulture stage. Nevertheless, while manual labour is indeed associated with lower carbon footprints, it does not appear as an alternative to reduce the carbon footprint on flat terrain, as farm workers are more expensive, scarce and with lower productivity timewise (Gierling and Blanke, 2021a).

An extensive characterization study of the carbon footprint associated with vineyard practices was performed by Jradi et al. (2018). More specifically, the authors evaluated the technical efficiency, in terms of carbon footprint, of thirty-eight wine producing companies in the Bordeaux region (in France) for the period of 2013–2015. The efficiency in terms of carbon footprint was assessed in terms of use of pesticides, fuel, and fertilizers during the viticulture stage (Jradi et al., 2018). As consistent with previous studies (Gierling and Blanke, 2021a; Marras et al., 2015; Steenwerth et al., 2015), fuel usage is the main hotspot in viticulture, with double the impact of employing fertilizers and pesticides (Jradi et al., 2018).

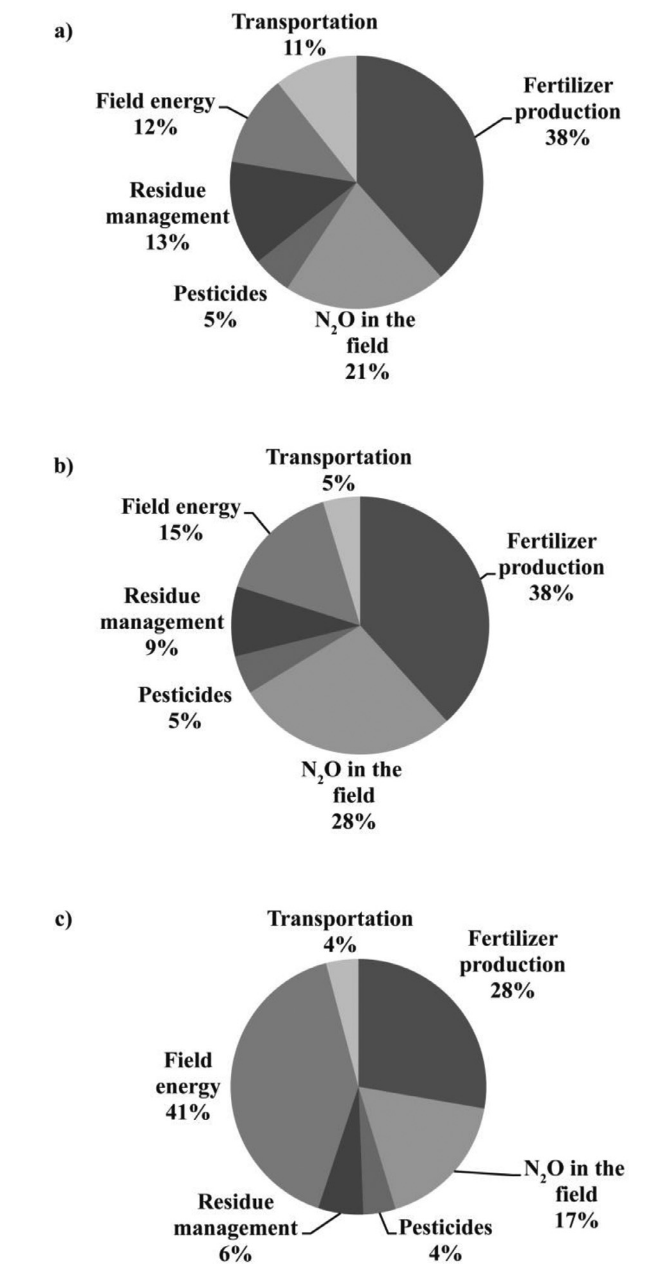

Fig. 1. Contribution of different management practices to the carbon footprint of grape production for the local variety Xynisteri (a), and the introduced Cabernet Sauvignon (b) and table grape variety Soultanina (c). Reproduced with authorization from Litskas et al. (2017).

The different carbon footprints for the viticulture stage are summarized in Table 1.

3.2. Viticulture and winemaking

The sustainability evaluation, in terms of carbon emissions, for wines produced in five wine regions of Portugal (Bairrada, Dão, Távora-Varosa, Douro and *Vinho Verde*) was performed in 2015 by Figueiredo et al. (2015). A LCA assessment of the carbon emissions was performed with a functional unit of 0.75 L of wine, with a cradle-to-gate approach including the stages of viticulture (grape growing and transportation) and winemaking. The authors considered four types of wine (white, red, rosé and sparkling) produced in 2010–2012 by eleven different grape producers with variable productivity (Figueiredo et al., 2015). The obtained carbon footprints varied between 0.15 and 0.45 kg CO_2 eq. per bottle of wine, with viticulture being the main contributor to the generated carbon emissions (88–92%). Interestingly, while carbon emissions were relevantly different between grape producers, they were not so different between wine types (Figueiredo et al., 2015). This can mean that main differences in carbon emissions could be associated with individual practices/experiences of each producer, and not due to specific requirements for wine production. It should also be noted that while the relative contributions of viticulture and winemaking found here follow the similar profile found elsewhere, the overall carbon footprints determined by Figueiredo et al. (2015) are significantly lower than values obtained for other studies, including ones for Portuguese wines (Neto et al., 2013, Martins et al., 2018; Martins et al., 2019; Taylor's, 2018).

