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Environmental Impact Assessment of an Organic Wine Production in Central Italy: Case Study from Lazio

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Abstract: Growing awareness of environmental sustainability in the agri-food sector has enhanced the gradual shift toward less-impactful food and organic production systems. In 2021, nearly three million hectolitres of organic wine were produced which accounted for 6% of the whole wine production in Italy (50.2 million hectolitres); thus, registering an increase of almost 60% in the last three years. The economic and cultural importance attributed to Italian wine production worldwide represents a key factor to assess and reduce the environmental burdens associated with the activities of this industry. Furthermore, literature studies have highlighted consumer sensitivity for sustainable winemaking processed, and there is even a trend towards eco-friendly wines. In particular, the bottling stage has been identified as an impactful stage for the environmental performance of the wine life cycle. This study examined the environmental impact assessment of organic wine production in the Lazio region, by performing a "cradle-to-gate" approach according to the life cycle assessment (LCA) methodology. High-quality inventory data for one year of operation was obtained directly from the farming company, "Tenute Filippi" (Cori, Lazio, Italy), and the wine process considered the input from grape cultivation to the winery phases. In these regards, the study also provided an impact assessment for the primary packaging of a 0.75 L wine bottle, with contributions from the different life cycle stages. The results showed a total amount of greenhouse gas emissions (GHGs) of 1.1 kg CO_2 eq, that are responsible for climate change. Referring to the individual production input, the primary packaging phase accounted for 55% of the total GHGs, with 0.86 kg CO_2 eq per bottle, followed by agricultural fuel use for grape production and harvesting activities, with 0.30 kg CO_2 eq. Building on these results, the study provides recommendations on the selection of the most significant and relevant indicators for the environmental life cycle impact assessment, thus, identifying possible hotspots in the wine sector.

Keywords: organic grape production; organic wine; environmental sustainability; life cycle assessment; wine-making; primary packaging; SimaPro software

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1. Introduction

Wine production is one of the oldest economic sectors and, presently, it represents one of the most important agricultural activities worldwide [1,2]. Since viticulture requires a temperate climate, wine production is mainly located in Mediterranean countries, and primarily in Europe, accounting for more than 64% of the global wine production, with 260 million hectolitres of wine produced in 2021 [3]. Out of the global wine production, Italy represents 19.3% (with 50.2 million hectolitres produced in 2021), ranking as the first wine producer in the world. As a result of its geographical conformation and heterogeneous weather conditions, Italian vineyards are characterized by a wide variety of types of wine marketed worldwide. The Italian processed grape market is mainly represented by "Protected Designation of Origin" (PDO) wines (with 23.1 million hectolitres produced in 2021) and Protected Geographical Indication (PGI) wines with 12.3 million hectolitres in 2021.

These certified products mainly designate a product origin, quality, and characteristics that are distinctive for a certain geographical environment, thus, representing a warranty of quality for consumers [4]. In recent years, consumers have also paid attention to purchasing organic products and wine, which is perceived as a choice of quality and safety, as it incorporates a guarantee of control and certification by specialized organizations [5]. In 2020, the European Commission opened a public consultation on organic farming to reach 25% of land cultivated organically by 2030. To achieve this goal, including in the European Green Deal, the Commission in 2021 allocated EUR 40 million to promote organic farming, ensure sustainable soil management, and encourage the purchase of organic products. Organic wine is assuming great importance in the international market; consumers, especially in high-income countries, are increasingly aware of consumer purchasing choices, thus, favoring the purchase of quality and organic wines. In this framework, the Italian wine sector has been characterized by an increase in organic wine production. In 2021, nearly 3 million hectolitres of organic wine were produced and accounted for 6% of the whole wine production in Italy, thus, registering an increase of almost 60% in the last three years [3]. The production of organic wine is regulated by the EU regulations, EC Reg. No. 34/07 and EC Reg. No. 889/08, which mainly concern organic farming and define the management of vineyards and the production of certified organic grapes from an agricultural point of view, and by EC Reg. No. 203/12, which specifically outlines the entire organic wine-making process.

To analyze the Italian wine-growing sector, a SWOT analysis was carried out, thus, providing an understanding of the main strengths (i.e., the internal advantages and opportunities), weaknesses (i.e., the internal risks and dangers), opportunities (i.e., the external advantages and opportunities, and threats (i.e., external risks and dangers) of the sector (Figure 1).

Figure 1. SWOT analysis of the Italian wine sector.

These variables provide an insight into the Italian wine sector concerning the external and internal environment in which it operates, supporting the strategic choices to be implemented. The Italian wine sector has considerable internal strengths that differentiate the sector from its competitors, thus, giving it an important competitive advantage.

The gradual change in consumer purchasing patterns can also be linked to a growing awareness of environmental sustainability in the agri-food sector, which has enhanced the shift toward less-impactful food production systems, as well as organic production [4]. The wine industry is one of the most impacting sectors worldwide, with significant implications for sustainability issues, as it contributes to a variety of environmental burdens, mainly due to the use of pesticides and fertilizers in the vineyard and the production of glass bottles, as already highlighted in the literature [4,6,7]. Therefore, there is growing pressure in the agri-food sector, both for producers and policymakers, to address the social and environmental impacts within the product life cycle. In this framework, the life cycle assessment (LCA) methodology represents a standardized and valuable tool to quantitatively measure the environmental impacts of a product throughout its life cycle, from cradle (including the supply of raw materials) to grave (end of product life) [8,9].

The sustainability assessment of wine production, from viticulture to the winemaking industry has been addressed by several authors at different levels of temporal resolution, revealing the scientific interest in this emerging topic. The LCA for the operations of an Italian winemaker case study has been proposed by different authors [7,10,11]. These studies assess the system activities, and input for the system (e.g., fertilizers, phytosanitary products, etc.) and quantify some categories of impact, including the global warming potential (GWP), fossil fuel consumption, and resource availability. For example, to improve energy and water efficiency, and to minimize the impacts related to the use of pesticides and chemicals in conventional viticulture, Volanti et al., (2022) investigated the environmental sustainability of organic grapevine crops [4]. Based on three Spanish grape processing systems, they showed a 10% reduction of the total impact of the organic vineyards compared to conventional production, without taking into consideration the wine-making process, and the packaging stage.

