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Environmental sustainability of wine sector: A focus on pesticide management

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ABSTRACT

The environmental sustainability of the wine industry is increasingly scrutinized due to its substantial use of pesticides, which are essential for maintaining crop yields and quality. This review explores the impact of pesticides within the vineyard lifecycle, emphasizing the need for effective management to align with broader sustainability goals. Despite several Life Cycle Assessment focused on grape and wine production and some reviews focusing on this topic were published, the role of pesticide application in the environmental profile of grape and wine production is still overlooked.

Our findings indicate a considerable variation in impact results, driven by differences in system boundaries and functional units used across studies. Pesticide emissions, particularly fungicides, significantly impact several environmental categories, including toxicity to aquatic environments and human health. Additionally, the energy-intensive production of these chemicals contributes to global warming potential and resource depletion.

The review advocates for improved pesticide management strategies in viticulture, promoting integrated pest management (IPM) to reduce dependency on chemical inputs. This shift not only supports environmental objectives but also ensures the economic sustainability of the wine sector. By integrating more accurate emission models, the assessment of toxicity related impact categories would become more robust and the benefits related to the adoption of sustainable practices could be better modelled.

1. Introduction

The winery industry, a nexus of agricultural prowess and economic vitality, occupies a pivotal role in global trade and cultural heritage. Central to the wine industry is an extensive network of vineyards spread across diverse continents and climates, each playing a unique role in the intricate global landscape of wine production. According to recent data from international organizations such as the International Organisation of Vine and Wine (OIV) and the Food and Agriculture Organisation of the United Nations (FAO), by 2022, the vineyard area reached 7.3 million hectares, resulting from a gradual decline over the past 20 years (OIV, 2023).

In 2021, world wine production reached around 29 million liters. Italy emerged as the largest wine producer, followed by France and Spain. Regarding exports, Italy was confirmed as the largest exporter globally, with around 2 million liters; France and Spain complete the podium, with around 1.9 and 1.4 million liters, respectively. Concerning the economic value of exports, France leads with a value of around 12 billion dollars, followed by Italy and Spain, with around 8 and 5 billion dollars, respectively (OIV, 2023). As with other agricultural inputs, the use of pesticides has become indispensable in viticulture for ensuring the production and commercialization of sufficiently high-quality products and securing a good economic yield (Peña et al., 2018a; Sharma et al., 2019). Notably, among the key environmental concerns associated with this production is the utilization and production of plant protection products, essential for controlling various biotic adversities such as fungal diseases (Plasmopara viticola, Uncinula necator/Oidium tuckeri, Botrytis cinerea, etc.) and pests (Lobesia botrana, Eupoecilia ambiguella, Scaphoideus titanus, etc.) (Balafoutis et al., 2017; Palliotti et al., 2023). In Europe, approximately 350,000 t of pesticides are sold annually, with 13 % typically allocated to Italian consumption (Eurostat, 2023, 2024). Additionally, it has been estimated that 20 % of pesticides are specifically employed in viticulture (Thiery et al., 2023).

The attention of European Union (EU) regulatory bodies toward pesticide usage in agriculture, as evidenced by initiatives like the European Green Deal and Farm to Fork Strategy, underscores the urgency of re-evaluating pesticide management practices in viticulture. These regulatory frameworks seek to align agricultural practices with

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environmental sustainability goals, prioritizing the reduction of pesticide dependency and the promotion of integrated pest management (IPM) strategies. In this context, viticulture emerges as a focal point for regulatory scrutiny, given its significance in the agricultural landscape and its potential to influence broader sustainability objectives within the EU's agri-food sector.

To assess the environmental sustainability of food and agriculture processes, different methodologies and approaches have been developed. However, among these, the Life Cycle Assessment (LCA) is by far the most commonly applied. Defined by the ISO standards (ISO 14040 and ISO 14044) (ISO, 2006; ISO, 2006), LCA allows a holistic assessment of the environmental performances of products, processes, and services in various sectors, including agriculture. Life Cycle Assessment is extensively used to assess agricultural environmental performance, identify supply chain hotspots, compare production systems, and identify mitigation solutions (Harb et al., 2021). According to established standards, LCA examines environmental aspects and potential impacts throughout a product's life cycle—from raw material acquisition through production, use, end-of-life treatment, recycling, or disposal. This comprehensive approach underscores LCA's importance in promoting sustainable agricultural practices and reducing environmental impacts.

Notably, the agricultural phase of wine production is highly impactful in the "cradle to distribution gate" process, highlighting the need for improvement in environmental efficiency (Arzoumanidis et al., 2014). In this context, the application of pesticides plays a significant, yet often overlooked role. These chemicals, pivotal in maintaining crop health and productivity, also contribute significantly to the environmental load of viticulture. Different environmental concerns are associated with pesticide application; among the most important are the pollution of aquatic and soil environments, toxicity to ecosystems (both terrestrial and aquatic), and human health, depletion of beneficial organisms (non-target), and the development of resistance in harmful organisms (target) (Fantke et al., 2011). Furthermore, the rise in resistance among harmful organisms creates a cycle where escalating pesticide use becomes necessary, adversely affecting both business economic performance and the environment (Peña et al., 2018b). Finally, another aspect to consider concerning pesticides is the impact generated during the production of these inputs, which require significant energy, resulting in adverse effects on greenhouse gas emissions and the use of fossil and mineral resources (Fusi et al., 2014).

To address these challenges more comprehensively within the framework of LCA for wine production, the incorporation of Product Category Rules (PCR International EPD® System Version 1.0, 2020) specifically for wine becomes essential. PCRs establish specific rules, requirements, and guidelines for conducting LCAs that are consistent and comparable among products within the same category. For wine, the PCRs provide a framework for systematically assessing the environmental impact of pesticide use, including specific guidelines on how to account for emissions related to the production and application of pesticides. By integrating PCRs, LCAs can adopt a more standardized and comparable approach, enhancing the accuracy and relevance of the results. This integration not only allows for better quantification of the environmental impact associated with pesticides but also provides producers and consumers with clear, rule-based information that can guide more sustainable practices in the industry. Such an approach is particularly relevant as it addresses the often-underrepresented area of pesticide application within existing LCA studies, thereby fostering a more dynamic, region-specific, and comprehensive application of LCA in promoting sustainable viticulture practices.

In this context, despite several LCA studies focused on grape and wine production, the role of pesticide application in defining the environmental profile of the grape and wine production process is still overlooked. The purpose of this review is to examine and summarize the available information on the environmental impacts associated with the wine sector, particularly those associated with pesticide application. The aim of the review is twofold:

1. Summarize the results of previously carried out LCA studies in wine sector, highlighting the role of pesticide application,
2. Understand how the emissions related to pesticide application are modelled and how different modelling choices affect the environmental results.

2. Materials and methods

2.1. Query and database

The manuscripts focused on the LCA applied to the wine sector, with particular emphasis on the impact related to the use of pesticides. Therefore, a literature review was conducted on Web of Science and Scopus databases.

2.1.1. Article selection criteria

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines provide a structured framework for reporting systematic reviews and meta-analyses, ensuring transparency and completeness (www.prisma-statement.org). A critical component of this framework is the 'Selection Criteria', which outline how studies are selected for inclusion in the review. This section is essential because it affects the validity and reliability of the results of the systematic review.

This study is part of the "Outcomes" methodology, identifying the outcomes of interest that the review intends to measure. These can be primary and secondary outcomes and must include details of how these outcomes are defined and measured. Specifically, articles on viticulture that have wine or grape production as a functional unit and report the field stage in the inventory or outcomes with a specific focus on pesticide application were reviewed.