3.3. Winemaking and bottling

In 2018, Martins et al. (2018) performed a comparative sustainability assessment of two Portuguese wines produced by the same company. One was branded wine produced in large quantities from grapes obtained in different vineyards. While the considered vineyards were mainly from the North of Portugal, they showed relevant variability in viticulture practices and climate conditions. The wine was a "terroir" one, which had higher market values but was produced in lower quantities with grapes from a single vineyard. In this study, a gate-to-gate LCA was performed, as the authors only considered the life cycle stages of winemaking and bottling (Martins et al., 2018). The functional unit was the standard one of 0.75 L of wine (Martins et al., 2018).

The carbon footprints (Fig. 2) of branded and "terroir" wines were of 1.10 and 1.23 kg CO_2 eq. per 0.75 L, respectively (Martins et al., 2018). Their profiles of carbon emissions are similar between each other, with packaging materials being the main contributors (58.3–71.0%), with large emissions associated with the production of glass bottles (Fig. 2). Other packaging materials are also important contributors to carbon emissions, with focus on tin capsules for "terroir" wine. Nevertheless, the carbon footprint regarding packaging materials is higher for the "terroir" wine than for the branded wine, which was justified by a more complex and heavier package of the former (due to its higher price) (Martins et al., 2018). The authors also hypothesized that the lower carbon footprint of packaging materials for this wine could result from a more efficient bottling process for the branded wine (Martins et al., 2018).

3.4. Viticulture, winemaking and bottling

In 2013, Benedetto aimed to assess the carbon footprint associated with wine production of a typical Sardinian white wine, by employing an attributional and partial LCA study (Benedetto, 2013). More specifically, a cradle-to-gate LCA study was performed to evaluate the carbon emissions associated with the production of the white wine "Vermentino di Sardegna" – "La Cala", from the Northern Sardinian winery "The Sella and Mosca". This study included the stages of viticulture (vine planting and grape production/harvesting), winemaking and bottling. The distribution stage was not included with the rationale that the market for this wine was too much fragmented to allow for a reliable calculation of associated environmental impacts. Data were collected in 2010. The functional unit employed was that of the typical volume of a wine bottle (0.75 L) (Benedetto, 2013). Carbon emissions were evaluated with the impact indicator Global Warming Potential 100 years (GWP 100 years), which includes all greenhouse gas emissions in each process and is quantified as kg CO_2 eq.

The author determined a carbon footprint of 1.64 kg CO_2 eq. per bottle of wine (0.75 L) (Benedetto, 2013). The author found that the life cycle stages that led to higher carbon emissions were clearly the bottling (56.71%) and viticulture (43.11%) ones, while winemaking led to comparatively negligible emissions (0.17%) (Benedetto, 2013). Among the phases that were considered to constitute the viticulture phase, vine planting is the main contributor to global emissions (30.12%), with

Table 1
Carbon footprints (kg CO_2 eq. per functional unit) determined for the viticulture life cycle stage of wine production.

Study	Functional Unit	Carbon Footprint	Country
Steenwerth et al. (2015)	One metric ton of wine grapes	87-584	United States
Marras et al. (2015)	One kg of grapes	0.39	Italy
Litskas et al. (2017)	One kg of grapes	0.28-0.85	Cyprus
Bartocci et al. (2017)	One kg of grapes	0.31-0.47	Italy
Gierling and Blanke (2021a)	Hectare	2990-4046	Germany
Vázquez-Rowe et al. (2013)	0.75 L of wine	0.11-1.61	Italy, Spain and Luxembourg
Laca et al. (2021)	0.75 L of wine	1.42	Spain
Neto et al. (2013)	0.75 L of wine	2.0	Portugal
Taylor's (2018)	0.75 L of wine	0.30-0.33	Portugal
Bosco et al. (2011)	0.75 L of wine	0.10-0.33	Italy
Point et al. (2012)	0.75 L of wine	0.80	Canada

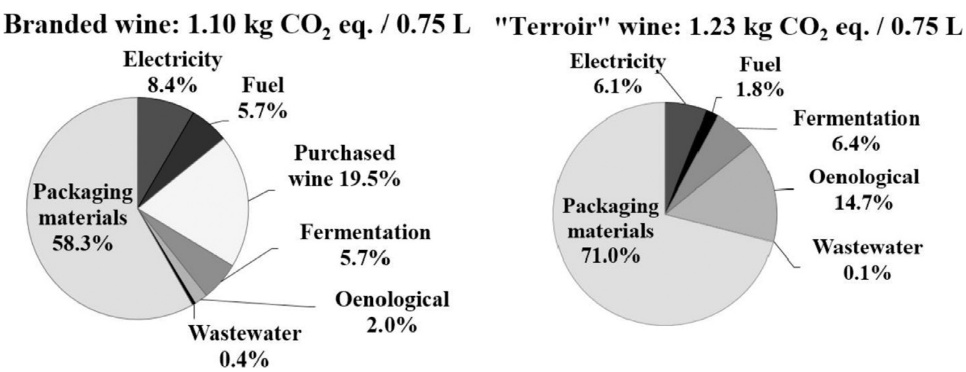

Fig. 2. Carbon footprints, and relative contributions by individual processes, obtained for two Portuguese wines: branded (left) and "terroir" (right) ones. Reproduced with authorization from Martins et al. (2018).

more than double than those caused by grape production/harvesting (12.99%). The higher emissions caused by bottling are mainly justified by the production of the glass bottles, while diesel use is the main responsible for emissions during the viticulture phase.

