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Review article

Selecting south European wine based on carbon footprint

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ABSTRACT

The largest wine producers globally are located in Southern Europe and climate is a major factor in wine production. The European Union aims to complement the consumer's choice for wine with information about environmental sustainability. The carbon footprint is a worldwide-standardized indicator that both wine producers and consumers perceive as the most important environmental indicator. So far, environmental life cycle assessment studies show variability in the system boundaries design and functional unit selection, and review papers do not include life cycle inventory data, and consider vineyards in various locations worldwide. This study aimed to investigate what are the key factors affecting the carbon footprint of red and white wine production in South European countries with the same climatic conditions, and benchmark both wine types. The results showed that the carbon footprints of white and red wines are comparable. The average carbon footprints were 1.02, 1.25, and 1.62 CO_2 eq. bottle of wine^{-1} for organic red wine, conventional red wine, and conventional white wine, respectively. The viticulture, winemaking, and packaging stages affect greatly the carbon footprint. Diesel consumption at the viticulture stage, electricity consumption at the viticulture and winemaking stages, and glass production at the packaging stage are the largest contributors to the carbon footprint. Wine consumption stage was omitted from most studies, even though it can increase the carbon footprint by 5%. Our results suggest that consumers should choose (conventional or organic) red wine that is produced locally.

Contents

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1. Introduction

The European Union (EU) aims to harmonize environmental assessments of wine (European Commission, 2018) with life cycle assessment (LCA) and is expected to put forward a proposal for an EU-wide food labeling scheme to consider nutritional aspects, sustainable and social elements of food products for sustainable decisions by consumers in 2023 (Fortuna, 2021). In this study, we reviewed LCA studies of South European wine and identified key aspects that affect the carbon footprint (CF).

Wine production is one of the oldest economic activities and represents a prosperous economic sector with global market size of 364.25 B$ (Fortune Business Inside, 2019). The majority of the major wine-growing regions are found between the 35th and 50th, and the 30th and 45th parallels in the Northern Hemisphere and Southern Hemisphere, respectively (Leeuwen and Darriet, 2016). Environmental factors affect greatly wine production. Among environmental factors, the climate is a significant contributor to vine development compared to grapevine variety and soil (Leeuwen et al., 2004). Thus, producers select plant materials according to local climatic conditions to optimize the compromise between quality and yield (Leeuwen and Darriet, 2016). The wine sector produces primarily two types of wine, still wine and sparkling wine, with still wine dominating the market. Still wine market consists of red, rosé, and white wines, with red and white wines accounting for 54% and 36% of the wine market, respectively (Siddle, 2019). The EU is the world-leading wine producer. Between 2014 and 2018, the average annual production was 167 million hectoliters, which accounts for 65% of global production (European Commission, 2020a). Spain, France, and Italy are the leading wine-producing countries (Ferrara and De Feo, 2018), and produce more than half of the global wine production (Statista, 2020).

The EU accounted for 60% of global wine consumption. However, per capita consumption is decreasing slightly in the EU (European Commission, 2020a). The most consumed wine in the EU is red, but its consumption is declining, while demand is growing for specific wine products, such as rosé wines. In 2020, the European Commission (EC) adopted the Farm to Fork (F2F) Strategy to achieve a fair, healthy, and environmentally-friendly food system, as part of the Green Deal (Purnhagen et al., 2021). The F2F strategy covers the entire food life cycle and aims to empower consumers through labeling information. Front-of-pack nutrition labeling was part of the F2F Strategy (European Commission, 2020b). Therefore, the EC published the product environmental footprint category rules (PEFCR) for wine (European Commission, 2018) to harmonize methods for measuring and communicating environmental performance. PEFCR considers the entire life cycle of wine, i.e. raw material acquisition, processing, distribution, use, and EOL processes, and accounts for 16 impact categories, such as climate change (Gonçalves and Silva, 2021). PEFCR considers a benchmark for still wine (European Commission, 2018). However, consumers' wine choice is more complicated than other food products because several key drivers exist except for the taste and price, such as the geographical indications, sustainable certification, and brand (Schäufele and Hamm, 2017; Stanco et al., 2020). Thus, the objective of the PEF label is to complement these key choice drivers by providing information about the overall environmental performance of bottled wine.

Sustainability is a paradigm that affects the wine sector because there is increasing pressure from customers and markets for economic or political reasons (Flores, 2018). A cross-analysis showed that wine producers find advantages in adopting sustainable and eco-efficiency practices due to improving quality and economic efficiency, respectively (Szolnoki, 2013). CF, corporate social responsibility, and the capacity to communicate innovation to consumers are crucial factors for Spanish (García-Cortijo et al., 2021) and Italian (Barisan et al., 2019) wine producers. In addition, consumers reported a willingness to pay a premium price for wine derived from sustainable production (Schäufele and Hamm, 2017). In particular, for young consumers, the willingness to pay and carbon-neutral brands are key factors when purchasing wine (Nassivera et al., 2020).

Environmental life cycle assessment (E-LCA) is standardized by ISO 14040 and 14044 (ISO, 2006a,b) and is already considered a powerful tool for achieving the environmental sustainability of products. E-LCA accounts for all stages of a product's life cycle, from raw material acquisition (cradle) to end-of-life (EOL) processes (grave). Literature investigating the CF of various wines is extensive (Rinaldi et al., 2016). However, E-LCA studies show high variability in the system boundaries design, consider various functional units and vineyards in various locations worldwide which affect the environmental impact results. Moreover, review papers do not assess the quality of life cycle inventory data (Ferrara and De Feo, 2018). Therefore, the comparison of wines becomes impossible due to methodological choices in LCA and variability of local climate. So far, the application of E-LCA on wine was reviewed (Ferrara and De Feo, 2018), a brief overview of the wine production chain was provided (Baiano, 2021), a detailed comparison of E-LCA of European and Canadian bottled wine was performed (Jourdaine et al., 2020), the CF of the Italian wine sector was benchmarked (D'Ammaro et al., 2021a,b), and an extensive review concerning CF analysis of wine was performed approx. a decade ago (Rugani et al., 2013).