2.1.2. Implementing PRISMA selection criteria

The literature review included the following steps:

1. **Identification** of the search criteria: To query the database, a number of keywords were identified ("vineyard", "grape", "wine" and "viticulture") associated with the words "life cycle assessment" or the acronym "LCA"; these keywords had to be present either in the title or in the abstract or in the keywords. Furthermore, it was chosen to only consider articles and literature reviews from 2012 published in English the query resulting from the above criteria is that represented in Table 1. From the databases search, 537 articles were found; before screening, 174 duplicate studies were removed

2. **Screening**: the query yielded 363 documents; after reading the abstracts, 276 were discarded as being of no interest to the present review because referring to other specific topics such as: studies on

Table 1-
Queries used for bibliographic research.

Query 1	((((ALL = ("lca" OR "life cycle assessment")) AND ALL = (grape OR wine OR vineyard OR viticulture)) AND PY = (2012–2025))) AND DT = (Article OR Review) AND LA = (English)
Query 2	((((ALL = ("LCA")) AND ALL = (grape OR wine OR vineyard OR viticulture)) AND PY = (2012–2025)) AND DT = (Article OR Review)) AND LA = (English)
Query 3	((((ALL = ("lca" OR "life cycle assessment")) AND ALL = (vineyard)) AND PY = (2012–2025))) AND DT = (Article OR Review) AND LA = (English)
Query 4	((((ALL = ("lca" OR "life cycle assessment")) AND ALL = (grape)) AND PY = (2012–2025))) AND DT = (Article OR Review) AND LA = (English)
Query 5	((((ALL = ("lca" OR "life cycle assessment")) AND ALL = (wine)) AND PY = (2012–2025))) AND DT = (Article OR Review) AND LA = (English)
Query 6	((((ALL = ("lca" OR "life cycle assessment")) AND ALL = (viticulture)) AND PY = (2012–2025))) AND DT = (Article OR Review) AND LA = (English)

the production of distillates or biodiesel, analyses of livestock, or energy uses of by-products.

3. **Analysis**: the remaining 87 articles analyzed and classified either as LCA studies (52 articles) or as 'useful' (35 articles).

2.2. Classification criteria for pesticide emission estimation models

LCA does not directly assess the emissions of pesticide active ingredients but rather the environmental impacts caused by these emissions that usually are estimated by models. These models used to estimate the emissions of pesticide active ingredients into air, water, and soil can be classified into two main categories: (i) detailed and (ii) simplified approaches.

2.2.1. Detailed models

Detailed models, such as Pest-LCI (Renaud-Gentié et al., 2015), PestLCI (Dijkman et al., 2012) and Pesticide Environmental Risk Indicator model (PERI) (Muhammetoglu et al., 2010), offer a comprehensive estimation of the fate of pesticides by considering both the physicochemical properties of the active ingredients (e.g., molecular weight) and a wide range of environmental and operational factors. These factors include climatic conditions (e.g., temperature, wind speed, solar radiation) and operational parameters (e.g., application techniques, canopy structure and density, proximity to water bodies). This approach allows for a more accurate representation of pesticide dispersion and behaviour.

2.2.2. Simplified models

On the other hand, simplified models, such as those outlined in the Product Environmental Footprint Category Rules PEFCR Pilot Phase Version 05.2 (2017), estimate emissions by applying a fixed distribution of the pesticide active principle between air, water, and soil, without considering the influence of specific climatic, environmental, or operational conditions. These models use generalized assumptions, which provide a more streamlined, though less precise, calculation of pesticide emissions. The supplementary materials provide further details on the assumptions and methodology behind these simplified approaches.

Unless than for arable crops (Rivera et al., 2017), in viticulture, no studies currently provide a direct comparison between simplified methods (e.g., PEFCR Pilot Phase Version 05.2, 2017) and detailed models (e.g., PestLCI 2.0) in terms of their influence on pesticide-related impact categories.

As noted by van den Berg et al., 1999and Wang and Rautmann (2008), the proportion of pesticide that does not reach the target (e.g., the canopy) is highly sensitive to the application technique, formulation, active ingredient, and environmental parameters. For this reason, comprehensive models like PestLCI 2.0, which explicitly account for these variables, are likely to generate more realistic emission estimates than simplified, generic approaches such as those proposed in PEFCR Pilot Phase Version 05.2, 2017. A more accurate estimation of emissions represents a prerequisite for obtaining reliable and meaningful impact assessment results (Christel et al., 2014).

Contrarily to simplified approaches that assume fixed emission fractions (e.g., 100 % to soil or pre-defined percentages across compartments) without considering site- or application-specific variability (Berthoud et al., 2011; Margni et al., 2002; Neto et al., 2013), detailed models such as PestLCI have been developed through an extensive scientific consensus process (Nemecek et al., 2022). In this context, the OLCA-Pest project was implemented to operationalise the assessment of pesticides in LCA; this process involved multiple expert and stakeholder workshops in Glasgow 2013, Basel 2014, Bordeaux 2015, and Dublin 2016 (Rosenbaum et al., 2015; Fantke et al., 2017; Nemecek et al., 2022). The result was the development of an operational, consensus-based version of PestLCI 2.0, integrated with the dynamiCROP model for plant uptake and USEtox for toxicity characterization. These developments provide a harmonized and scientifically robust solution for inventory and impact modelling of pesticide emissions in LCA.

Therefore, while simplified approaches may offer practicality, detailed models such as PestLCI 2.0 represent the most consensual, transparent, and scientifically validated option currently available for modelling pesticide emissions in LCA.

3. Results

3.1. Geographical and temporal distribution of the studies

Fig. 1 shows the geographical distribution of the reviewed LCA studies, 82 % were carried out in Europe, reflecting the continent's key role in wine production and consumption. This prominence is mirrored in the scientific literature, where countries like Italy, Spain, and France are at the forefront of wine-related research, as shown in Fig. 2. Italy, in particular, stands out with 46 % of the European LCA studies on wine sector.

The temporal distribution of LCA studies in viticulture (Fig. 3) shows how in the recent years the number of LCA studies in the wine sector is increasing, particularly between 2016 and 2021 (46 % of the total).

3.2. Functional unit and system boundary

The selection of the functional unit (FU) is key methodological step for each LCA, and it is affected by the selected system boundary.

Table 2 summarizes the main review results regarding the selection of FU and system boundary. The selected FUs were divided into volume-based, mass-based, and area-based. In general, the 0.75-l wine bottle is the most-commonly selected FU, appearing in 52.9 % of studies, consistently with the indication provided by the Product Category Rules (PCR) for wine, which indicate the volume of wine as the functional unit. Other frequently used FUs include mass-based units, such as tons or kilograms of grapes (39.2 % of studies), and area-based units, such as hectares of vineyard (7.9 % of cases).

Volume-based FUs, like the 0.75-l bottle, is the most selected FU when the LCA is carried out with a "from cradle to grave" perspective with system boundaries encompassing the entire life cycle of the wine—from raw material extraction to the end-of-life of the product. Also, when the system boundary includes the winemaking life stage volume-based FUs are the most common. In contrast, mass-based or area-based FUs are selected when the system boundaries focus considers a "from cradle to farm gate" approach. This last approach is the most applied when the goal of the study is to evaluate the environmental impacts associated with viticulture and initial processing phases of the wine supply chain.