Another LCA study of Sardinian white wine was performed by Fusi et al. (2014). It considered the life cycle stages of viticulture, winemaking, and bottling, and employed a functional unit of 0.75 L of white wine. An overall carbon footprint of 1.01 kg CO_2 eq. per 0.75 L was found, which was mainly explained by bottling (55.9% contribution) and winemaking (27.2% contribution), followed by viticulture (16.9%). These results cement bottling as the clear contributor to carbon emissions of Sardinian white wine. This study also indicates that significant differences in the relative contributions of the viticulture and winemaking stages exist, which should be further explored in the future.

Vázquez-Rowe et al. (2013) determined the carbon footprint of red, white, and sparkling wine produced in different farms in Italy (Tuscany and Sardinia), Spain (Galicia) and Luxembourg, with data collected between 2007 and 2010. The system boundaries considered were globally of viticulture (vine planting and grape growing), winemaking and bottling. However, some wines only included the viticulture stage, while others only included the winemaking and bottling ones. Among the viticulture stage, carbon footprints of 0.113–1.613 kg CO_2 eq. per bottle of wine were found for six wines. The grape growing sub-stage was found to be the most relevant one, with higher carbon emissions resulting from diesel consumption and fertilizers use. The carbon footprints for winemaking stage were similar to ones found for the viticulture stage, as they were found to be between 0.121 and 1.16 kg CO_2 eq. per bottle of wine. No relevant relationships were found between types of wine for this stage, but some correlation was found for their ageing time. As for the last stage (bottling), the authors found carbon footprints of 0.23–0.78 kg CO_2 eq. per bottle of wine, which can be mainly explained by the production of the glass bottles (as seen extensively in the literature here reviewed).

Further assessment of Italian wine was performed by Chiriacò et al. (2019), which studied a sustainable wine farm that produced organic and high-quality wines, and that is located in Castiglione in Teverina (Italy). A typical functional unit of one wine bottle of 0.75 L was employed, while considering the stages of viticulture, winemaking, and bottling. An overall carbon footprint of 0.79 kg CO_2 eq. per bottles was found, with 85% contribution from winemaking and bottling. The most relevant result from this study was the demonstration that accounting for biogenic GHC fluxes and carbon stock change at the viticulture stage led to the potential carbon neutrality of that stage (Chiriacò et al., 2019). Thus, proper inventory and measurement of carbon/GHC fluxes can result in quite different carbon footprints of the viticulture stage than expected.

Trombly and Fortier (2019) also evaluated the carbon footprint of a bottle of wine (0.75 L) produced in the Finger Lakes region of New York (US), with data collected from three wineries around Seneca Lake (with variable productivity). This study encompassed the stages of viticulture, winemaking, and bottling, thereby excluding distribution. Carbon footprints for the three wineries varied between 0.68 and 2.68 kg CO_2 eq. per bottle, in an inverse relationship with the wine productivity of the winery. This is an important finding indicating that there is a component of scale in the cultivation stage of viticulture, in terms of resulting carbon emissions. More specifically, the carbon footprint is significantly higher for the winery with lower production than for the other wineries. The electricity employed in wineries is also significantly lower for the larger winery. Finally, the bottling stage is the main responsible the overall carbon footprint for all three wineries.

A LCA approach was also used to evaluate the carbon footprint of Spanish wine (Laca et al., 2021). More specifically, the protected designation of origin (PDO) "Cangas" mountain wine was studied. This wine is only produced in forty hectares of small family-owned vineyards (Laca et al., 2021). A functional unit of 1 kg of wine grapes was used for only the viticulture stage, while the standard 0.75 L of wine (one bottle) was employed for the overall process (Laca et al., 2021).

It should be noted that the authors state that only two life cycle stages are considered: viticulture and winemaking (Laca et al., 2021). However, the authors included in the winemaking stage input information that is typically treated as a separate stage: bottling/packaging. A carbon footprint of 1.42 kg CO_2 eq. per kg of grapes was found for the viticulture stage. Contrary to other studies, diesel use was not the main contributor to carbon footprint, as all field work was made manually (Laca et al., 2021). So, diesel was only used for the transportation of workers to the vineyards. Given this, the main contributor to the carbon footprint of the viticulture stage (by more than 60%) was the incineration of pruning residues, followed by the use of phytosanitary products and application of fertilizers (contribution of ~25%). An overall carbon footprint of 2.35 kg CO_2 eq. per bottle of “Cangas” wine was obtained, with grape production, packaging material production, and waste management being main factors. In fact, the viticulture stage was responsible for more than 65% of the overall carbon footprint, with carbon footprint of 1.54 kg CO_2 eq. per bottle (Laca et al., 2021).