There is great interest from the EU to increase the environmental awareness of wine consumers and roll out labeling based on the PEFCR methodology in 2023 (International Wool Textile Organisation, 2021). The PEFCR presents a benchmark for still wine, but local climate affects greatly the viticulture (Leeuwen and Darriet, 2016) and several types of still wine exist. In addition, both wine producers (Maesano et al., 2022) and consumers (Barisan et al., 2019) perceive CF as the most important environmental indicator. To our knowledge, no study investigates criteria based on the PEFCR (European Commission, 2018) to compare inventory data and CF of wines produced under the same climatic conditions and benchmark them. Furthermore, no study presents in detail data from the Life Cycle Inventory phase which directly affect the CF or assesses their quality. Therefore, this review aims to investigate and benchmark the CF of red and white wine production in Southern Europe and identify which are the life cycle stages and inputs that affect CF.

2. Methodology

The material collected for the review was conducted from July to December 2021. First, we conducted a search in the Scopus database for several keywords, such as (a) "Life cycle assessment" AND wine", (b) Wine AND "carbon footprint", (c) "Greenhouse gas" AND wine, (d) "CO_2 emissions" AND wine, (e) LCA AND wine, and (f) "Global warming potential" AND wine, in the "Abstract–Title–Keywords" field for "Articles", "Articles in press", "Reviews", and "Conference papers" without any time constraint. The search provided 526 studies, which was reduced to 304 studies excluding the duplicates, and it was further reduced to 24 LCA studies after applying screening criteria. A total of 34 E-LCA case studies were identified and analyzed according to the key investigation issues. These issues are methodological choices during the Goal and Scope Definition phase, and they were selected based on the PEFCR (European Commission, 2018). For instance, studies with a functional unit of 0.75 L (one bottle) of wine were reviewed, and authors who decided to consider other functional units, e.g. 1 kg of harvested grapes, were excluded because the conversion of the mass harvested grapes to liters of wine varies. There is a high variability of vinification yield; 1 to 2.5 kg of harvested grapes per L of produced wine (D'Ammaro et al., 2021a,b; Harb et al., 2021; Navarro et al., 2017)). Fig. 1 shows the flow diagram of the selection procedure for including studies.

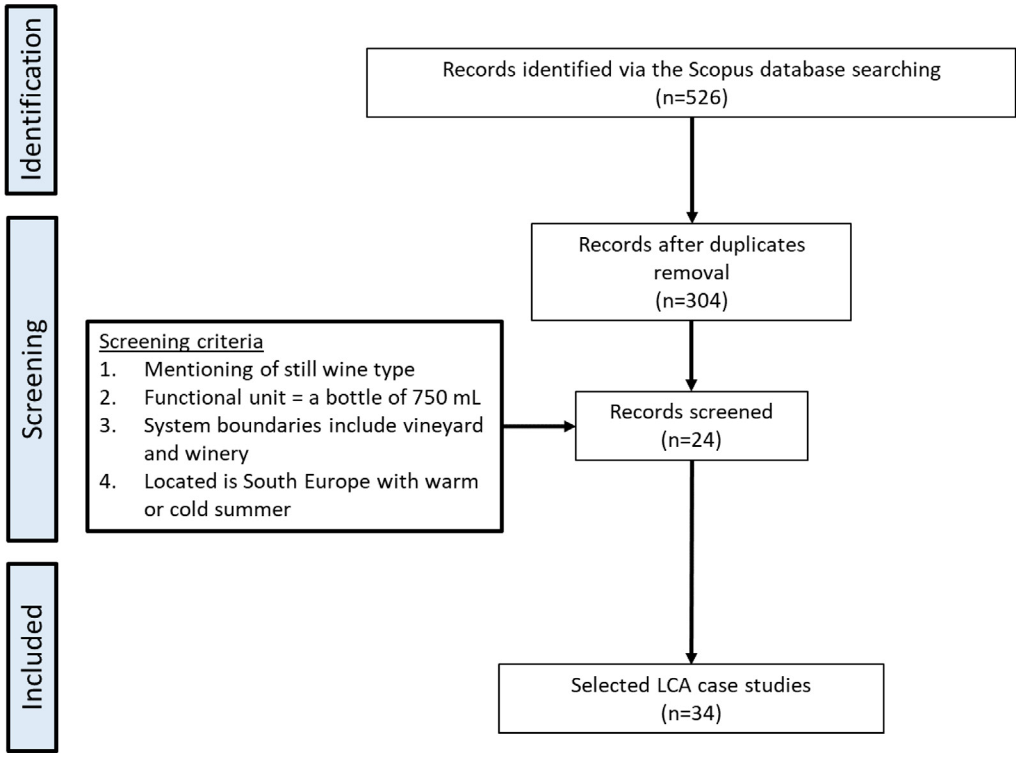

Fig. 1. Flow diagram of the selection procedure of LCA studies.

2.1. Key investigation issues

Wine type and grapes variety

The type of wine was identified and used grape variety was taken into account when mentioned. However, often more than one grape variety is cultivated and processed to produce red or wine wines (Barisan et al., 2019). The wine type and grape variety are expected to affect the CF.

2.1.1. System boundaries

The system boundaries consist of all the relevant stages in the life cycle of the wine. System boundaries can be cradle-to-grave, cradle-to-gate, gate-to-gate, or gate-to-grave. The PEFCR (European Commission, 2018) suggests designing from cradle-to-grave, i.e., from grape production to EOL, including the consumption stage (European Commission, 2018).

2.1.2. Life cycle inventory

Depending on the system boundaries, data for materials and energy consumption, and environmental releases per life cycle stage will be collected in the life cycle inventory step. Furthermore, data quality was assessed according to the Data Quality Score (DQS) of Salemdeeb et al. (2021). The DQS is based on a 1–5 scale, with 1 being the best and 5 being the worst, and the formula:

$$DSQ_{stage(i)} = \frac{R + C + TeR + GeR + TiR}{5}$$

2.1.3. Viticulture practices (conventional or organic)

This aspect refers to organic and conventional viticulture practices. The main difference between these agricultural practices is that the latter employs synthetic products, such as fertilizers and pesticides, which increase yield but harm the environment, e.g., increasing carbon footprint (Borsato et al., 2020) and deteriorating biodiversity (Caprio et al., 2015).