Considering the importance of Italian wine production, both in economic and cultural terms, an understanding of the environmental impacts associated with grape cultivation and wine-making activities, could be recommended. In this framework, the study examined the environmental impact assessment of organic wine production in Central Italy (the Lazio region), by performing a “cradle-to-gate” approach. High-quality inventory data for the year 2019 was obtained directly from the farming company, “Tenute Filippi” (Cori, Lazio, Italy), and the wine process considered the input from the grape cultivation (at the vineyard) to the wine-making process (at the winery). In particular, the study also provided an impact assessment for the primary packaging of a 0.75 mL wine bottle, with contributions from the different life cycle stages.

The importance of packaging decisions to reduce the environmental impacts associated with a given product or supply chain has been highlighted by recent studies. The bottling stage in the wine sector, especially glass bottle production, has been identified as an impactful stage for the environmental performance of the wine life cycle [12].

Siracusa et al. [13] used the LCA methodology to demonstrate that the thinning of a plastic film and the adoption of recycled polyamide in food packaging allow a reduction of 25% and 15% of the associated environmental damages, respectively. Indeed, more than 80% of the article considered only the carbon footprint (CF), and water footprint (WF) assessment related to wine products and the confectionary phase. To the best of our knowledge, there are no studies investigating the environmental performances of organic wine production in the Lazio region, considering a cradle-to-gate approach. To this purpose, the present study investigates the environmental sustainability of a 0.75 mL organic bottled-wine, by quantitively assessing 16 impact categories, as well as the energy input, demanding to identify hotspots and to determine best practices to minimize the environmental footprint.

2. Materials and Methods

A life cycle assessment (LCA) is a standardized tool to quantitatively evaluate the environmental impact associated with a product, process, or service [14]. In accordance with the ISOs [8,9], it should involve four phases: i. the goal and scope definition, describing the objective of the study, the functional unit (FU), and the system boundary; ii. a life cycle inventory (LCI), collecting the data necessary for the environmental assessment; iii. a life cycle impact assessment (LCIA), which is aimed at evaluating the sustainability in terms of the impacts on ecosystems, human health, and resources; and iv. the interpretation of results, in which the LCIA results are interpreted according to the objectives of the study. The SimaPro 9.2.2 (PRè-Sustainability, B.V.) software [15] was used for the evaluation of the environmental impacts of organic wine production in the Lazio region.

2.1. Goal and Scope Definition

The study aimed to assess the environmental impacts of organic wine production, identify possible hotspots in the life cycle, and investigate the most impactful phase from the adopted agricultural organic approach to the primary packaging phase. A cradle-to-gate study was performed: the entire wine production process, from grape cultivation to wine-making, including the bottling and packaging, was considered. The selected functional unit (FU) was one bottle of wine (i.e., 0.75 L of wine) and referred to the grape harvest in 2019. All the production flows analyzed were congruent with the FU examined.

2.2. System Boundaries

The system boundaries were defined on a cradle-to-winery gate approach, including all the input and energy flows associated with grapevine crops, the wine-making process, and bottling (Figure 2); whereas the distribution, retail, and consumption were not taken into account nor the waste management of wine by-products (i.e., stems, lees, and grape pomace), as they were reintroduced as a soil conditioner, constituting a natural fertilizer. The grape production included all the in-field operations, such as trellising, and fertilizer treatments, to prevent the development of fungi, insects, and microorganisms that could damage a harvest.

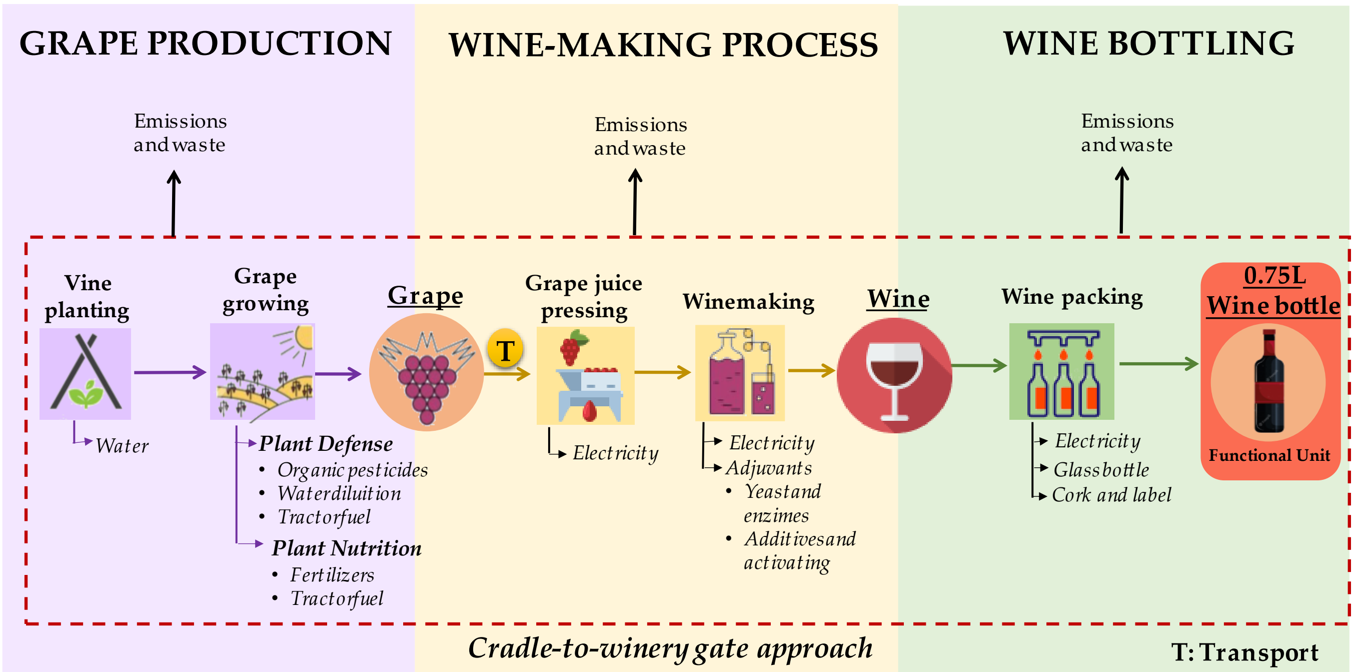

Figure 2. System Boundaries considered in the study according to a cradle-to-winery gate approach.