Another LCA study toward the determination of the carbon footprint of one PDO Spanish wine was also performed by Meneses and co-workers (Meneses et al., 2016), by considering the life cycle stages of viticulture, winemaking, bottling and disposal (with a functional unit of 0.75 L). More specifically, the authors studied an aged red from the PDO “Conca de Barbera” in Catalonia (Spain), which is “Criança 2005” and produced from Tempranillo and red Cabernet Sauvignon grape varieties. A total carbon footprint of 0.95 kg CO_2 eq. per 0.75 L was found for the considered process, with bottling being the main contributor (71.1%). As expected, glass production explains most of carbon emissions resulting from this stage. Viticulture explains most of the remaining carbon emissions (25.4%), while winemaking (3.4%) and disposal (0.1%) provide only negligible contributions. As for viticulture, the use of fertilizers is clearly the main responsible for carbon emissions, followed by a relevant margin by tillage, pesticides, and planting.

Litskas et al. (2020) were other authors that performed a LCA study focused on wine production considering two stages (viticulture and winemaking), in which bottling/packaging were included in the latter stage. This particular study was focused on wine production from 20 vineyards in Cyprus, which cultivate the indigenous Xynisteri variety (Litskas et al., 2020). A carbon footprint of 1.31 kg CO_2 per bottle of wine (0.75 L) was calculated, from which 84% was explained by contributions of the winemaking stage, while 16% were from viticulture. Among the winemaking stage, the most relevant hotspot is electricity consumption (46%), which was explained by the need of storing wine in tanks under controlled temperature, given the energy-inefficient buildings in the wineries and the hot summers and autumn months in Cyprus (Litskas et al., 2020). 18% of the contributions to the overall carbon footprint comes, as typical, from packaging material, which further highlights glass bottles as a main hotspot in wine production. Further contributions came from transportation (10%) and waste management (10%).

Finally, Navarro et al. (2017) calculated the carbon footprint of wine produced in the 2013 campaign in eighteen wineries (3 wine cooperatives) with vineyards in seven production regions and fourteen denominations of origin. Both Spanish and French wine were considered. The life cycle stages were considered to be viticulture and winemaking, but with bottling included in the winemaking stage. An average carbon footprint of 2.18 kg CO_2 eq. per bottle of wine (0.75 L) was calculated. Bottling was once again the main contributor (50%) to resulting emissions, followed by viticulture (27%) and winemaking (23%), as indicated in Fig. 3. Glass production is still the main responsible for emissions that result from bottling. As for viticulture, the main hotspot is diesel combustion for agricultural work, as consistent with previous studies (Gierling and Blanke, 2021a; Jradi et al., 2018; Marras et al., 2015; Steenwerth et al., 2015). Finally, emissions associated with winemaking were mainly attributed to the consumption of electricity and fugitive emissions (Navarro et al., 2017).

3.5. Viticulture, winemaking, bottling and distribution

Neto et al. (2013) assessed the sustainability of the production of a white wine (white *vinho verde*) exclusively produced in the Demarcated Region of *Vinho Verde*, located in the northern part of Portugal. This study considered data for the campaign 2008-2009 and employed the typical functional unit of 0.75 L of wine. It was considered activities that took place in the following stages: viticulture (grapes growing), winemaking (vinification to storage), bottles production, and distribution (Neto et al., 2013). Inputs for the viticulture stage were mainly water, energy, diesel, phytosanitary products, fertilizers, and transportation. For winemaking, the considered inputs were mainly water, energy, transportation, enologic products, yeasts, additives, and filtration and cleaning agents. Bottles production considered the fabrication of white glass bottles from about 61% recycled glass. Finally, the distribution stage considered that 50% of total wine produced in Portugal, while nearly 40% of total exportation was delivered by plane, truck and boat to USA, Angola, Canada, France, Brazil, and Germany. The carbon footprint of wine production was determined by using the CLM 2001 impact assessment method, by using the midpoint indicator GWP 100 years (Neto et al., 2013).

The authors determined a carbon footprint of 2.86 and 2.73 kg CO_2 eq. per bottle of white *vinho verde*, when considering either domestic or worldwide distribution, respectively (Neto et al., 2013). The stage with higher carbon emissions was clearly viticulture (2.0 kg CO_2 eq.), followed with a relevant difference by bottles production (0.44 kg CO_2 eq.) and winemaking (0.24 kg CO_2 eq.). The emissions caused by the distribution stage were only of 0.18 (domestic) or 0.052 (worldwide) kg CO_2 eq. Emissions caused by viticulture stage are mainly of CO_2 and N_2O, with the emissions of the former being caused by combustion of diesel and application of urea, while the emissions of the latter are caused by use of fertilizers (Neto et al., 2013). For bottles production, the higher emissions are associated with the use of fossil fuels during these processes. Given this, the results obtained for the white *vinho verde* are in line with other studies, with viticulture and bottles production being the main responsible for the carbon footprint of wine production.

