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Organic vs. conventional wine production: a comparative multi-year environmental LCA study in central Italy

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ABSTRACT

Comparative assessments of organic and conventional wine have reported divergent results and are largely based on single production years. This study evaluates and compares the environmental impacts of a 0.75 L bottle of conventional and of organic wine over three consecutive years. Using Life Cycle Assessment, the analysis covers all phases from raw material production to the farm gate. Primary data were collected from an Italian winery for 2022–2024, years with different climatic conditions, levels of field operations and grape yields. On average, the organic bottle shows higher impacts than the conventional one in 14 out of 18 impact categories considered. Differences are modest but systematic and mainly reflect more field operations, higher diesel use and lower yields in the organic vineyard. In both systems, glass bottle production is the dominant hotspot in most of the impact categories.

Organic viticulture shows a clear advantage in terrestrial ecotoxicity, due to the absence of specific synthetic fungicides. For marine ecotoxicity and human non-carcinogenic toxicity, differences are marginal, indicating broadly comparable performance. The comparison further shows that the gap between systems varies with climatic conditions, input profiles and yields, with rainier years associated with more field operations but not necessarily with higher impacts when management is adjusted. Overall, neither production system is environmentally superior across all impact categories. Organic management improves toxicity-related indicators but performs worse in climate- and resource-related categories, while conventional management shows the opposite pattern, highlighting the value of multi-year, multi-indicator LCAs to capture trade-offs in viticulture.

1. Introduction

Wine production is among the oldest economic activities, and it remains one of the most significant agricultural sectors worldwide (Ferrara and De Feo, 2018; Vinci et al., 2022). Historically, winemaking has been concentrated in Europe, particularly in Italy, France, and Spain (Iannone et al., 2016). Indeed, in accordance with data reported by the International Organization of Vine and Wine in 2023 (OIV Report, 2024), vinified production of the European Union is estimated at 144.5 million hectolitres and France (48 million hectolitres), Italy (38.3 million hectolitres), and Spain (28.3 million hectolitres) continue to dominate as the leading wine-producing countries, in the Northern Hemisphere. These nations are also the 2023 top wine exporters in the world, with Italy exporting 21.4 million hectolitres, followed by Spain (20.8 million hectolitres) and France (12.7 million hectolitres). These three countries generated, in 2023, a total economic value of 22.5 billion euros, representing 63% of the total global export value.

While it is well known that the wine sector plays a crucial role in the economy and society (Trigo et al., 2022), it is less known that wine production, as well as agriculture sector in general, impacts negatively on the environment and it is also a victim of the environmental crisis (Martucci et al., 2019; Colman and Päster, 2009). In fact, by analyzing OIV data, it is possible to notice a wine production decrease in Europe in 2023, compared to 2022, due to climatic events such as early frost, heavy rainfall and drought (OIV Report, 2024). Thus, given also the increasing awareness among consumers, about environmental issues, influencing their purchasing decisions (Benedetto, 2013), it is important to evaluate winemaking from the environmental point of view as well

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(Ferrara and De Feo, 2018).

The Environmental Life Cycle Assessment (E-LCA) methodology is the tool to identify and assess the environmental impacts throughout the entire life cycle of a product, process, or service. Over the years, several LCA studies have been carried out to identify and quantify the environmental impacts of the wine-growing sector. Most of them point out that the main environmental burdens are associated with the production of the glass bottle (Fusi et al., 2014; García et al., 2023; Mura et al., 2024) and the viticulture process (Iannone et al., 2016; Sinisterra-Solís et al., 2020; Vagnoni et al., 2024). Hence, it is necessary to identify alternative solutions that make wine-growing farms more sustainable from an environmental and not only an economic perspective. Regarding the packaging, there are studies that have carried out LCA analyses to explore less environmentally impactful alternatives (Cleary, 2013; Postacchini et al., 2018; Csiba-Herczeg et al., 2023; Ferrara et al., 2023). Instead, regarding viticulture, organic production is often indicated as the best solution to mitigate and reduce environmental impacts that come from conventional production (Borsato et al., 2020; Sinisterra-Solís et al., 2020; Vagnoni et al., 2024). The organic production is a system that aims to produce food with the minimal damage to the environment, animals or humans, by avoiding - or minimizing - the use of synthetic fertilizers, pesticides and growth regulators, and using crop residues, animal and green manures and mineral stones to maintain maximum soil productivity (Volanti et al., 2022; Homet et al., 2024). This farming system is considered to be more suitable for the conservation of the resources and the soil quality (Venkat, 2012) and it can increase biodiversity and promote the maintenance and improvement of ecosystem services, such as carbon stock in soil and related fauna (Borsato et al., 2020). In fact, the European Union has set a target of having at least 25% of agricultural land under organic management by 2030 (European Commission, 2020). Despite all these positive aspects, organic viticulture practices may not lead to a reduction of the carbon footprint. This can be due to several factors, such as a lower production yield, a reduced ability to resist some pests and diseases, the possible increase in the consumption of fossil fuel, and the transport of a large amount of manure and organic fertilizers (Boschiero et al., 2023; Ghiglieno et al., 2023). However, the evidence on this point remains difficult to reconcile: most of the available comparisons rely on a single production year and adopt heterogeneous functional units, so that it is still unknown whether the difference between the two systems is stable across seasons.

This study aims to perform an E-LCA to evaluate whether organic agricultural practices provide environmental advantages over conventional ones, based on a three-year assessment (2022–2024) that captures substantial interannual variability in climatic conditions, disease pressure, and vineyard management needs. By comparing the conventional and organic farming systems of an Italian winery over multiple seasons, this analysis identifies their respective environmental burdens and determines which system delivers superior environmental performance. This study is not intended to be an additional isolated example, but rather a targeted contribution designed to fill a recognized gap by providing a rigorously executed, multi-year analysis using a standardized LCA approach.

2. Literature review

Different E-LCA studies have been conducted to quantify the environmental impacts of winemaking sectors and identify their main environmental hotspots. Iannone et al. (2016) analyzed the winemaking phase of a red and a white wine and two qualities (high and medium) to assess the environmental impact of a 0.75 L bottle. Rinaldi et al. (2016), instead, took into consideration all phases from grape production to the marketing of the final product and calculated the carbon and water footprints of the wine industry. Then, Panizzon et al. (2024) compared the white and red wine traditional production in Brazil, again using a 0.75 L bottle as the functional unit and focusing solely on operations within the company's boundaries. All of them report that the production of red wine has higher environmental impacts compared to white wine production, especially due to the higher electricity consumption required for the higher fermentation temperature and a longer aging period associated with red wine.

Several studies have analyzed wine production without focusing specifically on the type of wine, but concentrating on the farming systems used. For instance, Benedetto (2013) and Fusi et al. (2014) analyzed wine production from conventional grapes, while Letamendi et al. (2022), Mura et al. (2023), and Vagnoni et al. (2024) focused on the wine production from organic grapes. Some studies have compared wine production using grapes grown with organic methods versus those grown with conventional methods. In particular, Pizzigallo et al. (2008) used a combination of emergy and LCA to compare organic and conventional farming systems at a winery in Siena, Italy. This analysis considered 1 mt of final product (bottled wine) and covered all stages from planting to glass recycling. Point et al. (2012) conducted a study on wine production in Nova Scotia, Canada, using a 0.75 L bottle as a functional unit. They evaluated various scenarios, including organic viticulture (with both equal and lower yields compared to conventional methods), the use of lighter bottles, and different transportation methods. García et al. (2023) combined LCA with LCC to assess the sustainability of wine production, focusing on different packaging options, conventional versus organic systems, and the use of irrigation. Finally, Abbate et al. (2024) employed LCA to compare the environmental performance of organic and conventional winery supply chains in southern Italy, again using a 0.75 L bottle of wine as the functional unit.

However, most of the analyzed studies focus only on the comparison between types of farming systems. For instance, Rouault et al. (2016) and Foerster et al. (2024) have compared integrated viticulture with organic viticulture, while Villanueva-Rey et al. (2014) have compared conventional viticulture activities with biodynamic ones. Most of this literature focused on the comparison between the conventional and the organic farming system. In particular, Villanueva-Rey et al. (2014) analyzed 12 crop production systems in California, including two wine grape systems. In addition to an environmental impact analysis through the LCA methodology, Falcone et al. (2015) also carried out a Life Cycle Costing (LCC) to evaluate economic impacts of different wine production scenarios in Calabria (Italy). They compared not only the conventional and the organic viticulture, but also two production systems (Espalier and Gobelet). Hence, four scenarios were analyzed: Organic Espalier (OE), Conventional Espalier (CE), Organic Gobelet (OG), and Conventional Gobelet (CG), with 1 ha of vineyard considered as the functional unit. Borsato et al. (2020) assessed both the environmental and economic performance of organic and conventional vineyard management systems, applying a multi-criteria approach with three environmental indicators: water footprint, carbon footprint, and vineyard management practices. Litskas et al. (2020) conducted an LCA study comparing three different farming systems in the Island of Cyprus: conventional high input, conventional low input, and organic systems. Sinisterra-Solís et al. (2020) applied the LCA method to analyse the environmental profile of the viticulture practices in Spain. This study considered two different types of grapes grown (Bobal and Tempranillo), two management systems (gobelet spur pruning non-irrigated and double guyot cane pruning irrigated) and both conventional and organic farming systems. Volanti et al. (2022) analyzed three scenarios: Scenario A (organic system distinct between irrigated and non-irrigated systems), Scenario B (organic system distinct between use of fertilizers and use of manure) and Scenario C (conventional system). Frem et al. (2023) explored the societal costs and the environmental impacts of four current grapevine production systems in Italy, comparing organic and non-organic viticulture practices for both common and quality wines. It is a study that focused solely on the production phase, with 1 ha chosen as the functional unit. Finally, Wang et al. (2023) assessed an organic and two conventional (Con.1 and Con.2) farming systems in the Chinese

region of Wuwei, using 1 ton of grapes ready for winemaking as the functional unit.