Considering the winemaking process, the LCI included the use of winemaking equipment (i.e., tannins, plant proteins, diammonium phosphate or DAP, etc.), refrigeration, and primary packaging (e.g., glass bottle, cork, heat shrink capsule, etc.). Farm construction and the production of agricultural machinery and winemaking equipment were not included in the analysis due to i. a lack of data, ii. the exclusion of operating goods in previous LCA studies on wine [11,16,17], and iii. the assumption that these inputs could be considered negligible because of their minor contribution to a single wine bottle.

2.3. Data Acquisition

The primary data were collected through the administration of questionnaires and face-to-face interviews with the farmers and employees in the farming company, "Tenute Filippi", in the year 2019. These surveys embraced a wide range of inputs for the cultivation sites, such as the fuel use, pesticides, field operations, machinery, or trellises for the grape cultivation, as well as the facilities and operational conditions adopted for the winemaking process, including the primary packaging. The farming company, "Tenute Filippi" is located in Central Italy, in Cori, in the province of Latina, in the Lazio region (Figure 3). The farm covers an area of 15 hectares (ha) in hilly surroundings, of which 7 hectares (ha) are planted with grapevines. On average, the company produces a total of 10 tonnes/year, and about 9300 bottles of wine had been produced in the year 2019.

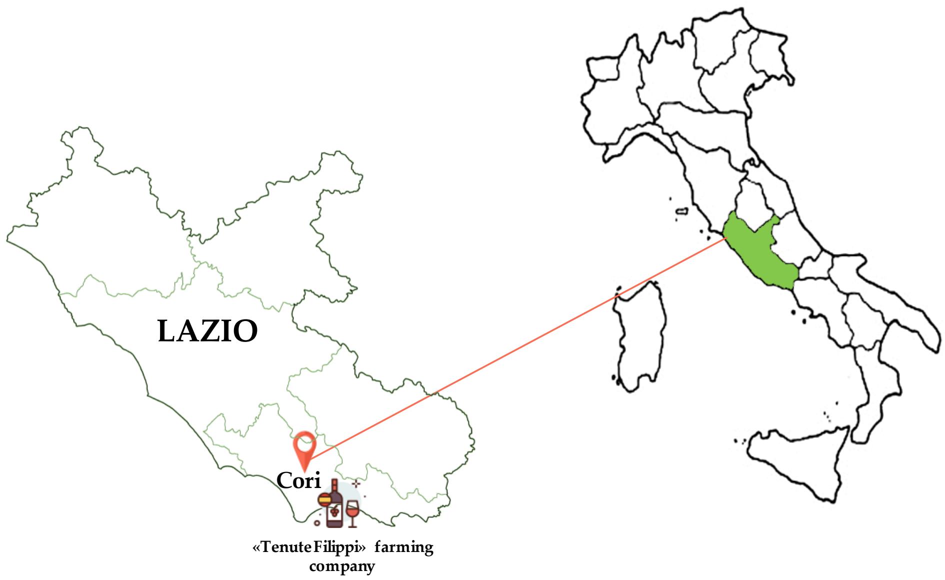

Figure 3. The geographical location of the winery involved in the study.

Direct emissions from field operations, such as the emissions from fossil fuel consumption by agricultural machinery, were estimated based on the characterization factors proposed by "Ente Nazionale per la Meccanizzazione Agricola" (ENAMA) (2005) [18]. Nevertheless, as mentioned in Section 2.2, only the on-field emissions were considered for compost, as the wine by-products (i.e., stems, lees, and grape pomace) were reintroduced as a soil conditioner, constituting a natural fertilizer; therefore, the compost processing stage was excluded from the system boundaries.

The secondary data referred to the input for phytosanitary defense (i.e., zeolite, sulphur, antagonistic fungi, etc.) as well as a trellis or diesel, and they were obtained from the database Ecoinvent v3.8, [19]. The organic fertilizer (i.e., humus, preparation 500, etc.) used in the organic viticulture, as well as adjuvants for the wine-making process (i.e., plant proteins, DAP, etc.), were obtained from the databases, Agribalyse v3.0.1 [20], and World Food LCA Database (WFLDB) [21].

2.4. Life Cycle Inventory (LCI)

Primary input data concerning the in-field operations and the wine-making process are shown in Table 1. These data consist of site-specific data collected through the administration of questionnaires and face-to-face interviews with the farmers and employees in the farming company, "Tenute Filippi", supported by the technical data sheets of the various machines used during the production process. The primary data were subsequently combined with the secondary data referring to the background production flows (i.e., fertilizers, and energy production) that were obtained from the databases, Agribalyse v3.0.1, Ecoinvent v3.8, and World Food LCA Database (WFLDB), provided in SimaPro 9.2.2.

Table 1. Inventory data used for each wine production stage (data referred to the functional unit—FU: one 0.75 L wine bottle).

Production Stage	Input	Unit	Quantity (0.75 L Wine Bottle)
Grape Production (at Vineyard)			
Plant defense	Copper	g	0.16
	Sulphur	g	0.54
	Zeolite	g	0.32
	Antagonistic fungi	g	0.32
Plant nutrition	Preparation 500	g	0.03
	Hummus	g	107.53
In-field operations	Diesel oil	L	0.04194
Plant water use	Water	L	0.86022
Output			
Grape		kg	1.075
Grape juice pressing (at winery)			
Transport (from vineyard to winery)	Diesel oil	L	0.01724
Crushing, stemming, and pressing facilities	Electricity	kWh	0.06476
Output			
Must		L	0.86
Pips, stalks, and grape skins		kg	0.30913
Wine-making process (at winery)			
Fermentation, clarification, and filtration adjuvants	Plant proteins	g	0.08
	Tannins	g	0.06
	Bioenology S14 A	g	0.015
	Metabisulphite	g	0.04528
	Diammonium phosphate (DAP)	g	0.012
	Yeast	g	0.015
	Activating enzymes	g	0.02275
Fermentation, clarification, and filtration facilities	Electricity	kWh	0.16272
	Water for dilution	L	0.04301
	Cellulose filter	g	0.065
Output			
Wine		L	0.75
Organic solid waste		L	0.02275
Wine packing (at winery)			
Washing bottles, packing, and primary packaging	Water	L	0.12903
	Electricity	kWh	0.00602
	Glass bottle	g	550
	Cork	g	5
	Capsule-PVC	g	1
	Label	g	2
Output			
No. 1 bottled wine		L	0.75