In 2018, Taylor’s (one of the oldest of the founding Port houses, and based in Porto and the Douro Valley, in Portugal) performed a carbon footprint calculation focused on its Late Bottled Vintage (LBV) Port at different life cycle stages (Taylor’s, 2018). Data was collected between 2014 and 2016 and was associated with: the vineyard and traditional winery at Vargellas; modern winery of Nogueira, where winemaking occurs; bottling centre, laboratory, and distribution in Vila Nova de Gaia (Portugal). The obtained carbon footprints were of 2.6 (2014), 3.1 (2015) and 3.0 (2016) kg CO_2 eq. per bottle of wine (0.75 L) (Taylor’s, 2018). While bottling activity was found to be the most relevant contributor, as in line with other studies, here the second most relevant process is fermentation. In fact, the agricultural phase (viticulture) resulted only in carbon footprints of 0.30–0.33 kg CO_2 eq.

Bosco et al. (2011) evaluated the carbon footprint associated with the cradle-to-grave life cycle of wine produced in the Maremma rural district in Tuscany, Italy. More specifically, it was considered four wines, two from closed cycle farms (with medium to large vineyards and small to medium wineries), and two from cooperative wineries. Three of the four wines were red, while one was white. The considered life cycle stages were from viticulture to waste management. The carbon footprint was found to be between 0.6 and 1.3 kg CO_2 eq. per bottle of wine for the four wines (Bosco et al., 2011). The stage that caused most carbon emissions was of bottling with a carbon footprint of 0.3–0.6 kg CO_2 eq. per bottle, followed by the viticulture stage (0.10–0.33 kg CO_2 eq. per bottle). Winemaking, distribution, and waste management were just somewhat minor contributors (0.02–0.44 kg CO_2 eq. per bottle). Among bottling/packaging, it was the latter process to induce more carbon emissions (0.30–0.57 kg CO_2 eq. per bottle) with bottling itself being a minor contribution. As for viticulture, most contributions (0.07–0.22 kg CO_2 eq. per bottle) where associated with processes such as fer-

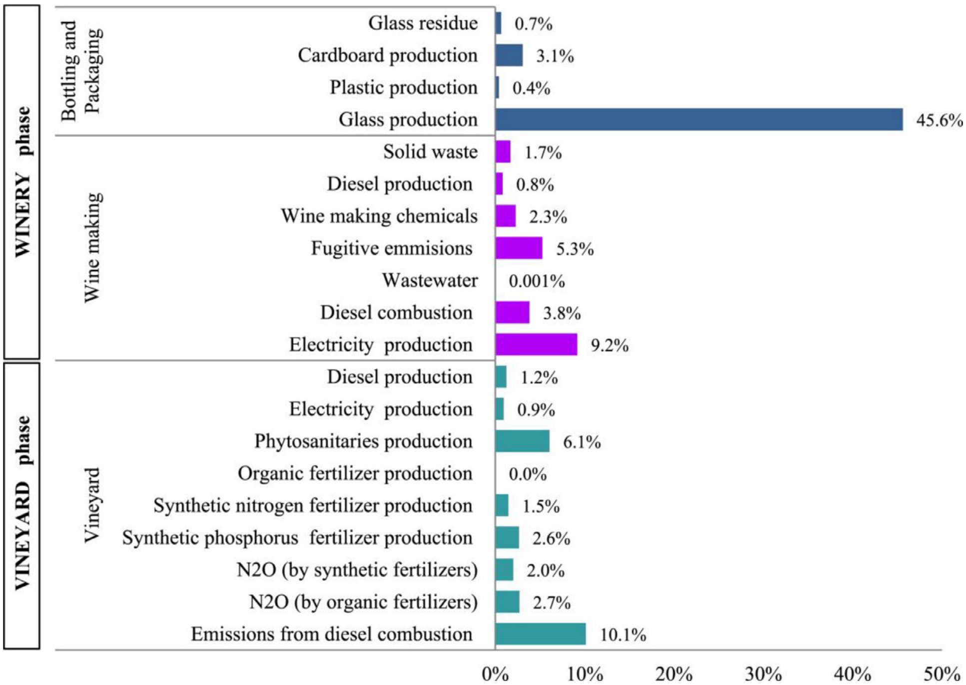

Fig. 3. Detailed contributions of considered life cycle stages to the carbon footprint of one bottled of wine (0.75 L). Reproduced with authorization from Navarro et al. (2017).

tilization, transport to winery, cultural practices, weed and pest management, pruning and harvest (Bosco et al., 2011). Given this, while the overall carbon footprint is somewhat lower than other typical studies, the carbon footprint profile of these wines is relatively similar to other studies here reviewed.