2.1.4. Carbon footprint

CF is a worldwide-standardized indicator of greenhouse gas (GHGs) emissions that convert the quantity of emitted GHGs to "units of carbon dioxide (CO_2) equivalent" (Röös et al., 2013). Each GHG has a characterization factor that compares the amount of heat trapped by a certain mass of the GHG to the amount of heat trapped by a similar mass of CO_2, see Table S1 in Supplementary Material. CF is the most popular environmental indicator for dissemination. CF is strongly linked to energy use and may, therefore, represent other underlying environmental impacts (Weidema et al., 2008).

3. Results

3.1. Wine type and grapes variety

Between conventional and organic red wine case studies, conventional wine production is assessed more than organic red wine production. The majority of the case studies of red wine were located in Italy (n = 22) and Spain (n = 3). Whereas concerning white wine five case studies were located in Italy, and one in Cyprus, Portugal, and Spain. The wine's country of origin was investigated to identify major differences. The majority of the studies (approx. 57%) did not mention the grape variety of the case study. In contrast, almost all studies with organic red wine mentioned the grape variety and two studies considered a blend of grapes for conventional red wine production (Bonamente et al., 2016; Tsangas et al., 2020). Cabernet Sauvignon, Merlot (Bonamente et al., 2016; Tsangas et al., 2020), Montepulciano (Arzoumanidis et al., 2017; Chiriacò et al., 2019; Pattara et al., 2012), and Vermentino (Benedetto, 2013, 2010) varieties were found multiple times. These studies are cross-analyzed to identify differences unaffected by climate and grapevine variety. The rest of the varieties are mentioned once; for instance, Syrah, Chianti, Xinomavro, Xynisteri, etc.

3.2. System boundaries

Fig. 2 shows the identified stages in system boundaries. It was found that processes that precede viticulture, such as vine planting

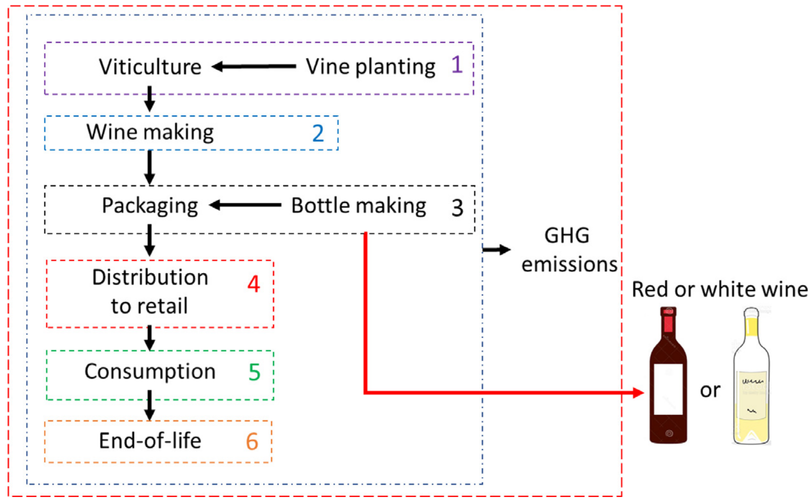

Fig. 2. System boundaries of reviewed studies.

and pre-production, were either merged with the viticulture stage or not mentioned at all. Only six LCA studies presented explicitly CF results per vine planting stage. Similarly, the stage of bottle making was presented as part of the packaging stage because studies did not explicitly state what materials were used and how much energy was consumed during the manufacturing of wine bottles. Furthermore, the consumption stage and EOL processes of consumed wine were also not mentioned by the majority of studies. Consumption was mentioned by two LCA studies for ten case studies. Six studies presented the contribution of EOL to the CF. In general, all LCA practitioners but one (Tsangas et al., 2020) mentioned explicitly (1) viticulture, (2) winemaking, (3) packaging, and (4) distribution to retail stages.

3.3. Life cycle inventory

Table 1 shows the quantities of various materials that were consumed during the entire life cycle of reviewed wines. Water input was excluded because freshwater production and distribution do not contribute to global warming (Rinaldi et al., 2016). Some studies presented the life cycle inventory based on the functional unit (0.75 L of wine), while others presented the life cycle inventory per land surface or on an annual basis. In the latter cases, the life cycle inventory was re-calculated by the authors of this study based on yield per surface or annual yields at the farm, and grapes amount needed to produce 0.75 L wine at the winery. Furthermore, the majority of studies presented fertilizers application based on the amount of nitrogen and/or phosphorus. Therefore, the authors of this study re-calculated the amount of nitrogen in compost (Vázquez-Rowe et al., 2012) and manure (Neto et al., 2013) to include it in Table 1. Lastly, four studies of organic red wine and one study of conventional white wine did not present the life cycle inventories at all, even though these studies present the contribution of life cycle stages to CF.

Table 1 shows that the choice of materials is not affected by the viticulture practice. Similar materials are consumed in organic and conventional practices. Regarding quantities, diesel and fertilizers are consumed mainly at the farm. Diesel consumption ranges between 0.006 and 0.23 L bottle of wine^{-1} and conventional red wine showed the lowest values but are very similar to red organic wine. In contrast, conventional white wine employed the largest amount of diesel in the viticulture stage. Fertilizers' consumption ranged between 0.007 and 0.26 kg bottle of wine^{-1} and conventional red wine shows the lowest values. Organic red wine employed similar amounts of fertilizers as conventional red wine, but conventional white wine employed the largest quantities of fertilizers. The application of pesticides is insignificant when compared with quantities of diesel and fertilizers because the quantities of pesticides are at least an order of magnitude lower than amounts of fertilizers. Nevertheless, conventional white wine employed the largest quantities of pesticides when compared to red wine. Concerning conventional white wine, electricity was considered at the viticulture stage but none of the studies explained the purpose of employing electricity. A possible explanation is electricity consumption for water drilling (personal communication, Vourvoukeli Estate, 2022).