All of these studies highlight that the conventional farming system generally has a higher environmental impact than the organic system, primarily due to the heavy use of fertilizers and chemical pesticides, as well as the fuel consumption associated with their distribution via tractors. However, some studies claim this is not exactly the case. For instance, Steenwerth et al. (2015) conducted a study comparing two wine grape productions in California, in the regions of Napa and Lodi. After modelling 240 scenarios, 12 of them were selected for the comparison, including both conventional and organic farming systems. Using 1 ton of grapes as the functional unit and focusing solely on global warming potential (GWP) as the impact category, their study found that the organic scenario consumed 25% more energy and had a GWP 18% higher than the conventional scenario. Similarly, Falcone et al. (2016) claimed that conventional practices represent the best compromise from both environmental and economic perspectives. This study obtained different results compared to their study of 2015, due to the different functional units considered. Indeed, while the 2015 study used 1 ha of planted surface, the 2016 study used 1 kg of grapevine, which corresponds to a 0.75 L bottle of wine. Finally, Ghiglieno et al. (2023) measured the carbon footprint of 25 wineries in northern Italy, finding that conventional wineries have higher indirect emissions than organic ones, while organic wineries have shown higher direct emissions than conventional ones.

In contrast to the other studies, these works suggest that there are either no significant differences in the overall carbon footprint between organic and conventional wineries or, in some cases, that the organic system has a higher environmental impact. The negative impacts associated with organic farming are primarily due to the use of copper for pest control, the additional fuel consumption from tractors needed for tillage, and the application of organic pesticides, which often require more frequent applications compared to chemical pesticides used in conventional viticulture.

In summary, the analysis of these studies reveals several key environmental hotspots, which vary depending on the stage of production. If the focus is solely on the winemaking phase, the main contributor to environmental impact is the electricity consumed by machinery in the winery, especially during red wine production. For the bottling phase, the production of glass bottles emerges as the primary contributor. When examining the viticulture phase, the conventional system's main impact comes from the use of chemical fertilizers, while in organic viticulture, the major contributors are copper distribution and the additional fuel consumption from tractors.

Thus, the comparison between organic and conventional viticulture shows a non-homogeneity in terms of results regarding their environmental impacts. Some studies claim that conventional viticulture has higher environmental impacts than organic one, while others claimed that organic viticulture is, in some cases, more damaging. Almost all of these assessments, however, are based on a single production year, so that the reported difference between the two systems reflects the climatic and phytosanitary conditions of one season only, and nothing can be inferred about its stability over time. A second source of divergence lies in the functional units adopted, which range from 1 ha of planted surface to one tonne of grapes to one packaged bottle, and which can affect the direction of the comparison and not only its magnitude. Because of the lack of consistency in the results, and of the absence of multi-year evidence, the need for this study has arisen to give the scientific world a contribution to the research on which kind of viticulture is environmentally preferable and why.

3. Materials and methods

This study has been carried out on a wine-growing Italian farm in the province of Ascoli Piceno, in the Marche region of Italy. With a maximum production capacity of 2.4 million bottles of wine, the farm is renowned for producing high-quality wines and adopting an ecologically responsible approach to vineyard management. It has 150 ha of vineyards, strategically distributed across various areas with distinct characteristics. The distribution of the vineyard in different areas allows the growth of both local varieties, such as Montepulciano, Sangiovese, Lacrima Nera, Pecorino, and Passerina, as well as international varieties of grapes, including Cabernet Sauvignon, Merlot, Pinot Nero, and Chardonnay.

3.1. Study area and site characterization

This study investigates the differences between conventional and organic production systems applied to Passerina, a white wine variety typical of central Italy. The Passerina white grape variety is traditionally cultivated in the hilly landscapes of the Marche region, particularly within the provinces of Ascoli Piceno and Fermo. The soils in this area display variable textures that predominantly correspond to the finer particle-size classes of the USDA (United States Department of Agriculture) soil taxonomy - fine loam, fine silt, and fine clay - characterized by relatively high clay content. Soil depth generally exceeds 80–100 cm, with an average available water capacity of approximately 150 mm, and pH values consistently within the alkaline range. The climate is typically Mediterranean, with relatively hot and dry summers and cold, wet winters. Mean summer temperatures range between 21 and 23°C, while winter averages fall between 6 and 7°C. Annual precipitation is between 650 and 850 mm, with minima in July and maxima occurring from October to December. In this study, conventional cultivation was carried out in Piattoni (Castel di Lama), whereas organic cultivation took place in Contrada Ciafone (Offida). Both sites are located in the province of Ascoli Piceno, in the Marche region of central Italy. This area falls within the DOCG (Italian acronym that stands for denomination of controlled and guaranteed origin) regulatory zone for certified Passerina wine production (Mipaaf, 2014).

Table 1, together with Fig. 1, present the annual rainfall and average temperatures recorded in Castel di Lama (conventional vineyard) and Offida (organic vineyard) over the 2022–2024 period. Although both sites are located within the same hilly sector of the southern Marche region, the data show clear interannual variability and some differences between locations. Castel di Lama registered 474.8 mm of rainfall in 2022, increasing to 666.0 mm in 2023 and 659.6 mm in 2024, indicating markedly drier conditions in 2022. Offida consistently exhibited higher precipitation, with 510.4 mm in 2022, 852.4 mm in 2023, and 699.8 mm in 2024; notably, 2023 represents an anomalously wet year, especially for the organic site. Temperature patterns were more uniform across sites. Castel di Lama recorded annual means of 15.7°C, 16.0°C, and 16.4°C, while Offida reported slightly higher values (15.9°C, 16.3°C, 16.5°C). Both vineyards show a progressive warming trend over the three-year period, consistent with broader regional climatic dynamics. All meteorological data were obtained from the regional hydrometeorological monitoring network (SIRMIP – Sistema Informativo Regionale Meteo-Idro-Pluviometrico) of the Marche Region (Regione Marche, 2025).

3.2. Life cycle assessment

3.2.1. Goal and scope definition

The goal of this study is to perform a comparative Life Cycle Assessment (LCA) of conventional and organic white wine production, focusing on the Passerina grape variety cultivated in the Marche region (central Italy). The assessment aims to quantify and compare the environmental impacts associated with both production systems and to identify the processes that contribute most significantly to the overall burdens. The results are intended to support scientific understanding of the environmental performance of alternative viticulture practices and provide evidence-based insights for stakeholders such as producers, researchers, and policymakers. The scope of the study follows the

Table 1
Monthly rainfall (mm) and average temperature (°C) at Castel di Lama and Offida in 2022, 2023, and 2024.

	2022				2023				2024			
	Rainfall		Temperature		Rainfall		Temperature		Rainfall		Temperature	
	Castel di Lama	Offida	Castel di Lama	Offida	Castel di Lama	Offida	Castel di Lama	Offida	Castel di Lama	Offida	Castel di Lama	Offida
JAN	26,2	35,8	5,4	6,5	81,0	131,6	7,1	7,6	56,8	51,8	7,9	8,7
FEB	61,0	96,4	7,5	8,3	65,6	98,6	6,9	7,7	31,0	33,0	9,5	11,2
MAR	11,4	9,8	8,0	8,2	12,6	15,6	12,0	12,0	55,0	61,6	12,3	12,2
APR	25,4	23,6	12,6	11,9	96,8	117,2	12,2	11,6	45,2	50,4	14,7	14,9
MAY	21,0	14,8	19,7	19,7	158,0	210,0	17,3	16,6	52,2	45,0	18,5	17,8
JUN	43,4	39,8	25,3	24,9	108,6	100,4	22,1	21,9	116,4	47,2	23,7	23,1
JUL	52,2	36,4	26,6	26,2	7,4	2,6	26,5	26,6	8,8	8,6	27,3	26,8
AUG	40,8	44,4	25,0	24,4	36,0	49,4	24,9	24,9	75,6	60,4	26,7	26,9
SEP	61,8	61,6	20,0	19,9	12,6	40,2	22,1	21,9	62,2	110,0	20,5	20,2
OCT	11,0	11,8	17,2	18,3	10,4	10,0	19,5	20,4	33,2	75,6	17,7	17,3
NOV	73,6	88,8	11,7	12,0	68,0	66,2	12,7	13,3	31,8	33,0	11,3	11,6
DEC	47,0	47,2	9,1	10,5	9,0	10,6	8,8	10,5	91,4	123,2	7,2	8,0
TOT rain/AVG temp	**474,8**	**510,4**	**15,7**	**15,9**	**666,0**	**852,4**	**16,0**	**16,3**	**659,6**	**699,8**	**16,4**	**16,5**