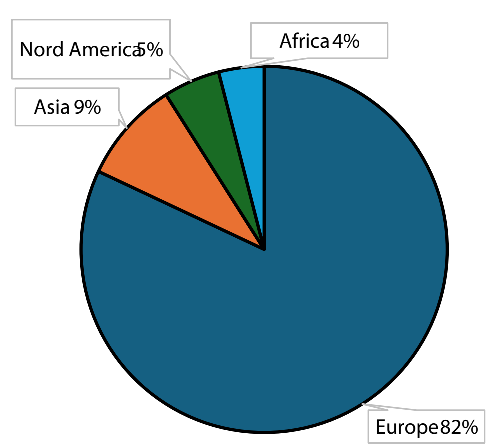

Fig. 1. Geographical distribution among the different continets of the reviewed LCA study.

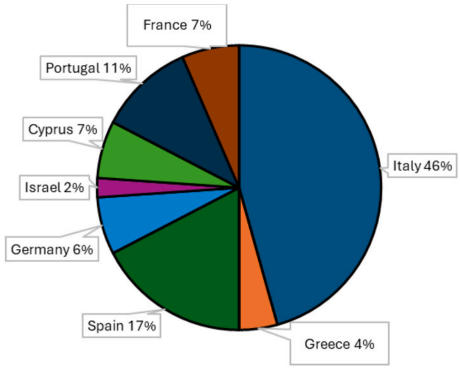

Fig. 2. Geographical distribution of the reviewed LCA study among the different european countries.

3.3. Inventory

In the reviewed LCA studies, the inventory is built using a combination of primary and secondary data. Primary data, directly collected by means of measurements, surveys and questionnaires, refers to inputs (such as fertilizers, pesticides, fuel, energy, machinery) consumption and grape and wine production. Secondary data is used to integrate primary data and includes information retrieved from literature, databases, or derived through estimations and assumptions. In the reviewed studies, the use of secondary data is more frequent in the modelling of grape cultivation and usually regards the emissions from pesticide and fertilizer application as well as the emissions related to fuel combustion during field operations. In particular, emissions from fertilizers and pesticides are estimated using available models, then the environmental impact is calculated using specific characterization factors.

Regarding the background data, both for cultivation steps and winemaking, as well as for the following life cycle stages, the most-commonly used databases for secondary data are Agribalyse® and Ecoinvent®.

3.3.1. Modelling pesticides emissions

Table 3 presents the key findings concerning both models (e.g., PestLCI) and estimation approaches proposed by authors (e.g., Margni et al.) for assessing pesticide emission in LCA studies. Out of the 52 reviewed studies, only 24 provided detailed information on the models used to estimate pesticide emissions. Among these, simplified approaches are the most common, representing 64 % of the cases, while detailed models account for 36 %.

In the reviewed studies, simplified approaches are the most utilized (15 out of the 24 studies).

3.4. Life cycle impact assessment (LCIA) methods

Fig. 4 shows the results regarding the use of the different Life Cycle Impact Assessment (LCIA) methods in the reviewed studies. In the period considered, ReCiPe and CML 2001 are the most frequently used, representing about 29 % and 17 %, respectively.

3.5. Sensitivity and uncertainty analysis

Regarding the analysis of sensitivity and uncertainty the results of the literature review are reported in the Supplementary Materials (Table S2). Sensitivity analysis is carried out in 40.8 % of the reviewed LCA studies while the uncertainty one only in 26.5 %.

About the parameters considered for the sensitivity analysis, a wide variability was observed. The crop yield, the amount of fertilizers and pesticides applied and the emissions related to fertilizer were the main considered parameters for sensitivity analysis of LCA studies focusing on grape production while, for studies considering also winemaking also the energy consumption and the type of bottle used were considered. Montecarlo analysis was the most applied with regard to the uncertainty analysis.

3.6. Environmental results

Despite the different reviewed studies present differences regarding LCA application and considerable heterogeneity about the selected functional unit, system boundaries, LCIA methods and evaluated impact categories, this section reports the main results concerning the impact on climate change and the contributions analysis. Besides this, the focus of the environmental impact related to pesticide applications is reported.

3.6.1. Global warming

The number of evaluated impact categories as well as their selection is one aspect that most varies among the different reviewed studies. Despite this, the impact on climate change is evaluated in all the studies.

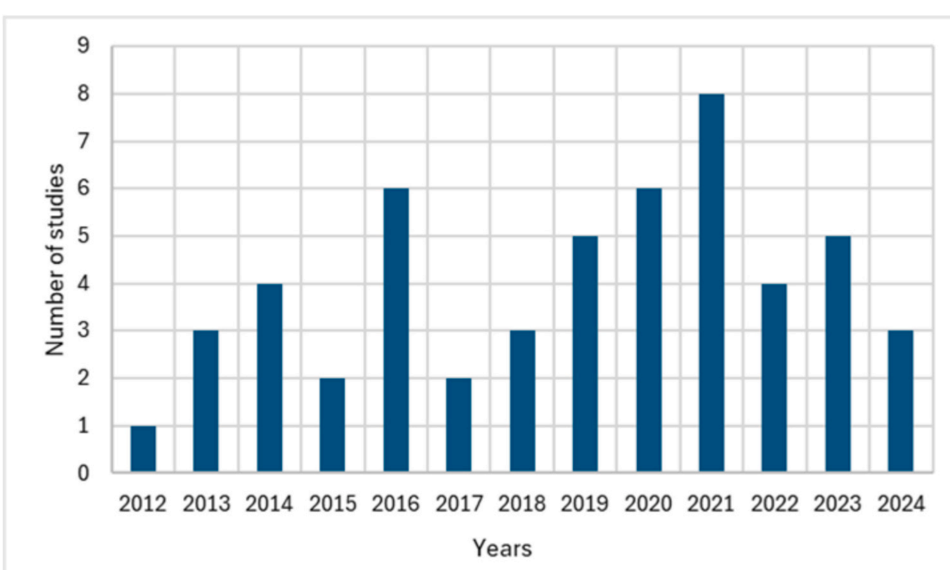

Fig. 3. Temporal distribution of the reviewed LCA studies.

Table 2
- Literature review results regarding functional unit and system boundaries.