Electricity is mainly consumed at the winemaking stage. Among the three wine types, the largest amounts of electricity are consumed for conventional red wine, but this is difficult to discern because studies may combine electricity consumption at the winemaking and packaging stages. Furthermore, electricity consumption depends on the vinification yield, i.e., larger vinification yield results in lower quantities of grapes to produce 0.75 L of wine and a shorter time duration for pressing operation. Quantities of gas (methane or biogas) in terms of energy are lower than diesel consumed in the viticulture stage and they are mainly consumed for heating purposes, such as heating offices. Similarly, quantities of yeast and chemicals (sulfur dioxide, bentonite, sugar, etc.) are very low if they are being compared with consumed fertilizers at the viticulture stage. Glass is the main consumed material in the packaging stage. The glass quantity is similar to all wine types but organic red wine studies presented larger glass quantities on average. Quantities of cork, cap seal, aluminum, etc. are insignificant when compared to glass. Electricity is also consumed during packaging, but many studies presented it with electricity consumption at the winemaking stage because these two stages can take place in the same facility. Nevertheless, electricity consumption during packaging is an order of magnitude lower than electricity consumption at the winemaking stage. Finally, only a few studies included EOL processes, i.e., what happens to the materials when they become waste, especially wine bottles. These studies concerned conventional red wine. In this case, the authors collected national-level data regarding waste treatment processes, such as recycling rate, etc.

Materials that are presented in Table 1 come with an embedded CF. The embedded CF exists due to the use of manufactured products in the production lines of these materials, and consequently all the environmental emissions prior to production. For instance, the production of fertilizers requires the production and use of nitric acid. Nitric acid is a source of N_2O emission which has a high characterization factor for global warming (see Table S1) and accounts for a 50% contribution to global warming in the 'market for nitrogen fertilizer' dataset (Jourdaine et al., 2020). Data for materials in Table 1 are typically collected from LCI databases, such as European Ecoinvent database (Wernet et al., 2016) and U.S. Life Cycle Inventory database (National Renewable Energy Laboratory, 2012). Furthermore, the application of fertilizer

Table 1
Materials and energy inputs mentioned in reviewed studies.

Study	Diesel (L)	Electricity[a] (kWh)	Fertilizers (kg)	Pesticides (kg)	Electricity[b] (kWh)	Gas (m^3)	Yeast (kg)	Chemicals[b,c] (kg)	Glass (kg)	Cork (kg)	Cap seal (kg)	Aluminum (kg)	Electricity[d] (kWh)	Waste (kg)
Organic red wine														
Chiriacò et al. (2019)	0.089	–	0.03	0.0017	0.5	–	0.0003	0.0002	0.36	0.0045	0.0008			
Meneses et al. (2016)	0.006	–	0.0283	0.0012	0.015	–	2.10^{-5}	5.10^{-5}	0.58	0.0042	0.001	0.0012	–	0.223
Harb et al. (2021)	0.0166		0.075	0.0011	0.0187		0.0001	0.0003	0.6	0.005			0.0078	
Conventional red wine														
Manzardo et al. (2021)	0.086	–	–	0.0049	2.065	1.164	–	–	0.54	0.008	–	0.003	–	–
D'Ammaro et al. (2021a,b)	0.072	–	–	0.0058	0.32	0.03	–	–	0.36	–	–	–	–	–
D'Ammaro et al. (2021a,b)	0.037	–	0.0077	0.0092	0.05	–	–	–	0.5	–	–	–	–	–
D'Ammaro et al. (2021a,b)	0.037	–	0.0077	0.0092	0.24	–	–	–	0.44	–	–	–	–	–
D'Ammaro et al. (2021a,b)	0.031	–	0.0292	0.0043	0.85	–	–	–	0.51	–	–	–	–	–
D'Ammaro et al. (2021a,b)	0.053	–	–	$9.6.10^{-6}$	0.95	0.04	–	–	0.5	–	–	–	–	–
D'Ammaro et al. (2021a,b)	0.043	–	–	0.0058	1.2	0.05	–	–	0.65	–	–	–	–	–
D'Ammaro et al. (2021a,b)	0.052	–	–	0.0101	1.2	0.05	–	–	0.6	–	–	–	–	–
D'Ammaro et al. (2021a,b)	0.063	–	0.008	0.0055	0.79	–	–	–	0.6	–	–	–	–	–
D'Ammaro et al. (2021a,b)	0.011	–	0.0011	0.0027	0.12	0.01	–	–	0.58	–	–	–	–	–
Tsangas et al. (2020)	0.016	–	0.0545	0.0086	0.1974	–	–	–	–	–	–	–	–	–
Gazulla et al. (2010)	0.007	–	0.007		0.1033	–	–	0.0001	0.4	0.003	0.005	–	–	–
Rinaldi et al. (2016)	0.030	–	0.0098	0.007	0.18	–	0.00004	0.0049	0.45	0.004	0.001	–	–	–
Bosco et al. (2013)	0.005	–	0.0045	0.0003	0.121	–	0.0003	0.0004	0.41	0.006	0.002	–	0.0291	0.41
Bosco et al. (2013)	–	–	–	–	0.121	–	0.0003	0.0004	0.41	0.006	0.002	–	0.0291	0.41
Bonamente et al. (2016)	0.023	–	0.0095	0.0063	0.1782	–	4.10^{-5}	0.0053	0.45	0.004	0.001	–	–	–
Bosco et al. (2011)	0.045	–	0.0799	0.0048	0.2603	–	0.0007	0.0013	0.5	0.013	0.002	–	0.0055	0.5
Bosco et al. (2011)	0.088	–	0.0334	0.091	0.0487	–	0.0001	0.049	0.6	0.007	0.0007	–	0.1883	0.6
Conventional white wine														
Litskas et al. (2020)	0.011	–	0.0035	0.008	0.747	–	–	–	0.4	–	0.0016	–	–	0.121
Vázquez-Rowe et al. (2012)	0.065	0.0144	0.0471	0.0019	0.71	0.0035	–	0.0027	0.57	0.0037	0.0019	0.0012	–	–
Rinaldi et al. (2016)	0.033	–	0.0109	0.0075	0.18	–	4.10^{-5}	0.0049	0.45	0.004	0.001	–	–	–
Fusi et al. (2014)	0.069	–	0.0037	0.0003	0.1108	0.0004	–	0.0001	0.56	0.0035	–	–	–	0.014
Neto et al. (2013)	0.234	0.259	0.0126	0.05	0.291	0.0047	0.0002	0.0032	0.53	–	–	–	–	–
Benedetto (2013)	0.079	–	0.0024	0.0052	0.0374	0.0004	0.0003	0.0111	0.52	0.0033	–	–	–	–
Bosco et al. (2011)	0.018	0.0277	0.0259	0.0003	0.449	–	0.0011	0.0032	0.59	–	0.0477	–	–	–