Point and co-workers also evaluated the carbon footprint of the full life cycle of a bottle of wine (0.75 L) produced in Nova Scotia (Canada) in 2006 from 100% locally grown grapes. The authors considered the major material and energy flows associated with viticulture, winemaking, bottles production, distribution, consumer transport, refrigeration, and bottle recycling. The obtained final carbon footprint was of 3.22 kg CO_2 eq. per bottle of wine (Point et al., 2012), with the main contribution being consumer shopping trip, with a carbon footprint of 1.20 kg CO_2 eq. per bottle of wine (37.3%). This is quite interesting, as studies typically do not include this parameter. Nevertheless, it is still debatable if from a commercial/producing perspective, the consumer transportation should be included in the carbon footprint calculator, as it is a parameter that producers cannot control. In fact, FIVS guidelines exclude this stage (FIVS, 2018). As for other stages, viticulture is the second highest stage contributing to carbon emissions (0.80 kg CO_2 eq. per bottle of wine), followed by bottling (0.44 CO_2 eq. per bottle of wine) and winemaking (0.37 CO_2 eq. per bottle of wine). Distribution, consumer storage and recycling are only negligible contributors (Point et al., 2012).

The carbon footprint of Italian wine was also assessed by Rinaldi et al. (2016), who have evaluated the life cycle of white and red wines produced in the region of Umbria. The authors considered a functional unit of 0.75 L, and the following life cycle stages: viticulture, winemaking, bottling, storage, distribution, and waste disposal. The carbon footprints for red and white wines were of 1.44 and 1.38 kg CO_2 eq. per bottle. Most of the contributions to the carbon footprint were from viticulture and bottling (~70%), while distribution accounts for basically all the remaining (~30%), with winemaking and other stages being basically negligible.

Another cradle-to-grave LCA study of an Italian wine was performed by Bonamente et al. (2016). This study focused on a typical Italian red wine produced from a blend of several grapes, with focus on Sangiovese and small amounts of Merlot and Cabernet Sauvignon. The red wine possessed the designation of controlled origin (DOC) and was produced by a medium-size winery located in central Italy. The functional unit was the standard 0.75 L that constitute a typical wine bottle, with the study considering the life cycle stages of viticulture, winemaking, bottling, storage, distribution, and waste disposal. While the overall carbon footprint (1.07 kg CO_2 eq. per bottle) (Bonamente et al., 2016) is lower than those determined by Rinaldi et al. (2016), 1.38–1.44 kg CO_2 eq. per bottle of Italian wine, the contribution profiles of the different stages is quite identical. Namely, 96.2% of contributions come from viticulture and packaging, while contributions from winemaking are basically negligible (Bonamente et al., 2016). Interestingly, the authors found distribution to generate high carbon emissions (0.44 kg CO_2 eq. per bottle), but which are offset by the End-of-life stage (Bonamente et al., 2016).

Gierling and Blanke (2021b) evaluated the product carbon footprint of red (Pinot Noir/Spatburgunder) and white (Riesling) produced from two wineries found the Rhine River valley, in Germany. A functional unit of 0.75 L was employed, with life cycle stages starting on viticulture (vine plantation) to disposal of glass bottles. The authors considered the carbon footprint of wine acquisition from consumers in the following formats (Gierling and Blanke, 2021b): round trip distance of 10 km to retail store (for on wine bottle); round trip distance of 60 km to winery (for six wine bottles). The authors found carbon footprints of 1.69–1.91 kg CO_2 eq. per bottle of white wine (depending on the winery), and of 1.86 kg CO_2 eq. for red wine (Gierling and Blanke, 2021b). These carbon footprints were mainly attributed to consumer behaviour (22–30%) and production and use of glass bottles (20–27%).

By its turn, the evaluation of the Australian wine industry revealed a carbon footprint of 0.6–1.4 kg CO_2 eq. per liter (Hirlam, 2021). The considered life cycle stages were viticulture (15% contribution), winemaking (17%), transport (28%), destination bottling (17%) and packaging (23%). Among the viticulture stage, diesel use (40% contribution) and electricity consumption (46% contribution) are the main responsible for carbon emissions. As for the winemaking stage, electricity consumption is responsible for 82% of associated emissions.

Following on their previous study of Portuguese wine where the carbon footprint of a "terroir" wine was determined for the winemaking and bottling stages (Martins et al., 2018), Martins et al. (2019) expanded their analysis of the Portuguese "terroir" wine by considering the following life cycle stages: viticulture, winemaking, bottling, storage, packaging, shipping, and distribution. These authors now estimated an average carbon footprint of 3.51 kg CO_2 eq. per 0.75 L of wine

Table 2
Carbon footprints (kg CO_2 eq. per 0.75 L of wine) determined for the wine production processes here reviewed, identified for the four main life cycle stages typically considered in the literature (viticulture, winemaking, bottling and distribution).