Reference	Functional unit	System boundaries
Aoujil et al. (2024)	1 ha	From cradle to grave
Bartocci and Fantozzi (2017)	1 L of wine	From cradle to grave
Benedetto (2013)	0.75 L of wine	From cradle to winery gate
Bonamente et al. (2016)	0.75 L of wine	From cradle to farm gate
Borsato et al. (2019)	0.75 L of wine	From cradle to winery gate
Canaj et al. (2021)	1 ton of table grapes	From cradle to farm gate
Casson et al. (2022)	1 ha	From cradle to farm gate
Chiarico et al. (2019)	1 ha	From cradle to grave
D'Ammaro et al. (2021)	0.75 L of wine	From cradle to grave
Despoina et al. (2019)	1000 L of wine	From cradle to grave
Falcone et al. (2015)	1 ha	From cradle to farm gate
Falcone et al. (2016a)	1 kg of grapes	From cradle to grave
Ferrara and De Feo (2018)	566 ton of grapes	From cradle to grave
Frem et al. (2023)	10 ton of grapes	From cradle to farm gate
Fusi et al. (2014)	0.75 L of wine	From cradle to grave
García Castellanos et al. (2022)	1 kg of grapes	From cradle to farm gate
Gierling and Blanke (2021)	0.75 L of wine	From cradle to grave
Harb et al. (2021)	0.75 L of wine	From cradle to grave
Hefler and Kissinger (2023)	1 ton of grapes	From cradle to farm gate
Iannone et al. (2014)	0.75 L of wine	From farm gate to grave
Iannone et al. (2016)	0.75 L of wine	From farm gate to grave
Laca et al. (2021)	1 kg of wine grapes	From cradle to farm gate
Litskas et al. (2020a)	1 ton of grapes	From cradle to field gate
Litskas et al. (2020b)	0.75 L of wine	From cradle to winery gate
Litskas et al. (2017)	1 ton of grapes	From cradle to winery gate
Roselli et al. (2020)	1 ton of grapes	From cradle to farm gate
Martins et al. (2024)	1 ha	From cradle to farm gate
Martins et al. (2018)	0.75 L of wine	From gate to gate (winemaking and bottling)
Masotti et al. (2022)	0.75 L of wine	From cradle to winery gate
Meneses et al. (2016)	0.75 L of wine	From cradle to grave
Mohseni et al. (2018)	1 ton of wine grapes	From cradle to farm gate
Neto et al. (2013)	0.75 L of wine	From cradle to winery gate
Point et al. (2012)	0.75 L of wine	From cradle to grave
Ponstein et al. (2019)	0.75 L of wine	From cradle to winery gate
Quinteiro et al. (2014)	0.75 L of wine	From cradle to winery gate
Renaud-Gentié et al. (2020)	1 kg of grapes; 1 ha of vineyard	From cradle to field gate
Rinaldi et al. (2016)	0.75 L of wine	From cradle to grave
Rouault et al. (2016)	1 kg of grapes	From cradle to farm gate
Russo et al. (2021)	1 kg of grapes	From cradle to farm gate
Saraiva et al. (2020)	0.75 L of wine	From vineyard to bottle
Sinisterra-Solis et al. (2020)	1 kg of grapes	From cradle to gate
Steenwerth et al. (2015)	1 ton of wine grapes	From cradle to winery gate
Tascione et al. (2024)	1 kg of grapes	From cradle to farm gate
Tsarouhas and Papachristos (2021)	0.75 L of wine	From cradle to winery gate
Vagnoni et al. (2023)	0.75 L of wine	From cradle to farm gate
Vázquez-Rowe et al. (2013)	0.75 L of wine	From cradle to winery gate
Villanueva-Rey et al. (2014)	1.1 kg of grape	From cradle to farm gate
Vinci et al., (2022)	0.75 L of wine	From cradle to winery gate
Viveros Santos et al. (2023)	1 kg of grapes	From cradle to farm gate
Volanti et al. (2022)	1 ha	From cradle to farm gate
Wang et al. (2023)	1 ton of wine grapes	From cradle to farm gate
Zhang and Rosentrater (2019)	0.75 L of wine	From cradle to farm gate

Table 4 reports the results for the Global Warming Potential indicator in the different LCA studies considering the different selected functional units.

Table 4 offers an in-depth look at the Global Warming Potential (GWP) across various agricultural systems and practices in the wine industry, utilizing three different functional units (FU): per area (kg CO_2 eq/ha), per mass of grape (kg CO_2 eq/kg), and per volume of wine (kg CO_2 eq/0.75 L). In detail, the GWP ranges are:

Table 3
- Main review results regarding the modelling of pesticide emissions.

Reference	Model and/or bibliographic reference	Model classification
Aoujil et al. (2024)	PERI model (Pesticide Environmental Risk Indicator) (Muhammetoglu et al., 2010)	Detailed
Benedetto (2013)	Nemecek and Erzinger (2005)	Simplified
Canaj et al. (2021)	Margni et al. (2002)*	Simplified
Casson et al. (2022)	PEFCR for Still and Sparkling wine (2020)	Simplified
Falcone et al. (2015)	Margni et al. (2002)*	Simplified
Falcone et al. (2015)	Margni et al. (2002)*	Simplified
Ferrari et al. (2017)	Mackay model (Mackay, 2001)	Simplified
Frem et al. (2023)	Nemecek and Schnetzer (2011)*	Simplified
Fusi et al. (2014)	Margni et al. (2002)*	Simplified
Harb et al. (2021)	PEFCR ON WINE version 5.2 (2017)	Simplified
Litskas et al. (2020a)	PEFCR for Still and Sparkling wine (2020)	Simplified
Meneses et al. (2016)	**.	Simplified
Mohseni et al. (2018)	IPCC (2006)*	Semplified
Neto et al. (2013)	Audsley (1997); Hauschild et al. (2008); Margni et al. (2002); Milà i Canals (2003);*	Simplified
Renaud-Gentié et al. (2020)	PestLCI 2.0 (Dijkman et al., 2012)	Detailed
Roselli et al. (2020)	Mackay (2001)	Detailed
Rouault et al. (2016)	PestLCI 2.0 (Dijkman et al., 2012)	Detailed
Russo et al. (2021)	Nemecek and Schnetzer (2011)*	Simplified
Sinisterra-Solis et al., 2020	Margni et al. (2002)*	Simplified
Tascione et al. (2024)	Mackay's model (level I) (Mackay and Paterson, 1981)	Simplified
Vagnoni et al. (2023)	Nemecek and Kägi, 2007*	Simplified
Villanueva-Rey et al. (2014)	PestLCI dispersion method (Birkved and Hauschild, 2006)	Detailed
Viveros Santos et al. (2023)	PestLCI 2.0 (Dijkman et al., 2012)	Detailed
Volanti et al. (2022)	PestLCI 2.0 (Dijkman et al., 2012)	Detailed

[*] This study provides detailed information on the model adopted to estimate emissions associated with pesticide application.
[**] The copper run-off rate to water was estimated to be 0.01 % of the employed copper as pesticide.

- **Functional Unit - Area**: GWP ranges from 57.4 to 7206.5 kg CO_2 eq/ha, with an average of 2158.95 kg CO_2 eq/ha.
- **Functional Unit - Mass of Grape**: GWP varies from 0.060 to 1.540 kg CO_2 eq/kg grapes, with a mean of 0.33 kg CO_2 eq/kg.
- **Functional Unit - Volume of Wine**: GWP spans from 0.530 to 3.220 kg CO_2 eq/ 0.75 L of wine, averaging 1.33 kg CO_2 eq/0.75 L.

Organic and biodynamic systems often show a lower GWP than conventional systems, suggesting a reduced impact on climate change due to a lower consumption of synthetic inputs (fertilizers in particular). García Castellanos et al. (2022) reported that organic vineyards with rainfed cultivation shows a GWP of 0.16 kg CO_2 eq/kg of grapes, compared to 0.25 kg CO_2 eq/kg for conventional, rainfed systems. Similarly, Rouault et al. (2016) found that organic systems produce 0.30 kg CO_2 eq/kg of grapes, which is less than the 0.36 kg CO_2 eq/kg observed in conventional vineyards. Moreover, Villanueva-Rey et al. (2014) highlighted even more pronounced differences in biodynamic versus conventional systems, with the former showing GWPs as low as