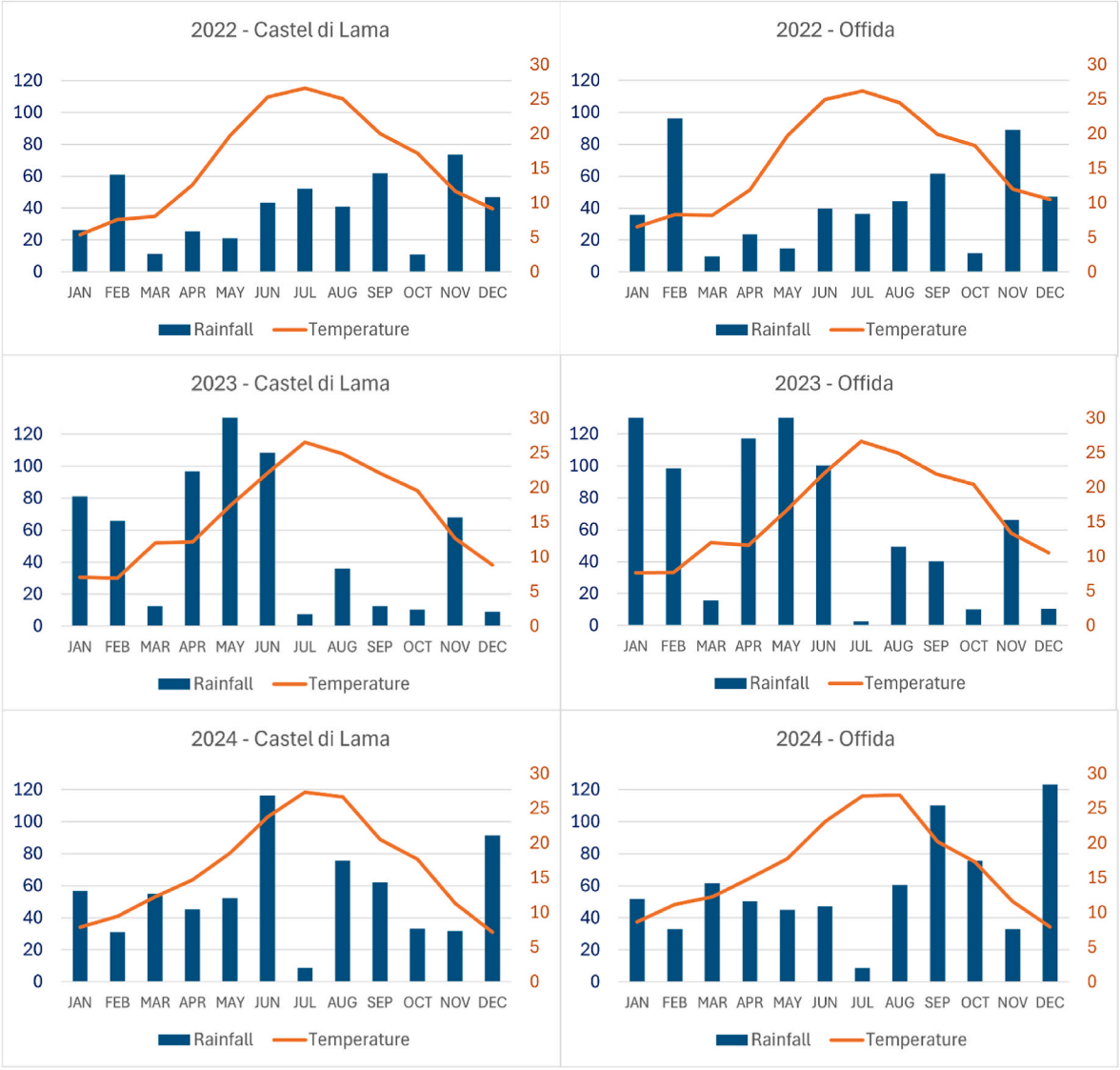


Fig. 1. Thermopluviometric diagram of the two locations in the period 2022-2024 - Cumulative rainfall (mm) in blue and average temperature (°C) in orange. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

methodological framework of ISO 14040:2006/Amd 1:2020 and ISO 14044:2006/Amd 2:2020, and aligns with the product-specific guidance provided in the Product Environmental Footprint Category Rules (PEFCR) for Still and Sparkling Wine, version 2.0 (2020). The geographical scope covers the province of Ascoli Piceno (Marche region), and the temporal scope includes three consecutive production years: 2022, 2023, and 2024.

3.2.1.1. Functional unit, reference flow and system boundaries. In accordance with the PEFCR, the functional unit adopted in this study is defined as the consumption of 0.75 L of packaged white wine, which reflects the service provided to the consumer and ensures comparability with other PEF-compliant wine LCAs. To operationalize this functional unit, the reference flow has been set as one 0.75 L glass bottle of white wine, corresponding to the specific quantity of product required to fulfil the functional unit. The selection of a 0.75 L glass bottle is justified by its widespread use in LCA studies where system boundaries include the winemaking and packaging phases, enabling consistent comparison with existing literature, and by its explicit endorsement within the PEFCR as a valid reference flow for the defined functional unit.

The system boundaries (Fig. 2) have been set "from cradle to gate" by including vineyard planting, viticulture, winemaking, and bottling phases.

The glass bottle production has been included within the boundaries, whereas production of scrap and agricultural waste have been excluded, as they are given to third parties and reused in other production processes. Grapevine nursery stages and young grapevines have also been excluded from the system boundaries. The winery purchases grafted vines from external nurseries, and no primary data were therefore available. No suitable process for grapevine nursery production was identified in the LCI databases consulted. This exclusion is consistent with established practice in the wine LCA literature (Vinci et al., 2022; Wang et al., 2023).

The end-of-life stage has not been included within the system boundaries because the vineyards under study do not employ irrigation systems, which in comparable LCA studies typically represent the main source of plastic waste. The only potential waste stream concerns the packaging of treatment products, whose quantities are minimal and managed through separate collection and certified recycling. Given their marginal contribution and limited relevance to the overall environmental profile, these flows have been excluded to maintain methodological coherence with the goal and scope of the study.

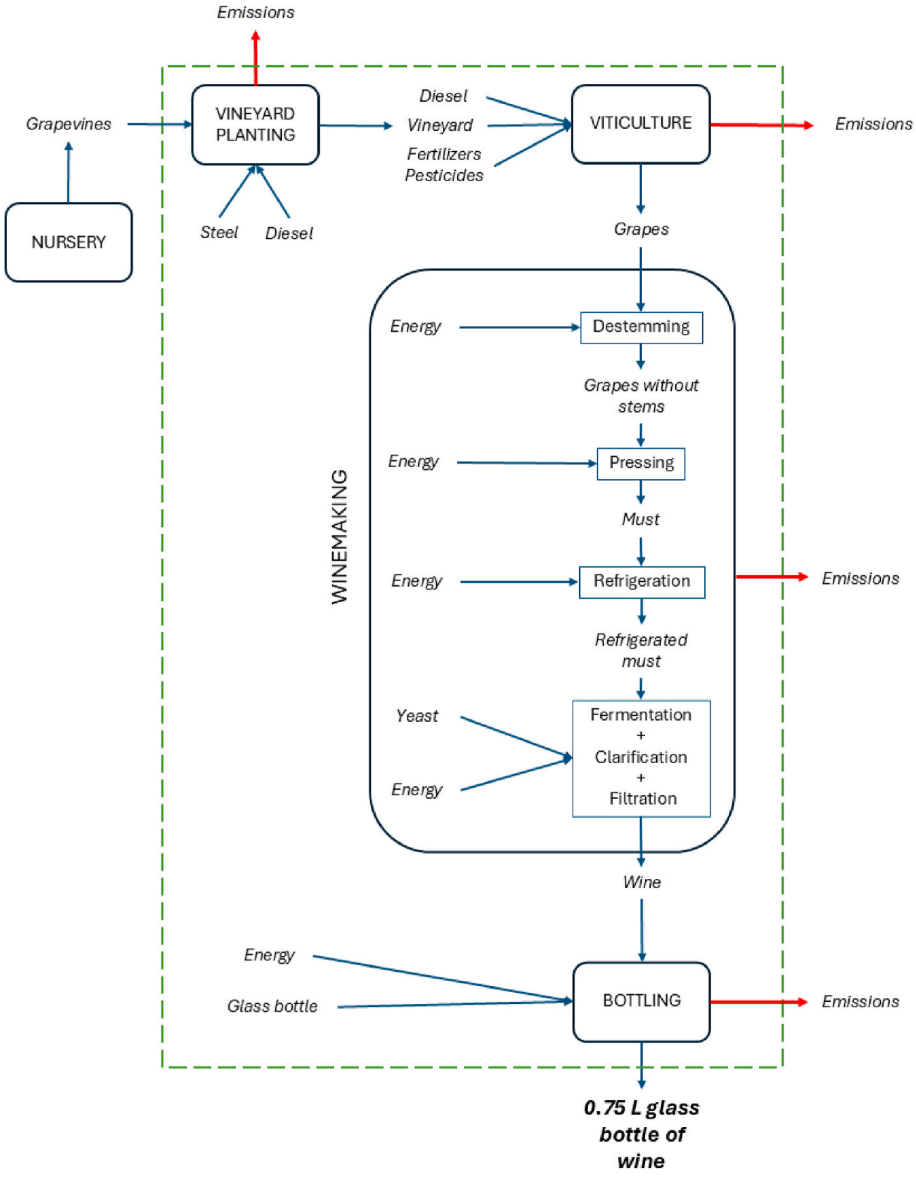


Fig. 2. The system boundaries.