Study	Carbon Footprint	Life Cycle Stages	Country
Figueiredo et al. (2015)	0.15-0.45	Viticulture and Winemaking	Portugal
Martins et al. (2018)	1.10-1.23	Winemaking and Bottling	Portugal
Benedetto (2013)	1.64	Viticulture, Winemaking and Bottling	Italy
Fusi et al. (2014)	1.01	Viticulture, Winemaking and Bottling	Italy
Trombly and Fortier (2019)	0.68-2.68	Viticulture, Winemaking and Bottling	United States
Laca et al. (2021)	2.35	Viticulture, Winemaking and Bottling	Spain
Meneses et al. (2016)	0.95	Viticulture, Winemaking and Bottling	Spain
Litskas et al. (2020)	1.31	Viticulture, Winemaking and Bottling	Cyprus
Navarro et al. (2017)	2.18	Viticulture, Winemaking and Bottling	Spain and France
Chiriacò et al. (2019)	0.79	Viticulture, Winemaking and Bottling	Italy
Neto et al. (2013)	2.73-2.86	Viticulture, Winemaking, Bottling and Distribution	Portugal
Taylor's, 2018)	2.6-3.1	Viticulture, Winemaking, Bottling and Distribution	Portugal
Bosco et al. (2011)	0.6-1.3	Viticulture, Winemaking, Bottling and Distribution	Italy
Point et al. (2012)	3.22	Viticulture, Winemaking, Bottling and Distribution	Canada
Rinaldi et al. (2016)	1.38-1.44	Viticulture, Winemaking, Bottling and Distribution	Italy
Bonamente et al. (2016)	1.07	Viticulture, Winemaking, Bottling and Distribution	Italy
Gierling and Blanke (2021b)	1.69-1.91	Viticulture, Winemaking, Bottling and Distribution	Germany
Martins et al. (2019)	3.51	Viticulture, Winemaking, Bottling and Distribution	Portugal

(Martins et al., 2019), which is significantly higher than the carbon footprint of just 1.23 kg CO_2 eq. per 0.75 L for when just winemaking and bottling where considered (Martins et al., 2018). The life cycle stage with most associated carbon emissions was distribution (2.09 kg CO_2 eq. per 0.75 L of wine), followed by winemaking (1.43 kg CO_2 eq. per 0.75 L of wine), aging (1.20 kg CO_2 eq. per 0.75 L of wine) and bottling (1.15 kg CO_2 eq. per 0.75 L of wine). Contributions from storage (0.004 kg CO_2 eq. per 0.75 L of wine) and packaging (0.70 kg CO_2 eq. per 0.75 L of wine) were relevantly smaller. Quite interestingly, while most of the studies here reviewed consider the viticulture stage to be one of the main contributors to carbon emissions, here the authors estimate viticulture to have negative contributions of -2.29 kg CO_2 eq. per 0.75 L of wine (Martins et al., 2019). This result from the inclusion in the viticulture stage of carbon sequestration that occurs during this life cycle stage during grape growth (Martins et al., 2019), which is not typically considered during evaluation of carbon footprint associated with wine production. Thus, this study indicates how inclusion of carbon sequestration and other mitigation strategies during viticulture can have a significant impact on the life cycle stage, which is generally considered a main hotspot in wine production. This is in line with the work of Chiriacò et al. (2019), which showed that including biogenic fluxes and carbon stock changes lead to potential carbon neutrality at the viticulture stage.

The overall carbon footprints here evaluated are all presented on Table 2.

4. Evaluation of carbon footprints, limitations and suggestions

Here we have reviewed several reports and studies that aimed to determine the carbon footprint, by employing LCA-based approaches, associated with wine production. The considered studies included different wine types (such as red, rosé, white and sparkling) from several relevant wine-producing countries, such as Italy, France, Portugal, Spain, US, Australia, Luxembourg, Canada, Germany, and Cyprus. The reviewed LCA-based studies also considered quite different system boundaries, with different combinations of life cycle stages involving viticulture, winemaking, bottling and distribution.

Quite different carbon footprints were obtained for the considered wine production processes (Table 2), with values ranging from 0.15 to 3.51 kg CO_2 eq. per bottle of wine (0.75 L). These widespread differences result from different systems boundaries, different methodological choices, and assumptions. The level of detail and quality of foreground data provided by each wine producer can also be expected to be different among studies. Furthermore, the carbon footprint for each wine can also be affected by the productivity yield at the viticulture stage (Jradi et al., 2018; Marras et al., 2015), which is also affected by climatic conditions (which can be quite different between countries and regions within each country). In fact, one study that evaluated the carbon footprint for different wine types at different Portuguese regions (Figueiredo et al., 2015), found more relevant differences between producers than between wine types. Other relevant differences can be the grape variety used by different producers. Namely, a comparative analysis of the viticulture stage for different grape varieties in Cyprus (Litskas et al., 2017) revealed a significant variety of carbon footprints for grape production involving different varieties (0.28–0.85 kg CO_2 eq. per kg of grape).

Nevertheless, the widely different carbon footprints make it very difficult to properly compare the carbon emissions associated with each wine and/or each grape/wine producing processes. In fact, while the carbon footprint range described above is for studies with quite different system boundaries, even if we compare studies that include similar life cycle stages (as viticulture, winemaking, bottling and distribution) we still observe variations in carbon footprint from 0.6 to 3.51 kg CO_2 eq. per bottle of wine (Table 2). In fact, while important organizations of the wine sector have been developing guidelines for reporting and accounting GHG emissions (FIVS, 2018; OIV, 2017), they are scarcely followed by the literature here reviewed. Therefore, this demonstrates the need for a standardized protocol and calculator tool for determining carbon footprints of the wine industry, with well-defined, comparable, and uniform system boundaries, inventory and methodological assumptions and methods. Only with such tools can the various players and stakeholders in the wine industry accurately assess and compare carbon footprints between wine products.