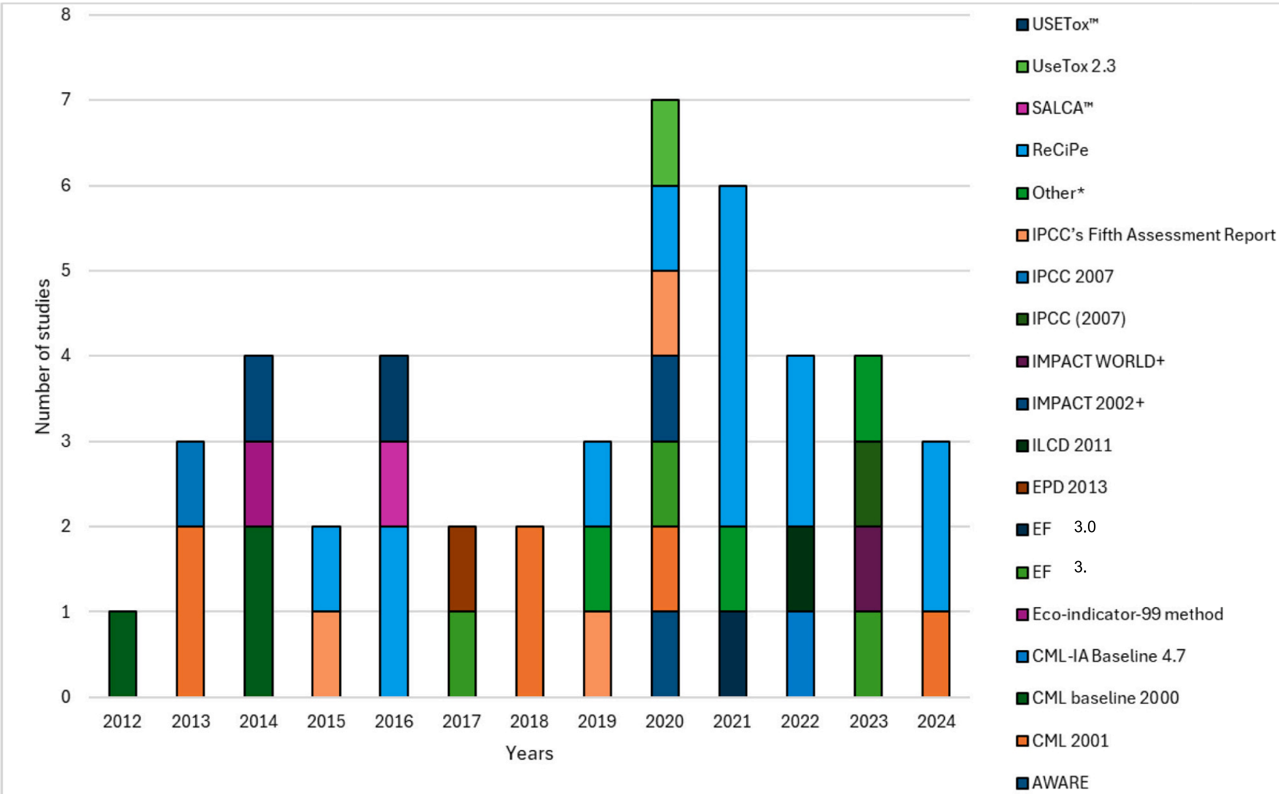

Fig. 4. LCIA methods used over the time.

0.08 kg CO_2 eq/kg of grapes in 2010, significantly lower than the 0.37 kg CO_2 eq/kg for conventional grapes in the same year.

GWP presents geographic variability being affected by climatic conditions, soil characteristics, and specific management practices. Steenwerth et al. (2015) pointed out that such regional variations are evident in California where GWP varies from 0.20 kg CO_2 eq/kg in Lodi to 0.46 kg CO_2 eq/kg of grapes in Napa. These findings underscore the importance of considering both the type of agricultural system and the specific regional conditions when assessing the environmental sustainability of viticultural practices.

Fig. 5 shows the variation of GWP for 1 ton of grape and 0.75 l of wine across three geographical area: Italy (ITA), Rest of Europe (ReR) and the Rest of the World (RoW). The data is presented using boxplots, which illustrate the variability through interquartile ranges, mean values (marked by "X"), and the upper and lower extremes.

The GWP for the Rest the World (RoW) shows the highest average values compared to Italy and the Rest of Europe, considering both the mass of grapes and the volume of wine as functional unit. Besides this, RoW GWP presents also a huge variability. This variability suggests that the cultivation practices as well as the growing conditions in this area are very different.

In contrast, Italy shows the lowest average GWP among the three regions. The reduced variability compared to RoW indicates greater uniformity in the cultivation practices and productive performances. This is the result of consistent technological standards, regulatory frameworks or widespread adoption of sustainable practices in the Italian wine sector.

The Rest of Europe (ReR) presents an average GWP higher than in Italy (+39 %) but lower than RoW (−37 %) with a moderate degree of variability.

The differences observed among the three functional units (per hectare, per kilogram of grapes, and per 0.75 l of wine) stem from the distinct phases and aspects each unit considers within the production process. The **area-based unit (kg CO_2 eq/ha)** primarily reflects emissions linked directly to agricultural practices such as fertilization, soil management, and phytosanitary treatments, without accounting for vineyard productivity. In contrast, the **mass-based unit (kg CO_2 eq/kg grapes)** introduces vineyard productivity, highlighting how higher-yielding systems typically show lower GWP values per kilogram of grapes even when emissions per hectare remain unchanged. Lastly, the **volume-based unit (kg CO_2 eq/0.75 L wine)** incorporates additional stages, including winemaking processes, bottling, transportation, and distribution. Consequently, regions or wineries with higher efficiency in grape-to-wine conversion and optimized logistics and packaging tend to present lower GWP per unit volume of wine produced.

This distinction underscores the importance of clearly defining the functional unit when evaluating and comparing environmental impacts, as each captures different aspects of sustainability within viticulture and wine production.

3.6.2. *Contribution analysis*

The environmental impact distribution across the wine life cycle phases varies due to differences in functional units, system boundaries, and LCIA methods. However, contribution analysis reveals some common trends. When system boundaries include winemaking, packaging, and distribution, glass bottle production is the main contributor for all the impact categories, except those directly linked to fuel consumption and nutrient emissions during grape cultivation. Fusi et al. (2014), Vinci et al. (2022), and Harb et al. (2021) underlined the significant role of glass bottle production, particularly in categories like acidification (up to 30 %) and resource depletion (around 25 %). For global warming potential (GWP), the bottle can contribute up to 40 % of the total impact. Zhang and Rosentrater (2019) pointed out that lighter bottles or alternative packaging materials CO2 emissthe environmental footprint by up to 20 %. Even though the energy consumption during winemaking plays a non-negligible role, bottle production often takes the largest share of the environmental burden.

Besides packaging, grape cultivation also stands out as a critical stage

Table 4
GWP results in the different reviewed studies.