Transportation between the vineyards and the winery has been excluded from the system boundaries. Although the distances involved (10 km for the conventional vineyard and 27 km for the organic vineyard) are consistent with common logistical configurations in the Italian winemaking sector, including transport-related emissions would introduce a context-specific logistical factor that is extrinsic to the production systems under comparison. Given that the longer distance of the organic vineyard is attributable to geographical circumstances rather than to differences in cultivation or winemaking practices, its inclusion would disproportionately affect the comparative results. To ensure methodological neutrality and enhance the generalizability of the outcomes, transport has therefore been omitted from the analysis.

In line with these exclusions, stoppers and labels have also been omitted from the analysis, since their environmental contribution is negligible, as reported by Pizzigallo et al. (2008) and Iannone et al. (2016).

3.2.2. Life cycle inventory analysis

All data used in this study refer to the production period 2022–2024 and include both primary and secondary sources. For the secondary data Ecoinvent v3.12 has been used as the primary database for the life cycle inventory. However, two specific inputs required for the analysis were not available in Ecoinvent: yeast for the winemaking phase and galvanized steel for the vineyard trellis structures. To ensure completeness of the inventory, these flows have been sourced respectively from Agribalyse v3.1.1 and Industry 2.0. All inventory data were compiled and the impact assessment computed in SimaPro 10.4.0.0.

Primary data covering the three production seasons assessed were collected in 2025 through structured interviews with the winery's agronomist, responsible for both vineyards, and with the technicians in charge of the winemaking and bottling lines. The interviews were used to retrieve and cross-check the winery's written records rather than to elicit recollections. The main source was the vineyard logbooks and treatment registers, which are compiled during the season and record the date, product and dose of each plant protection treatment; these were complemented by harvest records for the yields, and by the winery's operational data for the electricity consumption of the winemaking and bottling stages. Because these records are contemporaneous with the operations they document, the retrospective timing of the interviews does not affect the temporal representativeness of the inventory. Two elements were provided at an aggregated rather than a per-pass level and are reported as such: the number of field operations, supplied by category, and the diesel consumption, supplied as a single average value per mechanized operation.

The quality of the inventory was assessed against the data quality criteria of the PEFCR for Still and Sparkling Wine v2.0, which is the reference framework already adopted in this study for inventory modelling and emission allocation. Foreground data on inputs, field operations and yields display high technological, geographical and temporal representativeness, being measured at the two vineyards under study and referring to the exact production years assessed. Residual uncertainty is concentrated in two elements: the single average diesel consumption applied to mechanized operations of different intensity, which is discussed among the limitations in Section 7, and the two background flows for which no Ecoinvent process was available (yeast and galvanized steel).

All the processes included in the system boundaries are explained in the following subsections.

3.2.2.1. Vineyard planting. Both vineyards included in this study (organic and conventional) have an expected lifespan of approximately 40 years. They also have the same planting spacing of 270 cm × 80 cm and planting density of 4630 plants/ha. Each vineyard is established using a steel trellis system with supporting wires, and neither site is equipped with an irrigation system. Although young grapevines are an input at this stage, they have been excluded from the life cycle inventory due to the absence of both primary data and suitable secondary data in the LCI databases available for this study. The installation of the vineyard and its trellis infrastructure requires preliminary soil preparation activities, including deep trenching, performed prior to vine planting. These operations are carried out using a diesel-powered excavator. Fuel consumption for trenching depends on machinery type, soil characteristics, and the operational conditions, but an average value of 40 l/ha has been recorded for the vineyards under study. According to the EMEP/EEA Guidelines (European Environment Agency, 2023), the combustion of 1 kg of diesel releases 3.16 kg of CO_2. Based on this emission factor, trenching activities emit approximately 106 kg CO_2/ha during vineyard establishment.

Given the 40-year lifespan of the vineyards, these emissions have been allocated across the entire useful life of the plantation within the LCA model. For each production year, a constant annual share of the establishment-related emissions has been therefore assigned. However, since grape yield - and consequently wine output - varies from year to year, the impact per reference flow (0.75 L of bottled wine) has been derived by dividing this annual allocation by the actual number of bottles produced in each respective year. As a result, while the yearly emission quota remains constant across vintages, its contribution per bottle reflects the yield-dependent variability of production.

Table 2 reports the data inventory for the vineyard planting phase. All data refers to 1 ha.

3.2.2.2. Viticulture. In the viticulture phase, all activities from vine growth to grape harvesting have been taken into account. After planting, vines have been trained following the Guyot cultivation system, as prescribed by the DOCG (Denomination of Controlled and Guaranteed Origin) regulation for Passerina wine production (Mipaaf, 2014).

In both vineyards - regardless of whether they follow conventional or organic management - standard agronomic practices have been performed annually. These include dry and green pruning, defoliation, trimming, and manure application. Tillage has also been carried out on alternating rows. While dry and green pruning, defoliation and trimming have been performed manually, the manure distribution and the tillage practice - together with inter-row mowing in the organic vineyard - have been executed using standard agricultural tractors. Pesticide treatments, when applied, have likewise required tractor use; however, according to the winery, their application is not programmed but instead carried out strictly when necessary, based on seasonal climatic conditions and vine phenology. Consequently, pesticide use is inherently non-standardized.

Treatment strategies differ between systems: the conventional vineyard employs copper, sulfur, manure, and synthetic pesticides, whereas the organic vineyard relies exclusively on copper, sulfur, and manure. The manure applied in both systems has the following nutrient composition: nitrogen (N) 0.25%, phosphorus (P) 0.15%, and potassium (K) 0.20%.

Regarding field operations, the organic vineyard required 13, 14, and 17 treatments in 2022, 2023, and 2024, respectively, whereas the conventional vineyard required 9, 10, and 13 over the same years. A fixed set of mechanized agronomic practices was also carried out each

Table 2
Data inventory for vineyard planting phase (data referred to 1ha).

VINEYARD PLANTING		
Input		**Unit**
Steel	4020.00	kg
Diesel	33.40	kg
Land	1.00	ha a
Output		
Vineyard	1.00	ha
Emissions		
CO_2 to air	106.00	kg

year (i.e. manure application and tillage in both vineyards, plus inter-row mowing in the organic vineyard) amounting to 3 operations per year in the organic system and 2 in the conventional one. Accordingly, the organic vineyard performed a total of 16, 17, and 20 field operations in 2022, 2023, and 2024, respectively, while the conventional vineyard performed 11, 12, and 15 over the same period. These data were provided by the winery at the level of these categories rather than as a per-pass log of each individual operation. All field operations requiring mechanization have been carried out with diesel-powered tractors. Fuel consumption was based on an average of 20 L/ha per mechanized operation, a primary datum provided directly by the winery and representing the mean across all field operations performed in the two vineyards. Associated CO_2 emissions from diesel combustion have been estimated using the European Environment Agency (EMEP/EEA, 2023) emission factor of 3.16 kg CO_2 per kg of diesel combusted.

Emissions of pesticides, herbicides, and fertilizers have been modelled according to the Product Environmental Footprint Category Rules (PEFCR) for Still and Sparkling Wine v2.0 (2020). Following PEFCR requirements, pesticide emissions have been allocated as 90% to agricultural soil, 9% to air, and 1% to water. For copper-based products, the fraction assigned to the air compartment should be interpreted as a standardized representation of off-target dispersion during application (e.g., spray drift), rather than as volatilization of copper, which is a non-volatile substance. Nitrogen and phosphorus emissions from fertilizers have been quantified using the emission factors and compartment distributions reported in Table 17 of the PEFCR (European Commission, 2020), including N_2O, NH_3, NO_3^-, and P-based emissions.

Grape harvesting is carried out manually. Recorded yields amounted to 6 t/ha (organic) and 6.5 t/ha (conventional) in 2022; 8 t/ha (organic) and 9 t/ha (conventional) in 2023; and 6.5 t/ha (organic) and 7 t/ha (conventional) in 2024.

Table 3 reports the data inventory for both organic and conventional viticulture. All data refers to the reference flow (0.75 L glass bottle of white wine).

3.2.2.3. Winemaking. Once the grapes have been harvested, they are transported into the cellar and subjected to destemming. Destemming allows the separation of grapes from stalks. Then, the destemmed grapes are pressed in order to obtain the first must, which is then subjected to another pressing to get more juice. The must obtained is left to settle to allow the separation of solids that settle to the bottom. The clarified must is then transferred into another tank and cooled at 8-10°C. The next stage is the fermentation process that takes place at 15°C. After fermentation the wine goes through a period of aging and further clarification and filtration processes. Bentonite and similar processing aids are not used in the winemaking process of this case study, as wine stabilization is achieved through refrigeration, whose energy consumption is included in the LCI. Water use for cleaning and processing purposes was not included in the life cycle inventory due to the absence of available data. As cleaning procedures are identical for both production systems, this limitation does not affect the validity of the comparison.

The machines involved in the winemaking phase (Table 6) operate daily from September to October for approximately 11 h per day. Based on the winery's operational data, the total electricity consumption associated with winemaking has been quantified as constant over the three production years considered, at 0.0636 kWh per reference flow.

Table 4 reports the data inventory for winemaking phase. All data refers to the reference flow (0.75 L glass bottle of white wine).

3.2.2.4. Bottling. Finally, the wine is bottled and sealed, and it is ready to be shipped to the distributors. During the bottling phase, the wine is filled into 0.75 L white glass bottles weighing 420 g. The machines involved in this stage (Table 6) operate throughout the year, approximately three times per week for 8 h per day. Based on operational data provided by the winery, the average electricity consumption associated with bottling has been quantified as constant - over the three production years considered - at 0.068 kWh per reference flow.