Despite these significant quantitative differences between studies, most of them agree in the relative impact of main life cycle stages toward resulting carbon emissions. More specifically, most studies reviewed in Section 3 agree that the viticulture and bottling stages are the main responsible for the calculated carbon footprints (Bonamente et al., 2016; Rinaldi et al., 2016). In fact, several studies claimed that bottling is the main contributor to carbon emissions by a significant margin (Bosco et al., 2011; Gierling and Blanke, 2021b; Litskas et al., 2020; Navarro et al., 2017; Taylor's, 2018). The main hotspot in this stage is typically the use of the glass wine bottle, due to the significant carbon footprint of its production (Benedetto, 2013; Martins et al., 2018). Thus, efforts to reduce the carbon footprint of wine must target glass wine bottles. Suggestions for mitigating associated carbon emissions can be the use of glass bottles of lower weight, using recycled bottles or even substituting glass bottles by bottles made from materials with lower carbon footprints, such as polyethylene terephtahalate (Martins et al., 2018).

Other authors indicate that while bottling is still a relevant stage, viticulture can contribute the most for the carbon footprints of some wine (Laca et al., 2021; Neto et al., 2013). The main hotspots for the viticulture stage are typically combustion of diesel during the use of agricultural machinery (main component) and the use of fertilizers (to a lower extent) (Benedetto, 2013; Navarro et al., 2017; Neto et al., 2013; Vázquez-Rowe et al., 2013). The carbon footprint of the viticulture stage can also be affected by the productivity yield of the vineyard, as well as its scale of the producer, with lower productions being associated with higher carbon footprints (Trombly and Fortier, 2019). The extent of manual labour, instead of the use of machinery, is also a hotspot in the carbon emissions of this stage (Gierling and Blanke, 2021a; Laca et al., 2021). However, the replacement of machinery for manual labour is not a realistic alternative for most wine producers, due to cost and productivity issues (Gierling and Blanke, 2021a). It should be noted, however, that while most studies did not consider carbon sequestration by grape vines, it was shown that this parameter turned viticulture into a negative contributor to carbon emissions (Martins et al., 2019). Given this, the carbon footprint of the viticulture stage might be reduced if existing vineyards try to employ emission mitigation strategies based on carbon sequestration. That is, increasing the content of organic matter in soils of the vineyards with the objective of increasing the incorporation of carbon in the soils. Planting trees, besides grape vines, in the vineyards can also help to offset carbon emissions by sequestration of CO_2 into the new trees. In fact, it has been shown that the sum of biogenic GHG fluxes and the carbon stock change resulted in a net carbon sink at the viticulture stage, leading to potential carbon neutrality (Chiriacò et al., 2019).

Finally, some studies also reported winemaking as a life cycle stage with some relevant contributions to the overall carbon footprint of wine, but more rarely (Litskas et al., 2020). The hotspot in winemaking stage is invariably the electricity consumption required for winemaking itself and storage (Hirlam, 2021; Litskas et al., 2020; Navarro et al., 2017; Trombly and Fortier, 2019). Thus, strategies for reducing electricity consumption should include increasing the energy-efficiency of buildings associated with wineries, especially for storage purposes (Litskas et al., 2020), and increasing the amount of renewable energy in the employed electricity mix. For this, a suitable option could be the installation of photovoltaic panels on the winery's properties. Other life cycle stages, such as distributions, are typically associated with more negligible contributions to overall carbon footprint (Meneses et al., 2016; Point et al., 2012; Rinaldi et al., 2016).

5. Conclusions

In summary, we have reviewed the literature regarding the evaluation of the carbon footprint associated with wine production. We have analysed and discussed several studies published in the last decade, which focused on different wine types, several countries and wine regions, and different system boundaries. We have found that the obtained carbon footprints are highly variable, which demonstrate the need for a more uniform and standardised protocol and calculator for estimating this parameter in a more meaningful way and that is easier to compare by players and stakeholders in the wine industry. The life cycle stages that contribute the most to resulting carbon emissions were identified, and relevant hotspots characterized. More specifically, most studies identify bottling and viticulture as the most relevant life cycle stages. The impact of the former is associated with the production of glass wine bottles, while the impacts of the latter arise mainly from the consumption of diesel, fertilizers, and even phytosanitary products. While typically less relevant, the main impact of the winemaking stage is associated with energy requirements. Based on this, suggestions for reducing the carbon footprint of wine were made for different stages of wine production. Producers should be using glass bottles of lower weight, recycled bottles, or even bottles of other materials with lower carbon footprints. Carbon sequestration by soil and trees can be essential to mitigate emissions at the viticulture stage. Finally, using renewable energies should be the focus to reduce the carbon footprint of the winemaking stage. Thus, this review can help to guide future roadmaps aiming to determine and reduce the carbon footprint of wine.

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.

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