[a] At the viticulture stage.
[b] At the winemaking stage.
[c] Consists of consumed sulfur dioxide, bentonite, sugar, etc. at the winemaking stage.
[d] At the bottling stage.

results in direct N_2O emissions. The production of glass bottles requires high energy consumption which results in GHG emissions, mainly CO_2. Electricity generation on the national level is to a high extent fossil-based in Southern Europe. Therefore, at the winemaking and packaging stages, electricity consumption results in GHG emissions when sourced from national grids. Alternatively, wineries can generate renewable electricity with photovoltaics but this was not found in the reviewed studies.

Finally, waste disposal in some cases can result in reporting negative emission values by studies, not due to atmospheric carbon sequestration but because generated electricity due to waste incineration replaces national fossil-based electricity or recycling produces secondary material that replaces virgin materials in the market (Manzardo et al., 2021).

Fig. 3 shows the heatmap of $DQS_{stage(i)}$ (Salemdeeb et al., 2021) of reviewed studies. The majority of reviewed studies used primary data from the grapes and wine producers which corresponded to the area where the vineyard was located and represented an adequate period to even out normal fluctuations. However, data was not verified with on-site checking, by recalculation, through mass balances or cross-checks with other sources, and data was often collected 4 years or more before publication.

3.4. *Carbon footprint*

CF results are presented based on wine type and LC stage. Fig. 4 shows the CF of reviewed wine types. The three considered wine types have similar CFs. Organic red wine results in the lowest median CF but its CF range is very close to conventional red wine. In contrast, the median values for conventional red and white wines are similar but the CF range of conventional white wine is much larger than the other two. This result can be supported by the fact that the vinification yield of white wine is usually larger than red wine, resulting in more kg of grapes to produce one bottle (Navarro et al., 2017). An analysis of LC stages is crucial to show what are the reasons for these differences.

Figs. 5–7 show the contribution of considered LC stages to CF per wine type. Viticulture, winemaking, packaging and distribution stages are the CF hotspots for all still wine types. The packaging stage contributes between 40% and 70% for all wine types mainly due to the production of wine bottles. The primary production of glass bottles consists of raw material extraction and electricity consumption by machinery for all wine types. The viticulture stage contributes more in the cases of organic red and conventional white wines, and the winemaking stage contributes significantly to conventional red wine production. In addition, for all wine types, authors did not consider

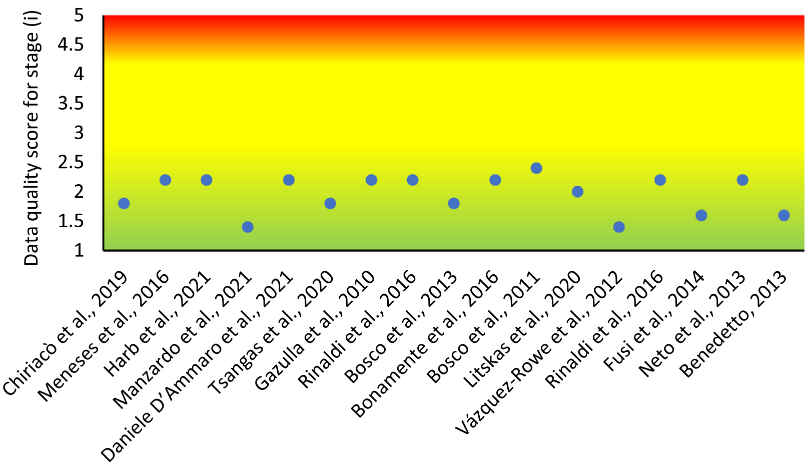

Fig. 3. Heatmap based on the data quality score for stage (i) according to Salemdeeb et al. (2021).

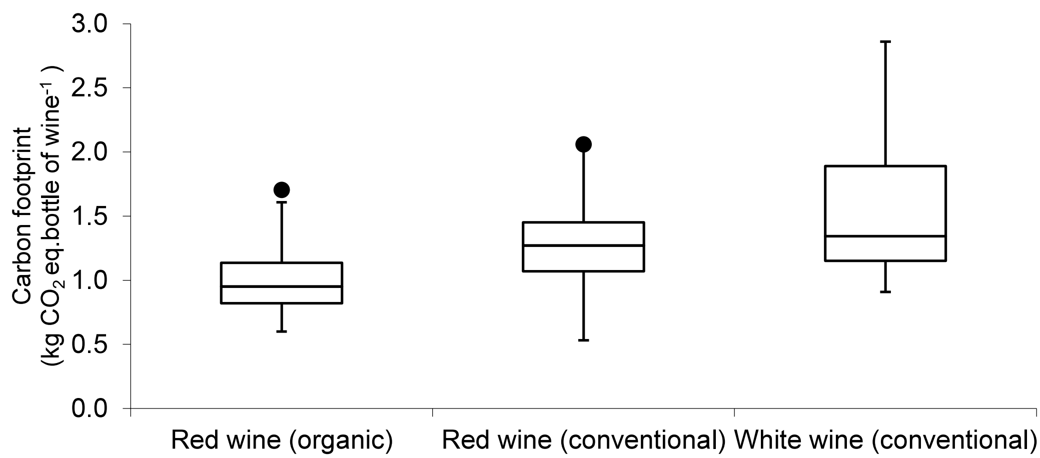

Fig. 4. The carbon footprint of organic red, conventional red, and conventional white wines.