Reference	System boundaries	FU Area kg CO_2 eq/ ha	FU Mass of grape kg CO_2 eq/ kg	FU Volume of wine kg CO_2 eq/ 0.75 L	Note (e.g., location and/or climatic conditions, cultivar, cultivation practice, type of the wine produced)
Bartocci and Fantozzi (2017)	From cradle to grave		0.47	1.46	Cultivar Sagrantino
			0.31	1.91	Cultivar Grechetto
Benedetto (2013)	From cradle to gate			1.64	
Bonamente et al. (2016)	From cradle to farm gate		0.27	1.07	
Canaj et al. (2021)	From cradle to farm gate	7206.50	0.31		Conventional
Canaj et al. (2021)	From cradle to farm gate	5349.10	0.26		Integrated
		3074.00			HWS *[1]
		1824.75			HCS *[2]
Casson et al. (2022)	From cradle to farm gate	3213.11			UrDWS *[3]
		1632.68			UrDCS *[4]
		2754.00			VrDWF *[5]
Casson et al. (2022)	From cradle to farm gate	1286.24			VrDCS *[6]
Chiarico et al. (2019)	From cradle to grave			0.80	
D'Ammaro et al. (2021)	From cradle to grave			1.47	
Falcone et al. (2015)	From cradle to farm gate	2466.62			Organic-Espalier
		2438.24			Conventional Espalier
Falcone et al. (2015)	From cradle to farm gate	2612.72			Organic Gobelet
Falcone et al. (2015)	From cradle to farm gate	2641.78			Conventional Gobelet
Ferrara and De Feo (2018)	From cradle to grave		0.06		
		3383.41			VCWNO *[7]
		1282.81			VCWO *[8]
		2464.45			VQWNO *[9]
Frem et al. (2023)	From cradle to farm gate	1630.70			VQWO *[10]
Fusi et al. (2014)	From cradle to gate		0.17	1.01	
García Castellanos et al. (2022)	From cradle to gate		0.16		Organic, rainfed
			0.25		Conventional, rainfed
Gierling and Blanke (2021)	From cradle to grave			1.91	Winery A white wine
				1.69	Winery B white wine
				1.86	Winery A red wine
				1.86	Winery B red wine
Harb et al. (2021)	From cradle to grave		0.45	0.98	
Hefler and Kissinger (2023)	From cradle to farm gate		0.36		Arid
			0.32		Semi-arid
			0.35		Mediterranean region
Iannone et al. (2014)	From gate to grave			0.68	White of High Quality
				0.53	White of Medium Qualit)
				1.58	Red of High Quality
				0.75	Red of Medium Quality
Laca et al. (2021)	From cradle to farm gate		1.54		
Litskas et al. (2017)	From cradle to winery gate		0.28		
Litskas et al. (2020a)	From cradle to gate			1.31	
Roselli et al. (2020)	From cradle to gate		0.29		
Martins et al. (2018)	Production phase of vine grapes			1.72	
Masotti et al. (2022)	From cradle to winery gate			0.70	
Mohseni et al. (2018)	From cradle to farm gate		0.51		
Neto et al. (2013)	From cradle to gate		2	2.68	
Point et al. (2012)	From cradle to grave		0.81	3.22	
Ponstein et al. (2019)	From cradle to gate			0.83	
Renaud-Gentié et al. (2020)	From cradle to field gate	976.67			
Rouault et al. (2016)	From cradle to gate		0.36		Conventional
			0.30		Organic
Russo et al. (2021)	From cradle to farm gate		0.46		
Saraiva et al. (2020)	From vineyard to bottle			0.29	Localizated in Leziria do Trejo *[11]
				0.43	Localizated in Alantejo *[11]
Sinisterra-Solís et al., (2020)	From cradle to gate		0.11		Conventional, spur-pruned bush vine, non-irrigated, Tempranillo Base model (BM)*[12]
			0.081		Conventional, spur-pruned bush vine, non-irrigated, Tempranillo Alternative model (AM)*[13]
			0.25		Conventional, double Guyot with trellis, irrigated, Bobal Base model (BM)
			0.23		Conventional, double Guyot with trellis, irrigated, Bobal Alternative model (AM)
			0.32		Conventional, double Guyot with trellis, irrigated, Tempranillo Base model (BM)
			0.31		Conventional, double Guyot with trellis, irrigated, Tempranillo Alternative model (AM)

(*continued on next page*)

Table 4 (*continued*)

Reference	System boundaries	FU Area kg CO_2 eq/ha	FU Mass of grape kg CO_2 eq/kg	FU Volume of wine kg CO_2 eq/0.75 L	Note (e.g., location and/or climatic conditions, cultivar, cultivation practice, type of the wine produced)
			0.068		Organic, spur-pruned bush vine, non-irrigated, Tempranillo Alternative model (AM)
			0.053		Organic, spur-pruned bush vine, non-irrigated, Bobal Alternative model (AM)
			0.096		Organic, spur-pruned bush vine, non-irrigated, Tempranillo Base model (BM)
			0.067		Conventional, spur-pruned bush vine, non-irrigated, Bobal Alternative model (AM)
			0.092		Organic, double Guyot with trellis, irrigated, Bobal Base model (BM)
			0.08		Organic, double Guyot with trellis, irrigated, Bobal Alternative model (AM)
			0.078		Organic, spur-pruned bush vine, non-irrigated, Bobal Base model (BM)
			0.093		Conventional, spur-pruned bush vine, non-irrigated, Bobal Base model (BM)
			0.11		Organic, double Guyot with trellis, irrigated, Tempranillo Alternative model (AM)
			0.13		Organic, double Guyot with trellis, irrigated, Tempranillo Base model (BM)
Steenwerth et al. (2015)	From cradle to winery gate		0.46		Localizated in Napa *12
			0.20		Localizated in Lodi *12
Tascione et al. (2024)	From cradle to farm gate		0.29		Smart (DSS)
			0.43		Smart (DSS)
			0.61		Smart (DSS)
			0.28		Traditional (No DSS)
Vagnoni et al. (2023)	From cradle to farm gate			1.20	
Vázquez-Rowe et al. (2013)	From cradle to winery gate			1.61	
Villanueva-Rey et al. (2014)	From cradle to farm gate		0.08		Biodinamic 2010
			0.06		Biodinamic 2011
			0.14		Biodinamic-Conventional 2010
			0.07		Biodinamic-Conventional 2011
			0.37		Conventional 2010
			0.28		Conventional 2011
Vinci et al. (2022)	From cradle to winery gate		0.29	0.84	
Volanti et al. (2022)	From cradle to farm gate	438.30			Scenario A1 *13
	From cradle to farm gate	475.90			Scenario A2 *14
	From cradle to farm gate	57.40			Scenario B1 *15
	From cradle to farm gate	289.30			Scenario B2 *16
	From cradle to farm gate	481.00			Scenario C1 *17

*1 HWS: Hose reel irrigation with water from a well and a fertilizer spreader. *2 HCS: Hose reel irrigation with water provided by a consortium and a fertilizer spreader. *3 UrDWS: Uniform-rate drip irrigation with water from a well and a fertilizer spreader. *4 UrDCS: Uniform-rate drip irrigation with water provided by a consortium and a fertilizer spreader. *5 VrDWF: Variable-rate drip irrigation with water from a well and fertigation. *6 VrDCS: Variable-rate drip irrigation with water provided by a consortium and fertigation. *7 VCWNO: Vine grapes cultivated for quality wine production based on non-organic agricultural practices. *8 VCWO: Vine grapes cultivated for common wine production based on organic agricultural practices. *9 VWQNO: Vine grapes cultivated for quality wine production based on non-organic agricultural practices. *10 VQWO: Vine grapes cultivated for quality wine production based on organic agricultural practices, according to FADN data. *11 Alantejo has higher average temperatures and lower rainfall than Leziria do Trejo. 12 * BM (*Baseline Modelling*) refers to the use of standard or generic data to estimate environmental impacts. 13*: AM (*Alternative Modelling*) involves the use of more specific, site-related data to produce more accurate and localized impact estimates. *14 The regional comparison shows that in Napa, energy use, GWP, and water use are significantly higher than in Lodi, with substantial differences per metric ton and per hectare. Hand harvesting and lower yields in Napa, reflecting the higher quality of the grapes, explain these elevated figures. The results highlight how regional differences in management goals, soil, and climate affect the environmental impact of viticulture, especially where lower yields are targeted. * 15 Scenario A1: Including extraction and transformation of diesel and chemical additives in a rainfed scenario. *16 Scenario A2: Including extraction and transformation of diesel, chemical additives, and water in an irrigated scenario. *17 Scenario B1: Including extraction and transformation of diesel, chemical additives, and water with fertilizers used. *18 Scenario B2: Extraction and transformation of diesel and water with animal manure to replace fertilizers. *19 Scenario B3: Including extraction and transformation of diesel, chemical additives, and water.

in the wine life cycle. Fuel consumption during vineyard operations, particularly for planting, pesticide application, and pruning, significantly contributes to the environmental impact of wine. According to Benedetto (2013) and Fusi et al. (2014), this life cycle stage is responsible for about 30 % of GWP, while in the study carried out by Harb et al. (2021), grape cultivation is responsible for 20–25 % of the impact for ozone layer depletion, eutrophication, and acidification, and 90 % of water resource depletion. Vagnoni et al. (2023) pointed out that the cultivation step is a key contributor for all the impact categories affected by the emissions of nutrients (acidification, eutrophication, and particulate matter) or pesticide active ingredients (toxicity-related impact categories.