The grape production stage considered the plant production, involving the processes of phytosanitary defence (e.g., zeolite, sulphur, copper, and fungi protection) and plant nutrition (fertilizers) necessary for grape growing after the vine planting. Vine seedlings, corresponding to 0.6 units per bottle of wine, were not included in the life cycle inventory, due to the lack of data. The producers of the "Tenute Filippi" company use organic raw materials to preserve the soil's long-term fertility. In particular, it uses natural products of animal origin for soil fertilization, including humus and Preparation 500, which consists of cattle manure 6 months-aged in horn, and then sprayed on the soil at low concentrations (about 0.1 kg/ha) twice a year [11]. To protect the vineyard from pathogenic molds and toxic compounds, the company uses organic fungicides, including copper, sprayed together with water, sulphur, and finally zeolite. Freshwater consumption is related to the direct water used for irrigation and the dilution volume used for plant protection and nutrition. The diesel oil consumption related to the activities of tractors for the in-field operations (e.g., fertilization and phytosanitary treatments), and the transport distance of 1 km from the vineyards to the winery.

The wine-making process stage involves the grape juice pressing and the wine-making process. During the first phase, the stems, lees, and grape pomace are reused as compost in the fertilization process; therefore, the waste management and emissions from organic waste were not included in the sustainability assessment. The wine-making process included the adjuvants (i.e., additives and activating enzymes), and facilities (i.e., cellulose filters, diesel oil, and water) used for the processes of fermentation, clarification, and filtration. The inputs used in this study for each wine production stage are listed in Table 1. The wine packing stage consists of three processes: washing bottles, packing, and primary packaging. The inputs used for this stage (i.e., glass bottle, cork, PVC capsule, etc.) were obtained from the database Ecoinvent v3.8 [19].

2.5. Life Cycle Impact Assessment (LCIA)

The *ILCD 2011 Midpoint+ V1.11* (European Commission—Joint Research Centre—Institute for Environment and Sustainability 2010) was used for the environmental life cycle impact assessment calculation. The method included 16 environmental impact categories (e.g., climate change, ozone depletion, eutrophication, acidification, human toxicity (cancer and non-cancer related), respiratory inorganics, ionizing radiation, ecotoxicity, photochemical ozone formation, land use, and resource depletion (e.g., materials, energy, and water) [22].

To quantify the energy required for the different stages of wine production, the cumulative energy demand (CED) was calculated according to the CED method V1.11, which has been a widely applied tool to study the energy used by a good or service during its life cycle [23].

2.6. Carbon Footprint (CF)

The carbon footprint (CF) was then calculated based on the LCI and LCIA results. The CF is a measure expressing the greenhouse gas emissions (GHGs) caused by a product, service, or process. It is expressed in kilograms of CO_2 equivalent (kg of CO_2 eq), and according to the Kyoto protocol, the following gases are considered: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrocarbons, hydrofluorocarbons (HFCs), sulfur hexafluoride (SF_6), and perfluorocarbons (PFCs). Each GHG has a different greenhouse effect; therefore, the CF was calculated according to Forster et al., (2007) [21], based on Equation (1):

$$\text{Carbon footprint} = \sum \text{G.G.}_{\text{i}} \times \text{k}_{\text{i}} \quad (1)$$

where G.G._{i} represents the amount of GHGs produced and k_{i} corresponds to the CO_2 equivalent coefficient for that gas.

The CF was obtained employing the Green Gas Protocol V1.03/CO_2 eq (kg) method (GHGP 2020), by using the SimaPro v.9.2.2. software.

3. Results

The LCIA results for the organic wine production are shown in Table 2. and the life-cycle phases that mostly contributed to the main impact categories have been identified.

Table 2. Environmental impact assessment of organic wine production (data referred to FU: one 0.75 L wine bottle).

Impact Categories	Unit	Grape Production (at Vineyard)	Wine-Making Process (at Winery)	Wine Bottling (at Winery)
Climate change	kg CO_2 eq	2.97×10^{-1}	-6.90×10^{-2}	4.72×10^{-1}
Ozone depletion	kg CFC-11 eq	4.12×10^{-8}	4.32×10^{-8}	5.63×10^{-8}
Human toxicity, non-cancer effects	CTUh	9.21×10^{-7}	2.15×10^{-7}	5.90×10^{-8}
Human toxicity, cancer effects	CTUh	8.83×10^{-9}	1.33×10^{-8}	1.34×10^{-8}
Particulate matter	kg $PM_{2.5}$ eq	2.64×10^{-8}	1.61×10^{-4}	7.68×10^{-4}
Ionizing radiation HH	kBq U_{235} eq	2.05×10^{-2}	1.55×10^{-2}	2.26×10^{-2}
Ionizing radiation E	CTUe	1.57×10^{-7}	1.14×10^{-7}	1.71×10^{-7}
Photochemical ozone formation	kg NMVOC eq	2.59×10^{-3}	1.82×10^{-3}	2.42×10^{-3}
Acidification	molc H^+ eq	2.58×10^{-3}	2.26×10^{-3}	4.94×10^{-3}
Terrestrial eutrophication	molc N eq	9.26×10^{-3}	8.17×10^{-3}	9.08×10^{-3}
Freshwater eutrophication	kg P eq	1.80×10^{-5}	6.75×10^{-5}	1.24×10^{-5}
Marine eutrophication	kg N eq	8.16×10^{-4}	9.89×10^{-4}	7.86×10^{-4}
Freshwater ecotoxicity	CTUe	6.25×10^{-1}	2.97	4.83×10^{-1}
Land use	kg C deficit	2.27	7.45×10^{-1}	1.54
Water resource depletion	m^3 water eq	3.99×10^{-4}	9.42×10^{-4}	1.74×10^{-4}
Mineral, fossil & renewable resource depletion	kg Sb eq	5.57×10^{-5}	1.70×10^{-4}	1.44×10^{-5}

The results obtained for organic wine production showed a variable contribution to environmental impacts at certain phases in the life cycle. The wine bottling phase had the greatest environmental impact in terms of GHGs emissions, followed by the agricultural and wine-making phases.

The characterized results obtained with the ILCD Midpoint+ method for the organic wine production impact assessment are shown in Figure 4.