biogenic CO_2 emissions during fermentation because they regarded them as sequestered atmospheric CO_2 during photosynthesis, except for Bosco et al. (2013), Litskas et al. (2020), Neto et al. (2013). The CO_2 from wine fermentation is approx. 0.085 kg bottle of wine^{-1} based on stoichiometry for a wine with 12% ethanol content. Similarly, reviewed LCA studies did not account for sequestered atmospheric CO_2 during vines growth or emissions due to biomass decomposition at the viticulture stage, except for Chiriacò et al. (2019). However, parts of the vine that are cut but not transported to the winery are commonly used as fertilizer (Soosay et al., 2012). In addition, the wine distribution stage may contribute to environmental impacts when consumed wine is not produced locally but imported from other places, as Ponstein et al. (2019) concluded regarding importing Australian glass bottled wine to Finland. In contrast, EOL and (mainly) consumption were left out of most studies' scope. The consumption stage regards drinking the wine and is not accounted for because no environmental releases are expected but consumers can refrigerate the wine for days or weeks before consumption. The PEFCR (European Commission, 2018) accounts for electricity for 2-day refrigeration of wine and not consumed wine that remains at the bottom of the bottle and is thrown in the drain (European Commission, 2018). In contrast, all authors but one (Harb et al., 2021) assumed that consumers drink all wine in the bottle and do not throw away part of it. The latter would result in producing more wine to consume 0.75 L. EOL was concerned mainly with packaging material disposal that was accounted for by studies or to a lesser extent viticulture waste or winery waste, such as wastewater due to grape pressing (Banti et al., 2020). Lastly, infrastructure construction and demolition, and vehicles production and disposal were excluded according to the PEFCR of wine.

3.4.1. Organic red wine

For organic red wine viticulture, winemaking, and packaging stages contribute from approx. 78% to 100%, with an aggregated median of 80.4% (see Fig. 5). Direct decisions by the wine producers made during combined viticulture and winemaking stages range between 5% and 70% contribution. The 5% contribution derived from an Italian wine but the production of bottles and containers (part of the packaging stage) resulted in an 88.8% contribution to CF (Pattara et al., 2012). The largest contributor is the packaging stage due to the glass production process and electricity consumption for the bottling process. This stage resulted in 0.179 to 1.138 kg CO_2 eq. bottle of wine^{-1} or 29.8% to 88.2% contribution. Electricity consumption is presented in LCIs (see Table 1) but pristine glass employed for the packaging stage comes with an embedded CF due to background data for glass manufacturing that is typically collected from databases. One study considered also the employment of green glass which impact greatly the CF (Arzoumanidis et al., 2017). The second-largest hotspot is the viticulture stage that ranges between 0.045 to 0.682 kg CO_2 eq. bottle of wine^{-1} (or 3.5% to 58.5% contribution). Two inputs are the main contributors here, diesel consumption due to agricultural machinery, and organic fertilizers production and application, except for one study which reported the use of compost as fertilizer (Chiriacò et al., 2019).

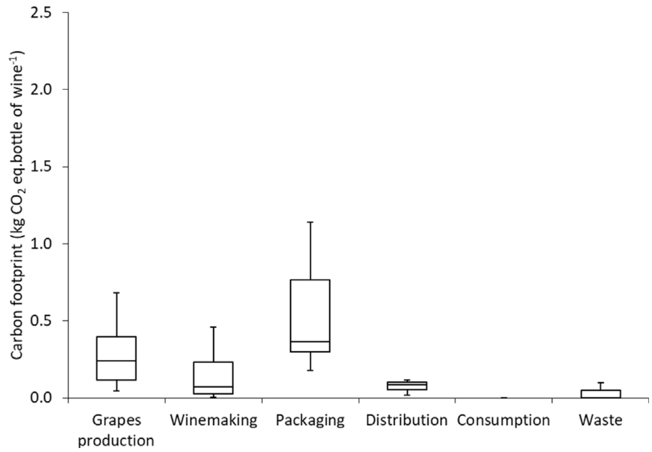

Fig. 5. Contribution of life cycle stages to carbon footprint for organic red wine.

The third hotspot is the winemaking stage. This stage ranges from 0.006 to 0.458 kg CO_2 eq. bottle of wine^{-1} (or 0.6% to 53.9% contribution). This stage mainly consists of electricity consumption for the operation of the winery. Other materials are also consumed at the winery (see Table 1) but their contribution is insignificant. Therefore, primarily the amount of electricity consumption affects this stage, and secondly the national electricity mix, (Chiriacò et al., 2019; Harb et al., 2021).

Three studies presented data on the distribution stage and EOL processes, and none was found to report the CF of the consumption stage. The largest contribution due to the distribution stage of 11.8% was found in Harb et al. (2021) because the wine was transported from southern France to the UK for 6963 km (equivalent to 3760 nautical distances). Pattara et al. (2012) also reported a 6.6% contribution due to transporting the wine to foreign countries. Only Harb et al. (2021) mentioned a non-negligible contribution of EOL processes (11.8% contribution) of waste wine bottles because non-recycled waste in the UK is incinerated (45%) or landfilled (55%). Finally, Harb et al. (2021) mentioned that 5% of the wine is considered lost (during the packaging stage) or not consumed, and consequently, poured down the drain but they did not explicitly show this a contribution due to consumption stage.