Table 5 reports the data inventory for the bottling phase. All data refers to the reference flow (0.75 L glass bottle of white wine).

Table 3
Data inventory for organic and conventional viticulture, 2022-2024 (data referred to reference flow).

	2022	2023	2024	Unit
ORGANIC VITICULTURE				
Input				
Vineyard	0.042	0.031	0.038	m2
Manure	0.667	0.500	0.615	kg
Sulfur	17.733	8.675	18.615	g
Copper	0.483	0.413	0.585	g
Diesel	44.533	35.500	51.385	g
Emissions				
CO_2 to air	140.725	112.180	162.375	g
Sulfur to soil	15.960	7.808	16.754	g
Sulfur to air	1.596	0.781	1.675	g
Sulfur to water	0.177	0.087	0.186	g
Copper to soil	0.435	0.371	0.526	g
Copper to air	0.044	0.037	0.053	g
Copper to water	0.005	0.004	0.006	g
Dinitrogen Monoxide to air	0.037	0.028	0.034	g
Ammonia to air	0.400	0.300	0.369	g
Phosphorus to water	0.050	0.038	0.046	g
Nitrate to water	2.217	1.663	2.046	g
CONVENTIONAL VITICULTURE				
Input				
Vineyard	0.038	0.028	0.036	m2
Manure	0.615	0.444	0.571	kg
Sulfur	5.538	5.233	5.443	g
Copper	0.369	0.561	0.471	g
Fosetyl-AI	0.386	0.367	0.857	g
Folpet	0.071	0.067	0.143	g
Diesel	28.262	22.267	35.786	g
Emissions				
CO_2 to air	89.306	70.222	113.083	g
Sulfur to soil	4.985	4.710	4.899	g
Sulfur to air	0.498	0.471	0.490	g
Sulfur to water	0.055	0.052	0.054	g
Copper to soil	0.332	0.505	0.424	g
Copper to air	0.033	0.051	0.042	g
Copper to water	0.004	0.006	0.005	g
Fosetyl-AI to soil	0.348	0.330	0.771	g
Fosetyl-AI to air	0.035	0.033	0.077	g
Fosetyl-AI to water	0.004	0.004	0.009	g
Folpet to soil	0.064	0.060	0.129	g
Folpet to air	0.006	0.006	0.013	g
Folpet to water	0.001	0.001	0.001	g
Dinitrogen Monoxide to air	0.034	0.024	0.031	g
Ammonia to air	0.369	0.267	0.343	g
Phosphorus to water	0.046	0.033	0.043	g
Nitrate to water	2.046	1.478	1.900	g

Table 4
Data inventory for the winemaking phase (data referred to reference flow).

WINEMAKING		
Input		Unit
Grapes	1.00	kg
Yeast	0.15	g
Electricity	0.0636	kWh

3.2.3. Life cycle impact assessment

The impact assessment has been carried out using the ReCiPe 2016 Midpoint (H) method. This choice has been motivated by the findings of our literature review, which has shown that ReCiPe - together with CML - is among the most commonly adopted LCIA methods in comparative studies on viticulture and wine production. Its widespread use enables

Table 5
Data inventory for the bottling phase (data referred to reference flow).

BOTTLING		
Input		Unit
Wine	0.75	l
Glass bottle	420.00	g
Electricity	0.068	KWh
Output		Unit
Bottle of wine	1	p

methodological consistency and facilitates comparison with existing research.

It is worth noting that the PEFCR for Still and Sparkling Wine v2.0 (2020), whose inventory modelling and emission allocation guidelines are followed in this study, recommends the Environmental Footprint (EF) method, the framework more directly linked to EU policy applications. The two methods are both midpoint-oriented but not fully equivalent, as they differ in the structure and aggregation of their impact categories, so that a one-to-one numerical comparison is not feasible. Climate change remains broadly comparable, since both rely on a 100-year global warming perspective, whereas greater caution is required for the toxicity related indicators, whose characterization factors for metals such as copper and for unspecified pesticides have been substantially revised in recent EF versions. The conclusions concerning the predominance of packaging and, secondarily, of energy and field mechanization are therefore expected to remain qualitatively robust under the EF framework, while the interpretation of toxicity related trade-offs is more method-sensitive. A detailed discussion is provided in the Supplementary Material (*Supplementary Note: methodological comparison between ReCiPe 2016 Midpoint (H) and the Environmental Footprint*



Fig. 3. Environmental impacts of conventional and organic viticulture, 2022-2024.

method).

The following ReCiPe 2016 Midpoint (H) impact categories have been included in the assessment: global warming, stratospheric ozone depletion, ionizing radiation, ozone formation (human health), fine particulate matter formation, ozone formation (terrestrial ecosystems), terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, land use, mineral resource scarcity, fossil resource scarcity, and water consumption. Together, these categories provide a comprehensive representation of the environmental impacts associated with the two production systems. The comparison between systems is expressed, for each impact category and year, as the percentage variation of the organic bottle over the conventional one, and summarized as the arithmetic mean of the three annual values.

4. Results

The aim of this section is to present the results of the two production systems, without interpreting the underlying causes, which are addressed in the next Discussion section. The results are organized by life-cycle stage and expressed for all midpoint impact categories.

Fig. 3 presents the environmental impacts associated with the viticulture phase for conventional and organic wine production, across the three years of analysis. The figure is derived from the detailed contribution breakdowns, reported in the corresponding tables for 2022 (Table S1), 2023 (Table S2) and 2024 (Table S3), provided in Supplementary Materials. In both systems, the dominant contributors group consistently by impact category type. The vineyard infrastructure governs ionizing radiation, mineral resource scarcity and water consumption; manure application drives stratospheric ozone depletion, terrestrial acidification and the eutrophication categories; diesel dominates the energy and combustion categories (both ozone formation categories and fossil resource scarcity); and copper-based treatments lead freshwater ecotoxicity, marine ecotoxicity and human non-carcinogenic toxicity. Sulfur acts only as a secondary contributor, mainly in the organic system, where it accounts for a relevant share of fine particulate matter formation (21–30%) and terrestrial acidification (14–22%). The clearest structural divergence between the two systems concerns terrestrial ecotoxicity: this category is governed by the viticulture field-emissions term in the conventional system (82–90% of the total), whereas in the organic system it is led by copper (57–61%). A more limited divergence is observed for human carcinogenic toxicity, which is co-dominated by copper, fosetyl-Al and diesel in the conventional system but led by copper in the organic one. In both systems, most impact categories reach their lowest values in 2023 and their highest in 2024, mirroring the number of field operations and the associated diesel and input use. The widest interannual variation occurs in the categories linked to fuel combustion and field activity (global warming, fossil resource scarcity, the two ozone formation categories and fine particulate matter formation) which rise appreciably from the low-input 2023 season to the more operation-intensive 2024 one (in the organic system, for instance, by roughly 40% for global warming and fossil resource scarcity, and by nearly 50% for fine particulate matter formation). Terrestrial ecotoxicity follows a distinct trajectory in the conventional system, where it nearly doubles in 2024 relative to 2023, in parallel with the higher application of fosetyl-Al and folpet in that season.

Comparing the two systems year by year, terrestrial ecotoxicity is the category in which the conventional system markedly exceeds the organic one, the latter being approximately 81%, 84% and 89% lower in 2022, 2023 and 2024. In nearly all other categories the organic system shows higher impacts, with the largest and most recurrent gaps in fossil resource scarcity (+43%, +43%, +32%), fine particulate matter formation (+41%, +11%, +36%), global warming (+38%, +38%, +29%), terrestrial acidification (+30%, +12%, +28%) and the ozone formation categories. The toxicity-related categories are less stable across the years: marine ecotoxicity and human non-carcinogenic toxicity are higher in the organic system in 2022 and 2024 but lower in 2023 (by 27% and 22%, respectively), whereas freshwater ecotoxicity is essentially on par in 2022 and lower in the organic system in both 2023 and 2024 (by 36% and 15%). Human carcinogenic toxicity is also lower in the organic system across all three years. The factors underlying these patterns are addressed in the Discussion section.

Fig. 4 reports the contribution analysis for the winemaking phase, of conventional and organic wine production, over the three study years. For each system and year, the figure shows the relative contribution of viticulture-related inputs, yeast and electricity to all midpoint impact categories. Across all panels, viticulture-related inputs clearly represent the dominant contributor, accounting for the largest share of impacts in nearly all categories and years for both production systems. Electricity provides a consistent but comparatively smaller contribution, while yeast remains negligible throughout. The overall pattern is highly similar between conventional and organic winemaking, and only limited year-to-year variation is observed. The figure therefore indicates that the internal contribution structure of the winemaking phase is stable across time and largely comparable across the two management systems, with viticulture-derived inputs driving most of the impacts and electricity contributing to a lesser extent.

Tables 7–9 report the midpoint environmental impacts associated with the bottling phase of a 0.75 L bottle of conventional and organic white wine for the years 2022, 2023 and 2024. To better understand the environmental hotspots within this phase, the total impact for each impact category has been disaggregated into the three primary contributors: glass bottle, wine (which accounts for the upstream viticulture phase) and electricity.

Across all three years, the results show a consistent pattern. The glass bottle remains the dominant contributor in most impact categories for both production systems, although its relative share varies between years and indicators. A few categories depart from this pattern: stratospheric ozone depletion, ionizing radiation and marine eutrophication are dominated by the wine, and the same applies to terrestrial ecotoxicity in the conventional system, where the wine accounts for most of the impact. Across the remaining categories, wine represents the second most relevant contributor, while electricity accounts for a smaller proportion of impacts. The three tables reveal clear differences between conventional and organic wine, whose magnitude varies by impact category and by year. Both systems exhibit annual variability, reflecting changes in field operations and production conditions.