The wine bottling phase constituted the main contributor to environmental impacts, with a relative contribution ranging from 39% to 67%, in 7 out of the 16 impact categories analyzed. Notably, the wine packing phase mainly involved climate change (4.72×10^{-1} kg CO_2 eq), particulate matter formation (7.68×10^{-4} kg $PM_{2.5}$ eq), acidification (4.94×10^{-3} molc H^+ eq), and ozone depletion (5.63×10^{-8} kg CFC-11 eq) impact categories, accounting on average for 55.6% of the contribution for each impact category. The former also represented a hotspot for non-renewable, fossil energy demand, with 7.71 MJ eq, thus, contributing to 48.1% of the total non-renewable, fossil energy demand, as shown in Table 3, and Figure 5. This is mainly attributable to glass bottle production, which contributed ranging from 35% to 64% of the total impacts of the whole wine production system. Considering the individual production inputs, it can be stated that the glass bottle, whose weight was 550 g, represented the largest carbon footprint, thus, being responsible for generating about 0.54 kg CO_2 (Figure 6). This is in agreement with the results reported in the scientific literature, reporting glass bottles for wine packing as one of the greatest contributors to the global impacts on wine production [6,24,25]. In particular, the closest agreement was found in the study of Masotti et al., (2022), highlighting similar CO_2 emissions (0.5481 kg CO_2 eq) associated with the use of heavy glass bottles weighing between

650 g and 550 g [11]. In these regards, glass bottle production was identified as the highest energy-demanding input in the overall wine production system.

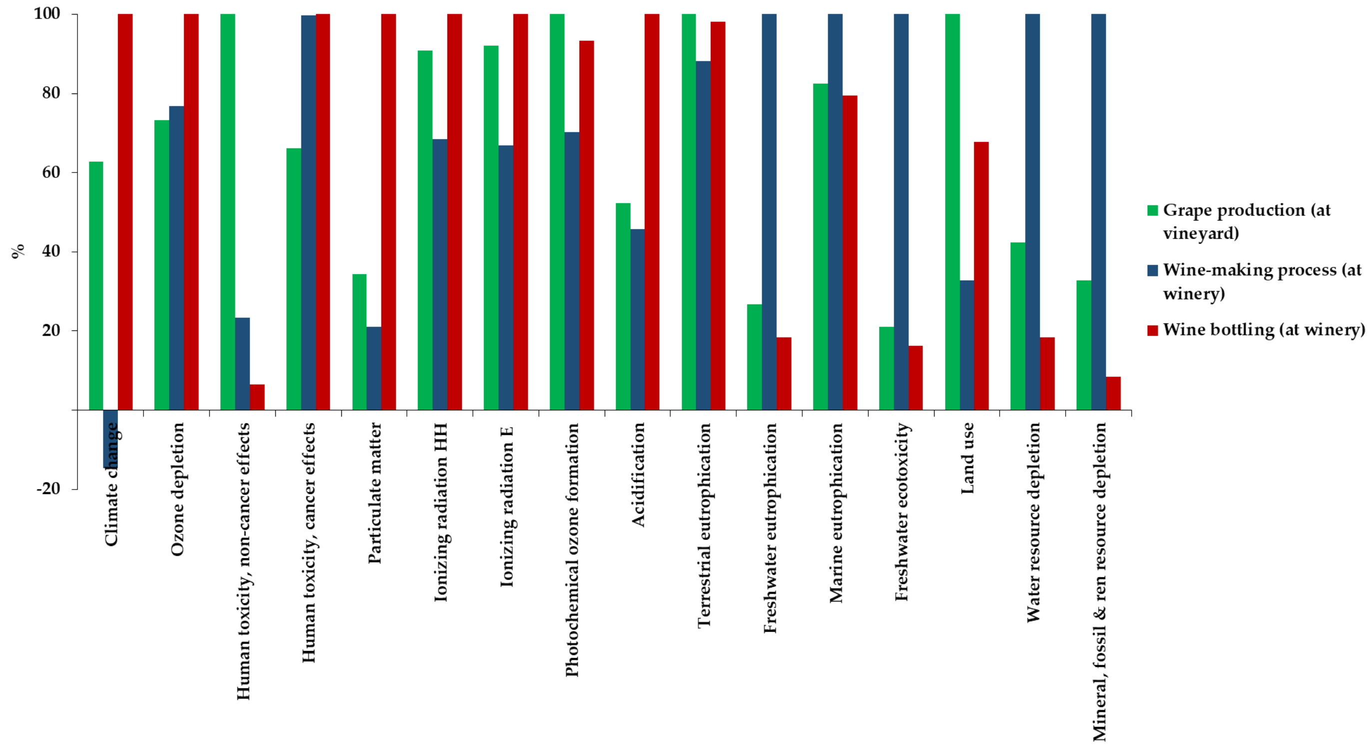

Figure 4. Characterized results of the organic wine production considering the system production from the vineyard (grape production) to the winery (wine-making and wine bottling processes).

Table 3. Results (MJ eq) of Cumulative Energy Demand.

Impact Category	Unità	Grape Production	Wine-Making Process	Wine Bottling
Non-renewable, fossil	MJ eq	4.188581	4.128974	7.706661
Non-renewable, nuclear		0.368467	0.281851	0.431374
Non-renewable, biomass		0.000948	0.000744	0.000317
Renewable, biomass		0.322749	3.393171	1.414292
Renewable, wind, solar, geothermal		0.011911	0.150735	0.055819
Renewable, water		0.205288	0.158478	0.157634

The vineyard phase mostly contributed to 4 out of the 16 impact categories, ranging from 36% to 50% (Figure 4) of the total environmental impacts. In particular, grape production mostly impacted the land use (2.27 kg C deficit), photochemical ozone formation (2.59×10^{-3} kg NMVOC eq), terrestrial eutrophication (9.26×10^{-3} molc N eq), and human toxicity-non cancer effects (9.21×10^{-7} CTUh). These results showed that the emissions arose from diesel oil for in-field operations, thus, being responsible for an average contribution value of 56.74% of the total environmental burdens in most categories. In particular, the diesel burned in agricultural machinery heavily contributed to the human toxicity-non cancer effects (81.6%), land use (59.15%), and climate change (48.4%), thus, being in line with other studies in the literature [6,11,24].