Three studies considered the same grape variety: Montepulciano. These studies presented different results in terms of CF and contributions of life cycle stages. Arzoumanidis et al. (2017) presented a CF of 1.7 kg CO_2 eq. bottle of wine^{-1}, and viticulture and packaging contributed 90% to the CF, with data for 2010–2011. Pattara et al. (2012) presented a CF of 1.3 kg CO_2 eq. bottle of wine^{-1}, and packaging contributed 88% to the CF. In contrast, Chiriacò et al. (2019) presented a CF of 0.8 kg CO_2 eq. bottle of wine^{-1}, and winemaking and packaging contributed 85% to the CF, with data for 2014–2015. Chiriacò et al. presented a much lower CF than Arzoumanidis et al. and Pattara et al. because they accounted for biogenic CO_2 sequestration and considered an ultra-light glass bottle, i.e., less glass resulting in lower embedded CF. In addition, precipitation in Italy in 2010–2011 was higher than in 2014–2015 (World Bank, 2022), which could have affected the vineyard operation negatively.

Most of the organic red wines were Italian which resulted in a CF range that included Spanish (Meneses et al., 2016) and Lebanese (Harb et al., 2021) wines.

3.4.2. *Conventional red wine*

For conventional red wine viticulture, winemaking, packaging, and distribution stages are the main contributors (see Fig. 6). Excluding distribution, these stages contribute from approx. 62.5% to 100%, with an aggregated median of 91.7%. Direct decisions by the wine producers during combined viticulture and winemaking stages range between 14.3% and 53% contribution. The largest contributor is the winemaking stage. This stage ranges from 0.03 to 0.78 kg CO_2 eq. bottle of wine^{-1} (or 2.3% to 72.9% contribution) due to the electricity consumption and gas consumption for heat purposes. This is contradicted by organic red wine where no gas is consumed and conventional white wine where the amount of consumed gas is approx. an order of magnitude lower than consumed gas for conventional red wine vinification (see Table 1). In particular, Manzardo et al. (2021) consumed high consumption of electricity and thermal energy during grape pressing, fermentation, sedimentation, and aging. In contrast, the low contribution of the winemaking stage is found in studies due to the high vinification yield. Other chemicals used in this stage, such as yeast, bentonite, sulfur products, and sugar, contribute insignificantly due to the very low employed quantities. The second hotspot is the packaging stage due to glass production; it ranges from 0.3 to 0.66 kg CO_2 eq. bottle of wine^{-1} (or 22.8% to 65% contribution). The amount of used glass to manufacture one empty wine bottle greatly affects the stage's contribution. The higher the glass weight results in higher electricity consumption at the glass production stage. The glass weight is typically not mentioned, but it may range from 0.36 to 0.65 kg glass.bottle of wine^{-1} (D'Ammaro et al., 2021a,b). Some studies report the electricity consumption for the bottling process but this is one or two orders of magnitude lower than consumed electricity in the winemaking stage. The third hotspot is the viticulture stage; it ranges from −0.012 to 0.5 kg CO_2 eq. bottle of wine^{-1} (or −2.3% to 49.8% contribution). This is one of the two stages for all wine types that a negative CF contribution is presented because one study (Bosco et al., 2013) calculated the amount of atmospheric carbon that is sequestered in the soil. The major contributors during this stage are diesel consumption due to agricultural machinery, and organic fertilizers production and application.

The distribution stage contributes to conventional red wine between 0.01 to 0.56 kg CO_2 eq. bottle of wine^{-1} (or 1% and 34.4% of CF). This is more than organic red wine due to the larger transportation distances of a produced wine bottle. Conventional red wine is the only wine type for which LCA practitioners considered consumption data. The source was a study by D'Ammaro et al. (2021a,b) that included several case studies. These authors reported different CFs due to wine consumption by the consumer but did not explain how they calculated these values. The second LC stage is where a negative CF value is found in the EOL processes. In general, this stage contributes from 0.02 to 0.03 kg CO_2 eq. bottle of wine^{-1} (or 2.3% to 4.1% contribution), except for one study (Manzardo et al., 2021) that considered environmental benefits due to materials recycling and reported a negative value of −0.1 kg CO_2 eq. bottle of wine^{-1} (or −5%).

Most of the conventional red wines were Italian with a CF between 0.6 and 2.0 kg CO_2 eq. bottle of wine^{-1}, which resulted in a CF range that included the Spanish (Gazulla et al., 2010) and Greek (Tsangas et al., 2020) wines.

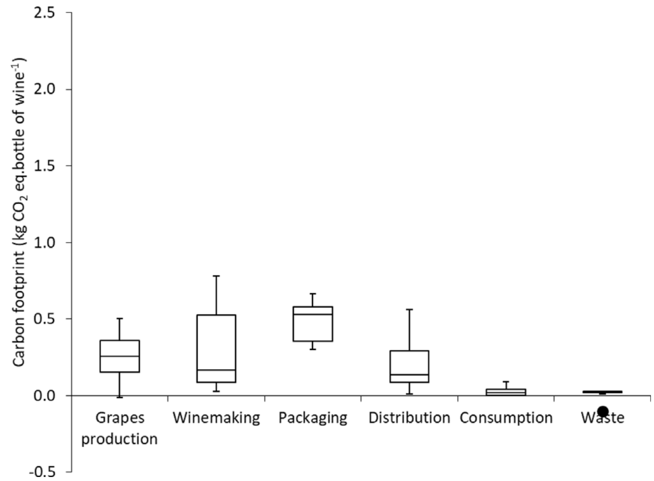

Fig. 6. Contribution of life cycle stages to carbon footprint for conventional red wine.