For each impact category, Table 10 reports the annual percentage variation between the organic and conventional 0.75 L bottles and the corresponding three-year average.

Overall, the comparative assessment reveals a consistent pattern: the organic system exhibits higher impacts in most categories, with positive variations in 14 out of 18 indicators on average. These differences remain generally moderate for key categories such as global warming (+8.1% on average), fossil resource scarcity (+8.5% on average), land use (+4.8% on average) and fine particulate matter formation (+4.6% on average), and are marginal for several others, including water consumption (+0.3%), human non-carcinogenic toxicity (+0.5%), mineral resource scarcity (+0.5%) and marine ecotoxicity (+0.03%). These trends largely reflect structural characteristics of the organic system: higher diesel consumption due to more field operations, recurrent use of copper- and sulfur-based plant protection products, and lower yields.

Interannual variability is present but limited. For most categories, the organic–conventional gap fluctuates only by a few percentage points across the three years. Marine eutrophication varies between +5.4% and +8.1%, while stratospheric ozone depletion ranges from +2.7% to +5.9%. Categories linked to diesel combustion (such as global warming and terrestrial acidification) show somewhat larger variability (+7.6–8.9% and +3.0–8.2%, respectively), reflecting changes in field activity and treatment intensity. The comparatively small differences observed in 2023 - e.g., the negligible gaps in freshwater eutrophication



Fig. 4. Environmental impacts of conventional and organic winemaking, 2022-2024.

(−1.3%) and water consumption (+0.3%), and the reduced or reversed discrepancies in several toxicity indicators - demonstrate how lower input use, coupled with relatively higher organic yields, can narrow the performance gap between systems.

Despite higher impacts in most categories, the organic system shows a clear environmental advantage in toxicity-related indicators. Terrestrial ecotoxicity demonstrates the most pronounced improvement, with the organic system performing 40–58% better and achieving a three-year average reduction of −46.7%. This benefit stems from the exclusion of synthetic fungicides such as folpet and fosetyl-Al, which contribute to the elevated field-emissions term that dominates terrestrial ecotoxicity in the conventional system. The organic system also shows small but consistent advantages in human carcinogenic toxicity (−1.7% on average) and freshwater ecotoxicity (−3.9% on average). Freshwater eutrophication and marine ecotoxicity present small variations fluctuating around zero (−0.5% and +0.03% on average), indicating functional equivalence between the systems under the conditions analyzed.

5. Discussion

5.1. Organic system: influence of manure and copper-based treatments

In the organic vineyard, the highest contributions to environmental impacts are associated with manure application and copper-based treatments. Manure is the dominant driver of impacts in stratospheric ozone depletion, marine eutrophication, and land use. These impacts originate from nitrogen and phosphorus emissions modelled according to the PEFCR: N_2O emissions contribute to stratospheric ozone

Table 6
Description of the machines involved into the winemaking and bottling phases.

MACHINE	DESCRIPTION	POWER
Winemaking stage		
Hopper	It is a container, made of stainless steel, where freshly harvested grapes are unloaded before to be destemmed	2 kW
Destemmer	It is used to separate the grapes from the stalks	22-25 kW
Pump	It is used to pump the wine and separate it from the solid parts.	1.5 kW
Press	It is used to press the grapes in order to obtain must	29 kW
Stalk chopper	It reduces the volume of grape stalks, which are not used in wine production, facilitating storage and disposal.	1 kW
Refrigerator	It is used in the cooling and fermentation phases in order to control the temperature and make it stable	50-60 kW
Bottling stage		
Bottling machine	It allows the filling and the sealing of the bottles	15 kW
Labelling machine	It applies labels on the bottle	35 kW
Compressor	Used by all the machines using compressed air in the packaging plant	10 kW
Auxiliary machinery	They include cartooning machine, hive insertion, and end-of-line gluing machine	4 kW

depletion, while NH_3 volatilization and NO_3^- leaching drive eutrophication processes. The multi-year dataset shows that these processes are sensitive to climatic conditions. In the exceptionally wet year of 2023 (852.4 mm of rainfall in Offida), nutrient leaching potential was likely amplified. Copper-based treatments are the main contributors to freshwater ecotoxicity, marine ecotoxicity, and human non-carcinogenic toxicity, where they account for the predominant share of the total impact. They also represent the leading contributor to terrestrial ecotoxicity within the organic system, as copper is persistent and accumulates in vineyard soils. High rainfall, as in 2023, increases the probability of copper mobilization, runoff and dispersion, magnifying ecotoxic impacts. Operational intensity also plays an important role. The organic vineyard performed 16, 17, and 20 field operations in 2022, 2023 and 2024, respectively, consistently more than the conventional system. This higher number of interventions contributes to greater diesel consumption, additional soil disturbance, and enhanced potential for nutrient mobilization following manure application.

5.2. Conventional system: contribution of synthetic pesticides

In the conventional vineyard, synthetic pesticides are the main contributors to terrestrial ecotoxicity and also account for a substantial share of human carcinogenic toxicity. Even though applied only when necessary, these products exhibit high characterization factors in ReCiPe (2016), which explains their substantial contribution to toxicity indicators. Unlike nutrient-driven impacts in the organic system, the environmental performance of synthetic pesticides is less affected by annual climatic variability and depends more strongly on their intrinsic hazard profile.

5.3. Interactions between climate, operational intensity and environmental impacts

Climatic variability interacts strongly with management practices. Across the analyzed period, increasing rainfall and slightly higher temperatures are associated with more field operations: from 11 to 15 in the conventional vineyard and from 16 to 20 in the organic one. Rainfall therefore appears to drive operational activity, particularly in the organic system, where contact fungicides require reapplication after wash-off events.

However, climate does not automatically result in higher impacts. In 2023 - the rainier year - diesel use, CO_2 emissions and key inputs (copper and sulfur) were at their minimum in the organic vineyard, producing comparatively smaller organic–conventional differences. In 2024, although rainfall remained higher than in 2022, but lower than in 2023, diesel and input use increased again, widening gaps in combustion and emission-related indicators (global warming, fine particulate matter formation, terrestrial acidification, fossil resource scarcity). The apparently counterintuitive reduction in input use observed in 2023, despite it being the rainiest year, could be explained by the temporal distribution of precipitation rather than its annual total. As shown in Table 1, rainfall in 2023 appears to have been heavily concentrated in the winter and early spring months, while the summer period (which represents a critical window for fungal disease pressure in viticulture) was comparatively dry, particularly in July. This distribution may have resulted in lower disease pressure during the key phenological stages of the vine potentially reducing the need for repeated fungicide applications. In contrast, the lower but more evenly distributed rainfall of 2022 and 2024 may have sustained disease pressure across a longer portion of the growing season, likely requiring more frequent treatments. These observations suggest that seasonal rainfall distribution, rather than annual

Table 7
Environmental impacts referred to the bottling of 0.75 L glass bottle of conventional and organic white wine in 2022.

Impact Categories	Unit	Bottle of conventional wine				Bottle of organic wine			
		Total	Process contribution in %			Total	Process contribution in %		
			Glass bottle	Wine	Electricity		Glass bottle	Wine	Electricity
Global warming	kg CO2 eq	8,05E-01	67%	28%	5%	**8,77E-01**	62%	34%	4%
Stratospheric ozone depletion	kg CFC11 eq	7,37E-07	31%	66%	3%	**7,72E-07**	30%	68%	3%
Ionizing radiation	kBq Co-60 eq	1,43E-01	13%	84%	3%	**1,53E-01**	12%	85%	3%
Ozone formation, Human health	kg NOx eq	2,07E-03	85%	12%	3%	**2,13E-03**	82%	15%	3%
Fine particulate matter formation	kg PM2.5 eq	1,45E-03	79%	18%	3%	**1,54E-03**	74%	23%	3%
Ozone formation, Terrestrial ecosystems	kg NOx eq	2,17E-03	84%	13%	3%	**2,23E-03**	81%	16%	3%
Terrestrial acidification	kg SO2 eq	4,13E-03	67%	30%	3%	**4,47E-03**	62%	36%	2%
Freshwater eutrophication	kg P eq	3,41E-04	72%	24%	4%	**3,45E-04**	71%	25%	4%
Marine eutrophication	kg N eq	2,18E-04	27%	73%	1%	**2,31E-04**	25%	74%	1%
Terrestrial ecotoxicity	kg 1.4-DCB	**4,62E+00**	46%	52%	2%	2,76E+00	78%	19%	3%
Freshwater ecotoxicity	kg 1.4-DCB	6,75E-02	69%	24%	7%	**6,77E-02**	68%	25%	7%
Marine ecotoxicity	kg 1.4-DCB	8,31E-02	71%	22%	7%	**8,60E-02**	69%	25%	7%
Human carcinogenic toxicity	kg 1.4-DCB	5,96E-02	85%	12%	4%	5,96E-02	85%	11%	4%
Human non-carcinogenic toxicity	kg 1.4-DCB	1,39E+00	79%	17%	4%	**1,43E+00**	76%	20%	4%
Land use	m2a crop eq	1,54E-01	43%	57%	1%	**1,61E-01**	41%	58%	1%
Mineral resource scarcity	kg Cu eq	6,30E-03	72%	26%	2%	**6,46E-03**	70%	28%	2%
Fossil resource scarcity	kg oil eq	2,16E-01	67%	27%	6%	**2,37E-01**	61%	33%	5%
Water consumption	m3	5,91E-03	64%	26%	10%	**5,97E-03**	64%	27%	10%

Table 8
Environmental impacts referred to 0.75 L glass bottle of conventional and organic white wine in 2023.