Furthermore, the total impact in the climate change category was mitigated by 89% by the wine-making process, resulting in a reduction of -6.90×10^{-2} kg CO_2 eq. This is attributable to the reduced energy consumption during the wine storage phase, lasting eight months since the wine is stored at room temperature without the use of electricity, owing to the favorable weather and pedo-climatic conditions of that geographical area. Since electricity is mainly produced from non-renewable fossil fuels, namely, oil and coal, with the consequent CO_2 emissions, a low-energy demanding process could potentially contribute to climate change mitigation [16].

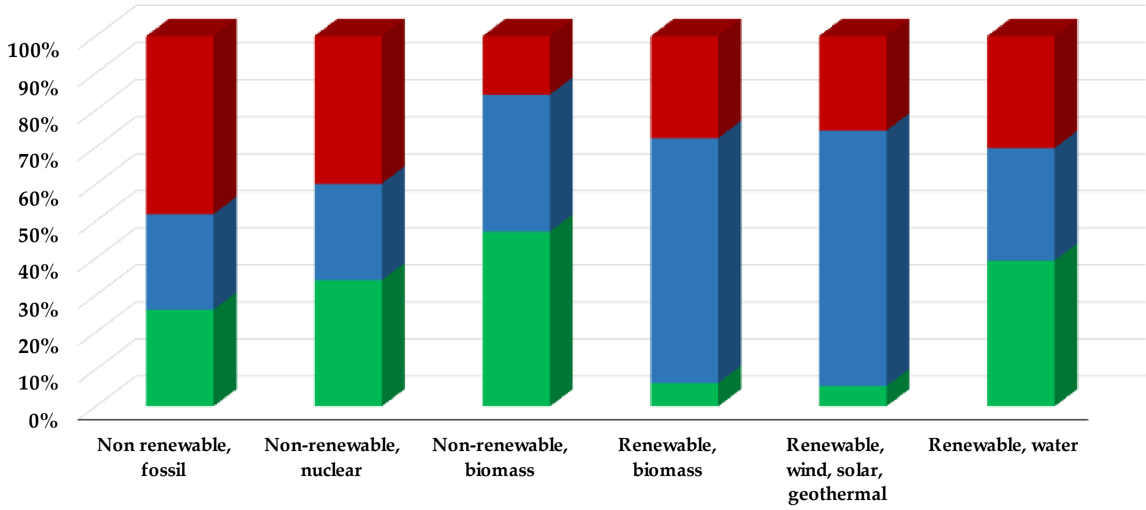

Figure 5. Characterized results for the cumulative energy demand of the wine production system analyzed.

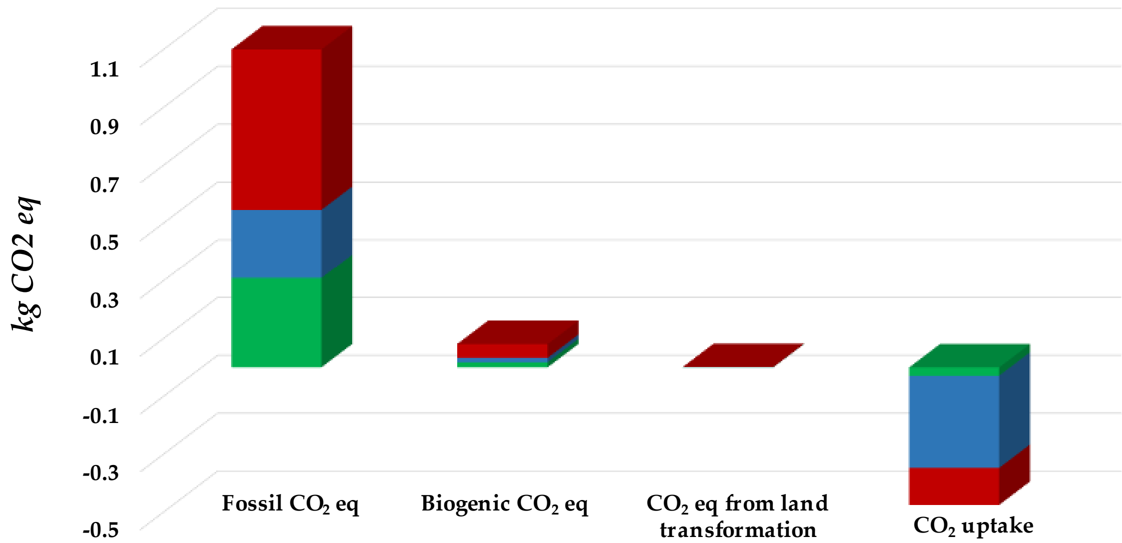

Figure 6. Greenhouse gas protocol results for the carbon footprint related to wine production.

Fossil fuel use for agricultural machinery implies the generation of direct nitrogen oxide emissions (NO_x), SO_2, and particulate emissions, thus, being responsible for photochemical oxidation formation [26]. The use of fertilizers (i.e., hummus, and Preparation 500) and pesticides (i.e., zeolite, sulfur, and antagonistic fungi) for plant nutrition and phytosanitary defense, respectively, represents the second contributor to the vineyard phase, thus, accounting for 6.1% of the total environmental burden in the land use, freshwater ecotoxicity, and climate change impact categories. Analogously to Masotti et al., (2022), also analyzing the organic wine production in Northeast Italy, fertilization and pest management resulted in being the second most impactful phases in the overall production system [11].

In particular, fertilizers can negatively impact on the land use impact category, since they require soil for livestock farming for manure production. The emissions of direct N_2O occurring during the application and production of fertilizers are mainly responsible for the climate change category, whereas the burdens for freshwater ecotoxicity are mainly related to glyphosate emissions to the air, occurring during the application of pesticides for plant phytosanitary defense. Additionally, as stated by different authors [6,10–27], pesticide treatments, as well as diesel production, are also responsible for hydrocarbons (PAHs), formaldehyde, barium, zinc, and benzene emissions to the air, soil, and water; thus, also representing a burden for human toxicity (with non-carcinogenic effects) [10]. Although the use of fertilizers and pest management were found to be the second most impactful processes in the viticulture phase, their relative contribution range was still significantly lower than the studies in the literature. As different authors have highlighted, fertilization and pest management have provided an average contribution ranging from 30% to 85% of the overall viticulture impacts [27,28]. This was attributable to the fact that the farming company, "Tenute Filippi", adopted natural organic fertilizers, which were produced entirely on-site (i.e., hummus), as well as reusing wine processing by-products (i.e., grape stalks, lees, and seeds) for soil fertilization with organic and natural nutrients.