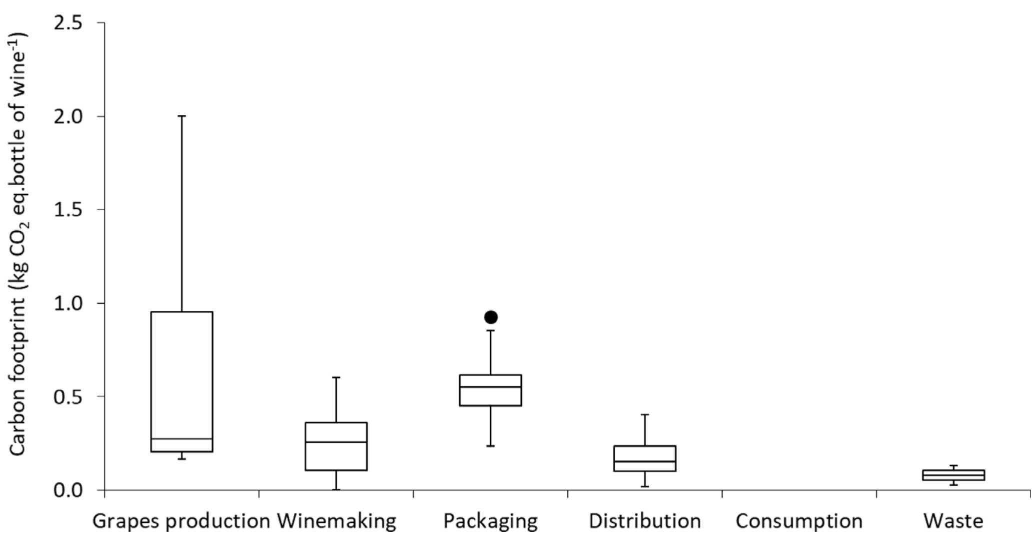

Fig. 7. Contribution of life cycle stages to carbon footprint for conventional white wine.

3.4.3. Conventional white wine

For conventional white wine, viticulture, winemaking, packaging, and distribution stages are the main contributors (see Fig. 7). Excluding distribution, these stages contribute from approx. 80% to 100%, with an aggregated median of 70.9%. Direct decisions by the wine producers during combined viticulture and winemaking stages range between 26.4% and 78.3% contribution. Both the viticulture and packaging stages are the largest contributors. The former has a larger maximum value of 2 kg CO_2 eq. bottle of wine^{-1} (Neto et al., 2013) due to the large amount of electricity consumed on the farm. The authors did not explain the reason for electricity consumption, but probably this was due to water supply. Furthermore, the larger range of viticulture stage may also be because usually, the vinification yield of white wine is larger than red wine (Navarro et al., 2017) resulting in more harvested grapes for the production of one bottle. On the other hand, the packaging stage has a larger median value of 0.55 kg CO_2 eq. bottle of wine^{-1} (Fusi et al., 2014). The viticulture stage is affected by diesel consumption and fertilizer production and application, but studies (Bosco et al., 2011; Neto et al., 2013; Vázquez-Rowe et al., 2012) reported for the first time electricity consumption in this stage which can be the same order of magnitude with electricity consumption in the winemaking stage. The packaging stage contributes mainly due to glass production and ranges from 0.23 to 0.93 kg CO_2 eq. bottle of wine^{-1}.0.75 L^{-1} (or 15.4% to 67% contribution). For white wine, the amount of glass needed in the bottling step ranges between 0.4 (Litskas et al., 2020) to 0.59 kg (Bosco et al., 2011) (see Table 1) and affects greatly the CF contribution. The third-largest contributor is the winemaking stage due to electricity consumption; it ranges from 0.002 to 0.6 kg CO_2 eq. bottle of wine^{-1} (or 0.2% to 46% contribution).

Distribution contributes between 0.02 kg CO_2 eq. bottle of wine^{-1} (2.2%) for transporting locally, i.e. 60 km (Bosco et al., 2011), and 0.4 kg CO_2 eq. bottle of wine^{-1} (29%) for transporting nationally, i.e. approx. 373 km (Rinaldi et al., 2016). Lastly, the consumption stage was not considered and EOL processes contributed between 0.03 kg CO_2 eq. bottle of wine^{-1} (3.3%) (Bosco et al., 2011) and 0.13 kg CO_2 eq. bottle of wine^{-1} (10%) (Litskas et al., 2020).

Benedetto (Benedetto, 2013, 2010) presented two CFs for the same grape variety: Vermentino grapes, and wine produced in Sardinia. One wine bottle resulted in a CF of 1.2 kg CO_2 eq. bottle of wine^{-1} and was produced in 2010, while the second wine bottle resulted in a CF of 1.6 kg CO_2 eq. bottle of wine^{-1} and was produced in 2013. In this case, inventory data regarded different harvesting years but the soil type was the same. The main differences derived from the preparation of the vineyard and the winemaking stage.

Five conventional white wines were produced in Italy, and one in Spain, Portugal, or Cyprus. The CF of Italian white wine ranged between 0.91 to 1.6 kg CO_2 eq. bottle of wine^{-1}. The CF of Cypriot white wine (Litskas et al., 2020) was within this range but Spanish and

Portuguese white wines' CF was 2.6 (Vázquez-Rowe et al., 2012) and 2.9 (Neto et al., 2013) kg CO_2 eq. bottle of wine^{-1} due to the viticulture stage. In both cases, electricity was consumed in the viticulture for water supply resulting in increasing the CF.

4. Conclusions

Focusing alone on the CF, consumers in South Europe should purchase local red wine because South European red wine has a lower CF than South European white wine. The wines are benchmarked as 1.02, 1.25, and 1.62 CO_2 eq. bottle of wine^{-1} for organic red wine, conventional red wine, and conventional white wine, respectively. Packaging, winemaking, and viticulture stages are hotspots of the wine supply chain. Distribution can be considered a hotspot if wine is exported for transoceanic transport. The consumption stage and EOL processes contribute to a low extent. The majority of reviewed studies omitted the consumption and EOL stages from their analyses. The former can result in increasing CF by 5% in case this amount of wine is not consumed but disposed of in the drain as recommended by the PEFCR.

If wine producers aim to significantly improve the CF of their wine, they should: (1) employ lighter glass bottles to minimize waste production, green glass, or investigate innovative and environmentally friendly packaging materials, (2) employ renewable energy in the winemaking stage, and (3) minimize diesel consumption in the viticulture stage through innovation and employ non-irrigation practices to avoid the electricity consumption at the vineyard. These recommendations may decrease the CF by approx. 0.5, 0.6, and 0.8 kg CO_2 eq per bottle of organic red wine, conventional red wine, and conventional white wine, respectively. Finally, the carbon balance should be measured including sequestered atmospheric CO_2 and emissions during fermentation to show the real effect of viticulture on climate change.

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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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.resenv.2022.100066.

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