3.6.3. Pesticide application impact

Among the different field operations carried out during the cultivation, pesticide application is one of the most environmentally impactful (Canaj et al., 2021). The control of fungal diseases such as downy mildew (Plasmopara viticola) and powdery mildew (Uncinula necator) requires constant monitoring and several pesticide applications (Rossi et al., 2024). These applications affect the environmental impact mainly due to the mechanization of pesticide applications, the consumption of pesticides (whose manufacturing is energy-intensive), and the emissions of active ingredients into air, water, and soil (Russo et al., 2021; Falcone et al., 2016a).

The mechanization of pesticide application involves significant

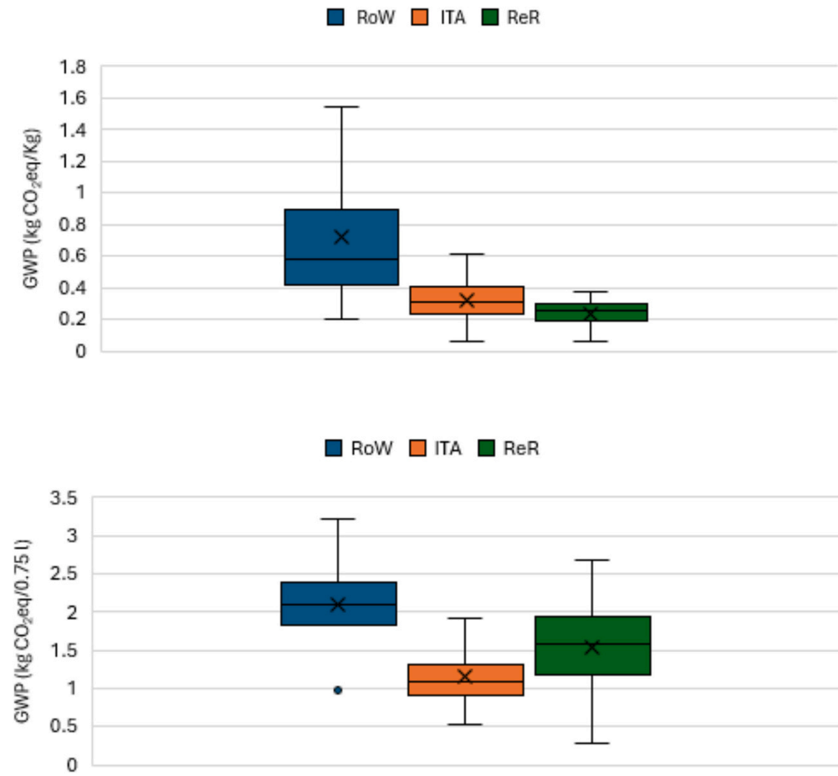

Fig. 5. GWP for 1 kg of grapes (on the top) and 0.75 l of wine (on the bottom) across different regions (RoW, ITA, ReR).

environmental impacts largely due to diesel consumption and the related emissions from tractor engines. According to Renaud-Gentié et al. (2020), diesel combustion—related to soil, canopy, and disease management—is identified as the main contributor to several environmental impact categories, including climate change, ozone depletion, photochemical oxidants, particulate matter, water depletion, and fossil depletion. Since disease management (phytosanitary treatments) typically requires frequent machinery passes throughout the growing season, an increase in pesticide treatments directly results in greater diesel consumption, thus amplifying associated environmental impacts.

Pesticide production encompasses various processes, including extraction and processing of raw materials, chemical synthesis, packaging, and transportation. These energy-intensive stages contribute significantly to global warming potential and resource depletion (Falcone et al., 2016b). Specifically, copper production used in fungicide formulations for disease management notably contributes to freshwater eutrophication, terrestrial ecotoxicity, marine ecotoxicity, and metal depletion (Renaud-Gentié et al., 2020). Additionally, Litskas et al. (2020a) highlighted that sulfur production (used extensively in organic vineyard systems) is a major contributor to environmental impacts, particularly regarding resource use-energy carriers (MJ), with increasing impacts in organic vineyards compared to conventional ones. The same authors also emphasized that sulfur production in organic vineyards significantly contributes to freshwater ecotoxicity (CTUe). Casson et al. (2022) quantified that pesticide production accounted, on average, for approximately 10 % of the total environmental impact within cradle-to-gate system boundaries, predominantly affecting global warming potential, depletion of non-renewable resources, and human toxicity due to the chemical composition of pesticides.

The emission of pesticide active ingredients into the environment can affect several impact categories. These emissions increase terrestrial and aquatic toxicity, as well as photochemical ozone formation. The emission of copper-based pesticide active ingredients affects soil toxicity. Falcone et al. (2016a) and Vagnoni et al. (2023) highlight that pesticide use during cultivation affects impact categories such as toxicity, eutrophication, and particulate formation. According to Litskas et al. (2020a) and Aoujil et al. (2024), pesticide emissions can account for up to 99 % of the impact on freshwater ecotoxicity.

The variability in reported impacts due to pesticide applications across different studies often reflects methodological differences in LCIA methods and the definitions of system boundaries. For example, studies employing the ReCiPe method offer a more comprehensive environmental assessment by including both midpoint and endpoint indicators. This methodological inclusiveness allows for a broad evaluation of impacts, ranging from direct emissions to ultimate environmental consequences. In contrast, the CML 2001 method specifically focuses on ecotoxicity, particularly emphasizing impacts on aquatic ecosystems. This focus results in a heightened emphasis on toxicity categories, aligning the study's outcomes closely with concerns about ecological health. Such methodological choices significantly influence the framing and conclusions of LCA studies, as they determine which environmental impacts are highlighted or downplayed.

4. Discussion and future perspectives

The application of LCA in the wine sector has provided valuable insights into the environmental impacts associated with grape cultivation and wine production. However, some methodological gaps and limitations are still present, and future research must address these challenges to enhance the robustness and applicability of LCA in this sector.

One significant limitation lies in the choice between simplified and detailed models for estimating emissions, particularly from pesticide applications. Simplified models offer a quick and accessible means to build inventories, relying on broad assumptions and generalized data. These models are favored for their simplicity and broad applicability, especially when site-specific data, which is often required for detailed models, is either unavailable or too costly to obtain. Despite their usefulness for large-scale assessments and when resources are limited, they fail to capture the specific environmental conditions and application practices unique to individual vineyards. As a result, they may produce estimates with significant uncertainties, which can affect the accuracy of environmental impact assessments. The complexity and variability of pesticide emissions—affected by factors such as the chemical properties of substances, soil composition, weather conditions, and application methods—make direct measurement challenging, time-consuming, and often impractical.