The wine-making process produces fewer environmental impacts in comparison to the viticulture and wine bottling phases, thus, contributing on average 30% to the overall wine production impacts. In particular, the wine-making process impacted the most on freshwater ecotoxicity (2.97 CTUe), and eutrophication (6.75×10^{-5} kg P eq), the depletion of water resources (9.42×10^{-4} m^3 water eq), marine eutrophication (9.89×10^{-4} kg N eq), depletion of mineral, fossil and renewable resources (1.70×10^{-4} kg Sb eq), and human toxicity with cancer effects (1.33×10^{-8} CTUh). These results are in agreement with those present in the literature, highlighting an average contribution per each cited category between 10% to 13% [6,27]. In particular, the environmental problems caused for freshwater ecotoxicity, and human toxicity are mainly linked to the release of heavy metals (i.e., nickel, and arsenic), and PAHs to the air [27]. Nevertheless, the electricity consumption mainly employed for refrigeration during the fermentation and clarification processes is the first factor contributing from 25% to 69% of the environmental impacts of this phase, as shown in Figure 3. This was mostly related to metal production and end-of-life treatment for electrical supply infrastructure [26].

Subsequently, the cumulative energy demand (CED) and carbon footprint were also calculated for a greater understanding of the results to confirm the LCA results.

As for the CED (MJ equivalent), it was divided into two main categories (renewable and non-renewable) and eight subcategories (fossil, nuclear, biomass, wind, solar, geothermal, and water), as shown in Table 3.

The results highlighted the wine bottling phase as the major contributor, with an average of 55% for the non-renewable fossil (7.71 MJ eq) energy demand. This could be primarily attributable to glass bottle production, which represents, indeed, a high-energy-demanding industrial process in the entire wine production chain [28–30]. In the vineyard phase, the agricultural machinery to cultivate the land for the production of 1.075 kg of grape until its harvest requires a diesel input that accounts for 26% of the CED, thus, representing the second-highest energy-demanding input of non-renewable resources: fossil (4.188581 MJ eq), and nuclear (0.368467 MJ eq). The wine-making process, represented by the storage of wine, makes up 42.4%, leading to the first-highest energy input for renewable resources: the biomass (3.393171 MJ eq), and the wind, solar, and geothermal (0.150735 MJ eq) in the whole wine bottle-life cycle. This was favored by the fact that the farming company, "Tenute Filippi", managed to reduce its energy consumption during the wine storage phase, thus, enabling favorable weather conditions and climate, to store the wine at room temperature without the use of electricity. For this purpose, electricity was produced using non-renewable fossil fuels, especially oil and coal. Furthermore, to minimize negative externalities, the pruning waste, and wine by-products (e.g., the marc, stems, and lees) could be used as biomass to produce energy, reducing the use of fossil fuels [29].

Presently, the increasing sensitivity both of the public authorities and citizens to promote a GHGs reduction target for European municipalities of 50% by 2030 [31], has allowed the implementation of different quantitative methods to calculate the impact in the global warming category (i.e., carbon footprint). According to ISO 14067, the CF should also consider both fossil and biogenic carbon, for accounting and reporting the financed GHG emissions from real estate operations. In these regards, the Green Gas Protocol V1.03/CO_2 eq (kg) method (GHGP 2020), taking into account both the fossil and biogenic CO_2 emissions as well as the CO_2 uptake, was applied for the carbon footprint assessment. Figure 6. highlights that 1.10 kg CO_2 eq per wine bottle corresponded to the fossil carbon. The study by Laca et al., (2021) [6] provided estimates of the GWP of red wine obtained in around 30 LCA studies worldwide. The authors observed a large variation in the results, ranging from 0.18 to 3.22 kg CO_2 eq per bottle, with an average estimated at 1.74 kg CO_2 eq; therefore, the total GWP obtained in the current study fell well within the reported range. The results were also within the range for the cradle-to-gate GWP, here estimated at 0.86 kg CO_2 eq per bottle. Wine bottling resulted in being the activity most responsible for about 55% of the fossil (0.55676988 kg CO_2 eq), and biogenic CO_2 (0.047892031 kg CO_2 eq) emissions, mainly due to the production of glass bottles [24,25].

Additionally, in wine bottling, some inputs positively affect the CO_2 uptake (−0.12790184 CO_2 eq), thus, mitigating the GWP derived from the whole wine production process. For example, the use of a nomacorc cap has a positive impact on the impact category represented by climate change, as this cap is composed of vegetable biopolymers derived from sugar cane that are recyclable. This leads to the absorption of 0.054 kg of CO_2 eq.

Finally, organic grape production was revealed to be the second contributor to fossil and biogenic CO_2 emissions (i.e., 0.309382193 CO_2 eq, and 0.017594364 CO_2 eq, respectively), thus, representing on average 24.4% of the total GHG emissions. These values were lower in comparison with those reported in the literature, ranging between 55% and 72% [6,27], due to the organic cultivation system applied for grape production.

This system would avoid the GHG emissions mainly derived from the application of synthetic fertilizers and urea, as well as the excessive combustion of diesel by agricultural machinery.

4. Discussion and Improvements

When considering a cradle-to-winery gate approach, it has usually been found that wine bottling and viticulture are the major contributors to the whole wine production system [24]. Currently, the consumer associates the quality of a wine with the weight of the bottle, namely, the heavier the bottle the higher the quality of the wine, and for this reason, the consumer should be sensitized and informed about the environmental impact connected with this choice. To improve the environmental performances of the bottling and packaging phases, different improvement opportunities for the environmental impacts and for settling the energy requirements have been proposed [24,32]. In particular, the use of 30% lighter glass bottles than those currently used by wineries could result in lower energy and resources consumption for glass production; thus, reducing between 2% and 10% of the overall environmental impacts associated with the LCA of a wine bottle [25,33]. The lower weight of the glass bottles could result in a 4% savings in the GWP corresponding to 0.43 kg CO_2 eq per bottle; this is equivalent to around 7000 tonnes of CO_2 eq [25], thus, promoting a lower energy demand [11]. However, the preference for using lighter-weight bottles could not only represent a reasonable improvement action for minimizing the environmental burdens but it could also be replaced with the use of alternative and less-energy-consuming packaging materials, as well as PET, bag-in-box, etc.