Impact categories	Unit	Bottle of conventional wine				Bottle of organic wine			
		Total	Process contribution in %			Total	Process contribution in %		
			Glass bottle	Wine	Electricity		Glass bottle	Wine	Electricity
Global warming	kg CO2 eq	7,44E-01	73%	23%	4%	**8,00E-01**	68%	29%	3%
Stratospheric ozone depletion	kg CFC11 eq	6,01E-07	38%	60%	2%	**6,36E-07**	36%	62%	2%
Ionizing radiation	kBq Co-60 eq	1,09E-01	17%	80%	3%	**1,19E-01**	16%	82%	3%
Ozone formation, Human health	kg NOx eq	2,01E-03	87%	10%	2%	**2,04E-03**	86%	12%	2%
Fine particulate matter formation	kg PM2.5 eq	1,40E-03	82%	16%	2%	**1,42E-03**	80%	17%	2%
Ozone formation, Terrestrial ecosystems	kg NOx eq	2,09E-03	87%	11%	2%	**2,13E-03**	85%	12%	2%
Terrestrial acidification	kg SO2 eq	3,86E-03	72%	26%	2%	**3,98E-03**	69%	28%	2%
Freshwater eutrophication	kg P eq	**3,25E-04**	75%	21%	3%	3,21E-04	76%	20%	3%
Marine eutrophication	kg N eq	1,74E-04	33%	66%	1%	**1,88E-04**	31%	69%	1%
Terrestrial ecotoxicity	kg 1.4-DCB	**4,52E+00**	47%	51%	1%	2,63E+00	82%	16%	3%
Freshwater ecotoxicity	kg 1.4-DCB	**6,93E-02**	67%	28%	5%	6,34E-02	73%	22%	6%
Marine ecotoxicity	kg 1.4-DCB	**8,55E-02**	69%	26%	5%	8,06E-02	73%	21%	5%
Human carcinogenic toxicity	kg 1.4-DCB	**5,88E-02**	86%	11%	3%	5,75E-02	88%	9%	3%
Human non-carcinogenic toxicity	kg 1.4-DCB	**1,41E+00**	77%	20%	3%	1,36E+00	80%	17%	3%
Land use	m2a crop eq	1,30E-01	50%	49%	1%	**1,37E-01**	48%	52%	1%
Mineral resource scarcity	kg Cu eq	**6,14E-03**	74%	24%	2%	6,03E-03	75%	23%	2%
Fossil resource scarcity	kg oil eq	2,00E-01	73%	23%	4%	**2,16E-01**	67%	29%	4%
Water consumption	m3	5,40E-03	70%	22%	8%	**5,42E-03**	70%	22%	8%

Table 9
Environmental impacts referred to 0.75 L glass bottle of conventional and organic white wine in 2024.

Impact categories	Unit	Bottle of conventional wine				Bottle of organic wine			
		Total	Process contribution in %			Total	Process contribution in %		
			Glass bottle	Wine	Electricity		Glass bottle	Wine	Electricity
Global warming	kg CO2 eq	8,31E-01	65%	31%	4%	**8,95E-01**	61%	35%	4%
Stratospheric ozone depletion	kg CFC11 eq	7,14E-07	32%	65%	3%	**7,33E-07**	31%	66%	3%
Ionizing radiation	kBq Co-60 eq	1,35E-01	14%	83%	3%	**1,42E-01**	13%	84%	3%
Ozone formation, Human health	kg NOx eq	2,09E-03	84%	13%	3%	**2,13E-03**	82%	15%	3%
Fine particulate matter formation	kg PM2.5 eq	1,45E-03	79%	19%	3%	**1,54E-03**	74%	23%	3%
Ozone formation, Terrestrial ecosystems	kg NOx eq	2,19E-03	83%	14%	3%	**2,24E-03**	81%	16%	3%
Terrestrial acidification	kg SO2 eq	4,11E-03	67%	30%	2%	**4,44E-03**	62%	35%	2%
Freshwater eutrophication	kg P eq	**3,46E-04**	71%	25%	4%	3,42E-04	72%	24%	4%
Marine eutrophication	kg N eq	2,07E-04	28%	71%	1%	**2,18E-04**	27%	73%	1%
Terrestrial ecotoxicity	kg 1.4-DCB	**6,67E+00**	32%	67%	1%	2,80E+00	76%	21%	3%
Freshwater ecotoxicity	kg 1.4-DCB	**7,21E-02**	64%	30%	6%	6,95E-02	67%	27%	6%
Marine ecotoxicity	kg 1.4-DCB	8,62E-02	68%	25%	6%	**8,82E-02**	67%	27%	6%
Human carcinogenic toxicity	kg 1.4-DCB	**6,16E-02**	82%	15%	3%	5,99E-02	84%	12%	3%
Human non-carcinogenic toxicity	kg 1.4-DCB	1,42E+00	77%	20%	4%	**1,45E+00**	75%	21%	4%
Land use	m2a crop eq	1,48E-01	44%	55%	1%	**1,54E-01**	42%	57%	1%
Mineral resource scarcity	kg Cu eq	6,42E-03	71%	27%	2%	**6,47E-03**	70%	28%	2%
Fossil resource scarcity	kg oil eq	2,24E-01	65%	30%	5%	**2,43E-01**	60%	35%	5%
Water consumption	m3	**5,86E-03**	65%	26%	9%	5,84E-03	65%	26%	9%

totals, could be a primary driver of treatment intensity in the organic vineyard, although a more detailed phenological and epidemiological analysis would be needed to confirm this interpretation.

Temperature plays a more moderate but still relevant role. The slight warming trend observed over the three years may have contributed to disease pressure when combined with rainfall during critical phenological stages, although the relationship between temperature, precipitation distribution and actual input use appears complex and did not follow a simple proportional pattern across the three years analyzed.

5.4. Winemaking and bottling: hotspot analysis

Across all three years and both production systems, the glass bottle consistently emerges as the dominant environmental hotspot, accounting for the largest share of impacts in most midpoint categories. Its contribution varies across impact categories, but remains the single most relevant process in the entire life cycle of both conventional and organic wine in most cases. This finding is in line with the broader LCA literature on wine production, where glass packaging has been repeatedly identified as the primary driver of environmental burdens (Cleary, 2013; Fusi et al., 2014; García et al., 2023; Ferrara et al., 2023).

The dominance of the glass bottle is particularly pronounced in categories such as human carcinogenic toxicity, ozone formation, and freshwater eutrophication, where its contribution far exceeds that of all other life cycle stages combined. This pattern is consistent across years and between the two production systems, indicating that the choice of primary packaging material exerts a largely system-independent influence on the overall environmental profile of the product.

The winemaking phase represents the second most relevant contribution across most impact categories, driven primarily by viticulture-related inputs rather than by electricity consumption or yeast use, as shown in Fig. 4. Electricity consumption in both the winemaking and bottling stages contributes a comparatively small and stable share of impacts, across all categories and years, reflecting the relatively low and constant energy intensity of these operations.

These results reinforce the importance of upstream packaging decisions in determining the overall environmental performance of wine, independently of vineyard management choices. Reducing the glass bottle weight from 420g to 300g can reduce environmental impacts related to its production by up to 29%, i.e. reducing the Global Warming

Table 10
Summary of the impact variations in % (organic over conventional): a positive value means the organic impact is higher than the conventional one.

Impact categories	Unit	Organic over conventional (% variation) 2022	Organic over conventional (% variation) 2023	Organic over conventional (% variation) 2024	Organic over conventional (% variation) 3-year average
Global warming	kg CO2 eq	8,93%	7,62%	7,71%	8,08%
Stratospheric ozone depletion	kg CFC11 eq	4,68%	5,88%	2,66%	4,41%
Ionizing radiation	kBq Co-60 eq	6,72%	9,43%	5,86%	7,34%
Ozone formation, Human health	kg NOx eq	2,63%	1,52%	1,98%	2,04%
Fine particulate matter formation	kg PM2.5 eq	6,27%	1,58%	5,85%	4,57%
Ozone formation, Terrestrial ecosystems	kg NOx eq	3,07%	1,90%	2,39%	2,45%
Terrestrial acidification	kg SO2 eq	8,18%	3,03%	7,85%	6,35%
Freshwater eutrophication	kg P eq	0,99%	−1,33%	−1,09%	−0,48%
Marine eutrophication	kg N eq	6,12%	8,13%	5,44%	6,56%
Terrestrial ecotoxicity	kg 1.4-DCB	−40,31%	−41,87%	−57,98%	−46,72%
Freshwater ecotoxicity	kg 1.4-DCB	0,32%	−8,48%	−3,60%	−3,92%
Marine ecotoxicity	kg 1.4-DCB	3,48%	−5,71%	2,31%	0,03%
Human carcinogenic toxicity	kg 1.4-DCB	−0,08%	−2,16%	−2,77%	−1,67%
Human non-carcinogenic toxicity	kg 1.4-DCB	2,92%	−3,71%	2,16%	0,46%
Land use	m2a crop eq	4,71%	5,72%	4,04%	4,82%
Mineral resource scarcity	kg Cu eq	2,47%	−1,84%	0,82%	0,48%
Fossil resource scarcity	kg oil eq	9,38%	7,91%	8,07%	8,46%
Water consumption	m3	1,02%	0,34%	−0,36%	0,33%

Potential (GWP) from 0.542 to 0.387 kg CO_2 eq per single glass bottle, thereby lowering the total impacts of the final product (0.75 L bottle of wine). A significant reduction in environmental impacts can also be achieved by increasing recycled glass content or transitioning toward alternative packaging formats such as aseptic cartons, bag-in-box systems, or PET bottles. The benefits of lightweight packaging are not limited to the production stage but extend to the transport stage: for the same volume of wine transported, lightweighting primary packaging reduces the overall vehicle load, resulting in reduced fuel consumption and associated transport-phase emissions.