Detailed models, such as PESTLCI 2.0 or the PERI model, provide more precise and context-specific estimations by incorporating a wide range of variables, including soil properties, climate, and specific pesticide application methods. However, these models are resource-intensive, requiring high-quality data, advanced computational tools, and specialized knowledge. Their complexity can limit their use, particularly in routine assessments or in contexts where such resources are unavailable.

Europe is not only the area where some of the most renowned wine-producing regions are located, but it also leads in terms of vineyard area and wine consumption. According to the International Organisation of Vine and Wine (OIV), Europe accounts for nearly 45 % of the world's vineyard area and over 60 % of global wine consumption.

Despite the development of new LCIA methods, there is no strict correlation between the year of publication and the adoption of a specific method, suggesting that researchers prioritize methodological continuity and comparability over the adoption of newer but less applied LCIA methods. Furthermore, the continued use of older methods such as IMPACT 2002+ and Eco-indicator 99 reflects a preference for familiarity and methodological robustness, which may outweigh the appeal of newer methods. This trend underscores the careful consideration researchers give to methodological choice, influenced by study-specific objectives, environmental impact categories, and possibly regional or institutional preferences. The data suggests that while there is an openness to innovation, the priority remains on maintaining methodological rigor and ensuring the comparability of results across studies. This nuanced approach highlights the importance of established methods in achieving reliable and reproducible outcomes in environmental assessments, and it raises important questions about how the field balances innovation with the need for consistency and robustness in life cycle assessment methodologies.

Regardless of the selected functional unit, the GWP variability is always remarkable. This variability depends on fertilizer applications, pest control methods, and technological efficiency in vineyards and wineries. Each decision along the production chain, from the type of grape grown to the methods of processing and transportation, plays a critical role in determining the wine production impact on global warming. Moreover, the adoption of Decision Support Systems (DSS) shows potential for reducing CO_2 emissions, as evidenced by the varied values between traditional methods and those incorporating DSS (Tascione et al., 2024).

The GWP results underline the importance of agricultural management choices and technology adoption in mitigating the environmental impact of viticulture. It provides critical insights for further research and the implementation of more sustainable practices in the sector. Another area for future improvements is the consideration of emerging environmental concerns and sustainability metrics that are not fully addressed by current LCA methodologies. Issues such as biodiversity loss, soil health, and social sustainability are increasingly important but are often underrepresented in traditional LCA frameworks. Incorporating these factors into LCA models will provide a more holistic view of the sustainability of viticulture practices.

This variability emphasizes the importance of fostering sustainable practices and integrating innovative technologies. Italian viticulture, for instance, benefits from a convergence of sustainable agricultural approaches, favorable climatic conditions, and rigorous environmental regulations. These elements collectively create a model for a more sustainable viticultural system. Organic and biodynamic farming practices, widely adopted in Italian vineyards, reduce dependency on synthetic chemicals, thereby effectively lowering greenhouse gas emissions. These practices not only align with traditional agricultural methods but also enhance biodiversity and soil health, both of which are crucial for ecological stability and climate resilience.

Recent evidence shows that the implementation of digital agriculture tools, such as variable-rate applications and predictive disease management systems, can significantly reduce the environmental impact of viticulture, particularly in the farm stage (Rossi et al., 2024).

Similarly, the integration of canopy digital twin models with precision spraying technologies has shown to reduce pesticide use by up to 50 %, demonstrating clear benefits in terms of environmental performance and input efficiency (Sarri et al., 2024).

Regulatory frameworks in Italy and across the European Union play a significant role in guiding environmental sustainability within the wine sector. These regulations impose strict standards on CO_2 emissions, waste management, and resource utilization, fostering the adoption of low-impact practices across the industry (OIV, 2023).

Family-run vineyards, which dominate the Italian wine landscape, often employ less industrialized production methods, blending traditional techniques with modern innovations. This approach not only supports the competitiveness of these smaller operations but also helps maintain lower carbon footprints and fosters a sustainable business model (OIV, 2023).

In summary, Italian viticulture exemplifies how traditional practices, modern technological innovations, and stringent regulatory standards can converge to reduce the carbon footprint and enhance sustainability. This integrated approach not only preserves the heritage and quality of Italian wine but also positions it as a global leader in environmental stewardship. Italian wine production serves as a model for other regions, demonstrating how the wine industry can effectively address climate change and promote long-term ecological balance without compromising economic viability.

Finally, the integration of LCA with other sustainability assessment tools could offer a more comprehensive evaluation of viticulture practices. For instance, combining LCA with economic assessment or social LCA could provide a multi-dimensional perspective on the sustainability of wine production. Such an integrated approach would allow for simultaneous consideration of environmental, economic, and social impacts, leading to more informed and balanced decision-making.

In addition, future research should explore the application of dynamic LCA approaches, which incorporate temporal variability into the assessment of environmental impacts. Unlike conventional static models, dynamic LCA can account for changes over time in factors such as agricultural practices, climatic conditions, and technological developments. This is particularly relevant in viticulture, where long-term processes and seasonal dynamics significantly influence sustainability outcomes. As highlighted by Levasseur et al. (2010), incorporating time into LCA provides a more realistic representation of emissions and resource use across the life cycle, enhancing the robustness and applicability of the results.

In summary, while LCA is a powerful approach for assessing the environmental impacts of viticulture, its application is currently limited by several factors, including the choice of models, data availability, and the adaptability of existing databases. Addressing these challenges through methodological advancements, enhanced data collection, and the incorporation of new sustainability metrics will be key to improving the utility and accuracy of LCA in viticulture. As the field evolves, a more dynamic, region-specific, and integrated approach to LCA will be necessary to fully capture the complexities and nuances of sustainable viticulture practices.

5. Conclusions

The environmental impacts of the wine industry, particularly those associated with pesticide application in viticulture, are significant and multifaceted. Pesticide application notably affects key impact categories, including ecotoxicity in freshwater and soil, human health, and resource depletion. The use of copper-based pesticides exacerbates soil and marine ecotoxicity, while pesticide runoff contributes to water pollution and eutrophication. Additionally, pesticide production and application involve considerable energy consumption, contributing to global warming potential and resource depletion.

The literature review highlighted the importance of Life Cycle Assessment (LCA) in understanding and finding potential mitigating solutions for these impacts. Although few studies directly address pesticide emissions' contribution, the available data consistently identify pesticides as a major contributor to environmental harm in viticulture. The comparison between simplified and detailed emission models emphasizes a trade-off between generalization and precision. Simplified models provide accessible, large-scale estimates but lack accuracy in specific contexts, whereas detailed models offer precise assessments tailored to local conditions but require extensive data and resources.

To address the environmental challenges posed by pesticide use in viticulture, a balanced approach that combines insights from both simplified and detailed models is needed. Such integration can inform effective decision-making, promote sustainable agricultural practices, and align viticulture with broader environmental sustainability goals, including those set by the European Green Deal and the Farm to Fork Strategy. Reducing chemical inputs, enhancing biodiversity, and adopting integrated pest management (IPM) are crucial steps toward minimizing the wine industry's ecological footprint and ensuring its long-term sustainability.

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 data to this article can be found online at https://doi.org/10.1016/j.eiar.2025.108022.

Data availability

Data will be made available on request.

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