Furthermore, focusing on the glass bottle's end-of-life (EoL), it was highlighted that an increase in the glass-recycling rate from 60% to 85% could reduce the environmental impacts associated with the GWP by 11.1% [33]. This was also in accordance with the study of Amienyo et al., (2014), pointing out a reduction of 2% in the GWP by achieving a 10% increase in the amount of recycled glass [25]. This would result in a savings of 0.22 kg CO_2 eq per bottle of wine, thus, corresponding to about 3600 tonnes kg CO_2 eq per year.

Another improvement for the sustainability assessment of wine packing could be glass substitution with different materials. As proposed by Clearly et al., (2013) [34], who studied the application of polyethylene terephthalate for wine bottling, observed an endpoint level impact reduction by 7–9%, in particular for human health (−7.1%), and resources availability (−8.3%). Furthermore, the use of alternatives for packaging, involving the use of sustainable materials for the labels, cork, and capsules (i.e., ultrathin ceramics, paper, and caps from bio-based materials, etc.) [35], could represent an improvement in mitigating the environmental impacts of the wine bottling stage. As a result, for the use of the normacorc cap in this study, a reduction of −5% in the environmental impact related to the GWP was observed, corresponding to 0.054 kg CO_2 eq.

Considering the environmental impacts associated with the agricultural phase for organic grape production, the sources of variability of the results among the literature studies are mainly related to different factors, such as the cultivation systems and agricultural practices (i.e., conventional, organic, and biodynamic), the types of grape, soil and climate conditions of the vineyard, etc., which significantly influence the annual yield of vineyards, and directly impact on the wine production [24,26]. The study of Villanueva-Rey et al., (2014) showed how the adoption of alternatives and more sustainable agricultural practices (i.e., organic and biodynamic), can reduce up to 50% of the environmental impacts of viticulture, thus, highlighting cultivation systems as the first discriminant for the wine production impact assessment [17]. It is also worth noting that in the LCA of agricultural systems, variations in the soil carbon stocks represent a key factor for biodiversity and soil quality improvement, as different authors have stated [17,36]. Furthermore, when considering the wine-making process, it is worth highlighting that reduced use of energy during the wine storage process could mitigate the impacts related to CO_2 emissions by about 89%. In this sense, possible improvements to reduce the GHG emissions during the winemaking phase caused by electricity could include the use of an energy source (i.e., photovoltaic panels), with the creation of an Off Grid winery, disconnected from the national energy distribution network, with a view to sustainability. A possible solution aimed at minimizing the use of electricity could be the installation of inverters and variable speed drives on the machinery, adapting the energy consumption to the actual needs per process, thus, achieving greater energy efficiency [37].

Improvement opportunities for the viticulture environmental performance could, therefore, consider the optimization of upstream processes for the use of bio-diesel for in-field operations, pesticides, and fertilizers composed of organic and bio-based ingredients [33,38,39], as well as acting on downstream processes, reintroducing, for example, the processing of by-products as other inputs for a new process to valorize the agricultural chain [40].

The management of organic and solid waste from wine production (i.e., grape pomace, lees, stalks, etc.) is also a determining factor in the wine-making process, thus, influencing the environmental impacts in variable percentages, between 10% and 30%, depending on the winery and wine type [41]. In this framework, many studies have evaluated different alternatives, for the management and waste valorization, such as composting stalks and wastewater sludge for the production of organic fertilizers [42], the design of adsorbent materials for heavy metals [43,44], as well as the recovery of bioactive compounds from wine wastewater for formulating functional foods [45].

5. Conclusions and Future Perspectives

In the wine sector, adopting a proactive and sustainable approach is a valuable action, as it is most affected by climate change; consequently, introducing such models contributes to mitigating global temperature increases. A focus on sustainability in this sector was here presented, through the cultivation of organic grapes and the implementation of sustainable practices during the winemaking process. A LCA was applied concretely, to study the production cycle of a 0.75 L bottle of wine, produced by the "Tenute Filippi" farming company. Considering a cradle-to-gate approach, it was possible to identify the hotspots of wine production comprehensively, both by considering their environmental impact assessment as well as the energy input demand. The LCIA results showed that the wine bottling stage represented the main contributor ranging from 39% to 69% of the environmental impacts, mainly due to the glass production process, as well as the use of fertilizers and pest management that were found to be the second most impactful processes in the vineyard phase. Based on the hotspot analysis, several options were identified to reduce the environmental impact of the wine industry, among which the use of a 10% lighter glass bottle could be beneficial to the environment, thus, saving at least 0.43 kg CO_2 eq per wine bottle. Furthermore, the reuse of biomass from pruning the grapes as natural organic fertilizers, as well as wine processing by-products (i.e., grape stalks, lees, and seeds) represented a potential alternative for soil fertilization with organic and natural nutrients.

However, a limitation of this study resides in the exclusion of some upstream activities (i.e., transportation and production of phytosanitary products, corks, labels, and caps), as well as the downstream activities, such as waste management, a bottle's EoL, and the transport, storage and distribution phases of the wine bottles to consumers. This was due to two main reasons: (i) a lack of available data, and (ii) the negligible aspect of these activities, as confirmed by other studies in the literature [27,33]. In this framework, it would be worth carrying out a more complete study, covering more wine production life cycle phases, and revealing each one's relative importance.

Furthermore, the present study does not provide a comparison with other cultivation systems and agricultural practices (i.e., conventional, organic, and biodynamic), and it should be considered as the first reference for further studies to evaluate the environmental sustainability in a comprehensive form, thus, developing a harmonized study for the comparison among LCA results for further implementation by the same farming company.

Therefore, based on the results obtained, it is desirable to rationalize and sustainably manage resources in wine production, acting both on the upstream and downstream levels. The former should provide resource efficiency, and increased productivity in the production process, thus promoting the use of renewable resources, and orienting production toward "*zero* waste". Meanwhile, downstream activities should promote sustainable management, and valorisation, and reintroduction of wine by-products into the economic system, to reduce synthetic fertilizers, improving their efficiency of use through the introduction of new technologies (i.e., precision agriculture) and new technical means (i.e., bio-stimulants). As in the automotive industry, there should be greater interest in electrifying agricultural machinery, reducing the potential environmental impacts associated with fossil fuels.

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