5.5. Comparison with previous studies

The findings of this study are broadly consistent with major trends in the LCA literature on wine production. As highlighted by Cleary (2013), Fusi et al. (2014), García-García et al. (2023) and Ferrara et al. (2023), the glass bottle remains the dominant hotspot in most impact categories, and the present analysis confirms the central role of packaging regardless of the cultivation system considered.

With respect to vineyard processes, these results also align with previous studies showing that the relative performance of organic and conventional systems is strongly category-dependent. As reported by Borsato et al. (2020), Litskas et al. (2020), Sinisterra-Solís et al. (2020) and Volanti et al. (2022), neither system emerges as universally preferable, and the outcome depends on indicators, management strategies and local conditions. In line with this multidimensionality, the organic vineyard in this case study performs better in toxicity-related categories, particularly in terrestrial ecotoxicity, whereas the conventional vineyard displays lower impacts in indicators linked to diesel consumption, nutrient emissions and land occupation.

When compared with studies explicitly comparing organic and conventional vineyards - such as those by Pizzigallo et al. (2008), Point et al. (2012), Falcone et al. (2016), Steenwerth et al. (2015), Wang et al. (2023) and Ghiglieno et al. (2023) - these results show a strong degree of convergence in qualitative terms: no system proves to be environmentally superior across all categories, and differences arise primarily from yields, operational intensity and site-specific agronomic constraints. The magnitude of the reported differences, by contrast, varies considerably across studies, and is worth examining. A clear example is the comparison with Steenwerth et al. (2015). They report an 18% higher GWP for the organic scenario, against the +8.1% found here, and the difference largely reflects the different scope of the two functional units: their assessment is referred to one tonne of grapes and therefore stops at the vineyard gate, whereas ours refers to the packaged bottle. Restricting our comparison to the viticulture stage brings the organic–conventional GWP gap between the two systems to +38%, +38% and +29% in 2022, 2023 and 2024 (Section 4), which exceeds the 18% they report. The smaller difference observed for the packaged product follows from the inclusion of primary packaging: the glass bottle alone accounts for 61–73% of the GWP of the finished bottle and is identical in both systems, so it compresses the relative difference generated upstream in the vineyard. The remaining difference is consistent with the different grape varieties, climatic conditions and management practices of the two case studies, and does not affect the direction of the comparison. A related but different effect is illustrated by Falcone et al. (2015, 2016), whose conclusions on the same case study reversed when moving from 1 ha of planted surface to one bottle-equivalent: product-based units, unlike area-based ones, carry the lower yields of organic management directly into the result. At the same time, the present work provides additional insight that complements the existing literature. Unlike many comparable LCAs, which rely on a single production year or on a representative year, this study covers three consecutive years characterized by distinct rainfall levels, temperatures, operational requirements and yields. This multi-year perspective reveals that the environmental gap between organic and conventional systems is not fixed but changes over time, expanding or narrowing depending on the combined effect of climate, input use and productivity. The influence of rainier years on field operations and nutrient mobilization, the adjustments made by the farm in response to annual conditions, and the resulting year-specific impacts per bottle together offer a more dynamic

and contextualized understanding of viticultural sustainability.

6. Conclusion

This study has assessed and compared the environmental impacts of a 0.75 L bottle of conventional and organic white wine, produced by an Italian winery, over three consecutive years, applying an environmental Life Cycle Assessment, from raw material production to farm gate. Based on the three-year averages, the organic bottle shows higher impacts than the conventional one in 14 out of 18 midpoint categories. For global warming specifically, the average impact per 0.75 L bottle is 8.1% higher in the organic system than in the conventional one. For several other midpoint indicators, on average, the differences between systems remain limited: stratospheric ozone depletion (+4.4%), ozone formation for human health (+2.0%) and terrestrial ecosystems (+2.5%), fine particulate matter formation (+4.6%), human non-carcinogenic toxicity (+0.5%), land use (+4.8%), mineral resource scarcity (+0.5%) and water consumption (+0.3%). All of them show average impacts for the organic system that are around or below 5% higher than those of the conventional system. These results mainly reflect vineyard operations: the organic system performs more field activities, consumes more diesel and achieves lower grape yields, resulting in higher fuel and energy-related burdens per bottle. The conventional system benefits from higher yields and lower fuel demand but relies on synthetic fungicides, which are the main contributors to its terrestrial ecotoxicity and account for a substantial share of human carcinogenic toxicity. At the same time, the comparison highlights clear advantages of organic viticulture in specific indicators. Terrestrial ecotoxicity is, on average, about 47% lower for the organic system, reflecting the absence of synthetic fungicides used in the conventional vineyard. The organic system also shows small advantages in human carcinogenic toxicity (−1.7%) and freshwater ecotoxicity (−3.9%), while freshwater eutrophication (−0.5%) and marine ecotoxicity (+0.03%) are essentially equivalent between the two systems. Overall, the three-year picture describes a set of trade-offs: organic management improves toxicity-related indicators, whereas conventional management performs better in climate- and resource-related indicators.

Climatic variability across the three years also influences the results. Rainier and slightly warmer conditions are associated with more field operations in both systems, particularly in the organic vineyard, but the magnitude of the impacts depends on how input use and yields co-vary. Notably, the results suggest that it is the seasonal distribution of rainfall, rather than its annual total, that could be the primary driver of treatment intensity in the organic vineyard. In 2023, despite being the rainiest year overall, input use was at its minimum, likely because precipitation was concentrated in the winter and early spring months, leaving the critical summer period comparatively dry.

7. Implications, limitations and future research

Several improvement options emerge from this analysis, with implications for producers and for policy. Upstream measures - lighter bottles, higher recycled glass content and alternative packaging formats - could significantly reduce overall impacts in both systems, independently of vineyard management. In the field, the adoption of electric or biofuel-powered tractors, improved planning of operations and precision technologies for the timing and dosing of plant protection products could further lower diesel consumption and reduce the number of field operations in the vineyard. Collectively, these strategies align with the EU Green Deal - specifically objectives 4 and 5 of the Common Agricultural Policy (CAP) strategic plan - contributing to climate change mitigation, resource efficiency, and the sustainable management of water, soil, and air. For policy, the results further suggest that the case for supporting organic viticulture rests more solidly on toxicity-related indicators, where its advantage is substantial and consistent across the three years, than on climate- and resource-related ones.

Despite its comprehensive scope, this study presents limitations that should be acknowledged. First, it focuses on a single winery and two vineyards in one region. Although it covers three consecutive production years, the analysis remains specific to this production context, and the findings cannot be generalized automatically to other wine-growing areas or production systems. Second, some uncertainty stems from the inventory data: several background processes have been modelled using commercial LCI databases, which introduce additional uncertainty in upstream inventories, while mechanized field operations have been modelled using a single average diesel consumption value. In the latter case, operation-specific fuel consumption data would allow a finer characterization of this contribution and represent a useful direction for future refinement. Third, the assessment follows standard attributional LCA practice and does not fully capture soil-related processes, such as carbon sequestration, changes in soil organic matter or below-ground biodiversity. These aspects are particularly relevant for organic systems and are increasingly recognized as important components of agricultural sustainability, yet they remain rarely quantified in wine LCAs. Their omission may partly underestimate potential long-term benefits of organic management. Fourth, emerging technological options for viticulture are not considered in this study. Indeed, several new grapevine breeding and genetic improvement techniques may affect the future environmental profile of wine production. Among these, genome editing (e.g. CRISPR/Cas9) has been identified as a promising tool to increase disease resistance in grapevine, by introducing targeted mutations in susceptibility or defense-related genes, with the potential to reduce fungicide use (Capriotti et al., 2020). However, these applications are still at an early experimental stage and face significant technical, regulatory and societal barriers. Under the current EU framework, genome-edited plants are generally classified as GMOs and are therefore not compatible with certified organic cultivation (Regolamento (UE) 2018/848, 2018). As a result, such cultivars can realistically be considered only as a prospective option for conventional systems in the near term.

Future research should address these limitations by extending the analysis to multiple wineries and regions and by integrating indicators of soil health, carbon sequestration and ecosystem services into multi-year LCAs of viticulture. In addition, scenario-based studies explicitly exploring the environmental implications of innovative strategies - such as disease-resistant varieties, low-input technologies and electrified or alternative-fuel machinery - would provide a more complete and robust evaluation of the sustainability of organic and conventional wine production.

CRediT authorship contribution statement

Aurora Pichini: Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Lorena Crescenza:** Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. **Daniele Duca:** Validation, Supervision, Resources. **Filippo Emanuele Ciarapica:** Software, Resources, Project administration. **Leonardo Postacchini:** Writing – review & editing, Validation, Supervision, Resources, Conceptualization.

Declaration of competing interest

The authors declare no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2026.149365.

Data availability

The authors do not have permission to share data.

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