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Environmental Footprints of Red Wine Production in Piedmont, Italy

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Abstract

Italy is a global top wine producer, with emphasis on high-quality wines. This study investigates the Carbon Footprint (CF), Water Footprint (WF), and Ecological Footprint (EF) of twelve red wine producers in Piedmont, Northern Italy. The analysis was based on a 0.75 L wine bottle as functional unit (FU). Twelve producers were interviewed and given questionnaires, which made it possible to gather primary data for the environmental evaluation that described vineyard and agricultural operations and wine production. The average CF was 0.88 ± 0.3 kg CO_{2eq}, with 44% of CF associated with the glass bottle, 20% to the diesel fuel fed to the agricultural machines, 32% to electricity consumption, and 4% to other contributions. The average WF was 881 ± 252.4 L, with 98% Green WF due to evapotranspiration, and 2% Blue and Grey WF. The average EF was 81.3 ± 57.2 global ha, 73% ascribed to the vineyard area and 27% to CO_2 assimilation. The obtained CF and WF values align with existing literature, while no comparison is possible for the EF data, which are previously unknown. To reduce the environmental impacts of wine production, actions like using recycled glass bottles, electric agricultural machines and renewable energy can help. However, high-quality wine production in Piedmont is deeply rooted in tradition and mostly managed by small producers. Further research should investigate the social acceptance of such actions, and policies supporting economic incentives could be key enablers.

Keywords: assessment; environmental; footprint; vinification; wine; water

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1. Introduction

European policy initiatives foster biodiversity, sustainable agriculture, and the Circular Economy in the wine sector [1]. The European Commission (EC) enacted the Common Agricultural Policy (CAP) in 1962 [2] to support farmers, improve agricultural productivity and competitiveness [3], and ensure a sustainable management of natural resources [4] to mitigate climate change, emphasizing rural development. In the CAP Strategic Plan 2023–2027 [2], EC funding to support the wine sector amounts to 323.9 M Euro, with 5% of the total budget associated with environmental objectives, such as investments in wine farming. The System of National Integrated Quality Production (SQNPI) [5] established guidelines for obtaining Sustainability Certification for Wine, which is also promoted in the CAP. In Italy, the disciplinary (i.e., official document outlining the rules that ensure the authenticity and quality of wines, particularly those with protected designations like DOC, DOC) of the wine sector certification system was approved in March 2023 to support integrated production policies [6]. According to the OIV (International Organization of

Vine and Wine) [7], the global vineyard area in 2022 was 7,254,512 ha, corresponding to 60.1% of wine grapes, 30.3% of table grapes, and 9.6% of grapes for drying. Italy is the first producer and exporter of wine in the world and the third consumer. In 2022, Italy produced 49,843 hL of wine from 718,198 hectares of vineyards, representing 19.3% of global wine production [7]. ISTAT, the Italian Institute for Statistics [8], reports that the northern regions of Italy produce more wine (56% of the total) than the Central, southern, and island regions combined (44%). Since 2009, all wines certified of high quality in Italy have been combined into a single denomination "Protected Designation of Origin" (DOP in Italian) [9]. However, the relevant specifications for wines that have obtained DOC (Controlled Designation of Origin) and DOCG (Controlled and Guaranteed Designation of Origin) quality certifications are still provided as reference [10]. In the European Union's wine classification system, both DOC (Denominazione di Origine Controllata) and DOCG (Denominazione di Origine Controllata e Garantita) fall into the category of PDO (Protected Designation of Origin), as also defined by the European regulation adopted by the Italian government [11]. While both designations aim to protect the geographical origin and guarantee quality, DOCG represents the highest level of certification in Italian wine production. Wines marked with the DOCG mark must meet more stringent requirements, including a lower yield per hectare, longer mandatory ageing periods, and comprehensive chemical and organoleptic tests before placing on the market. In addition, DOCG wines are submitted to an official sensory evaluation by expert panels and must bear a numbered state seal for traceability. DOC wines, although subject to strict rules, are subject to slightly less restrictive controls and generally come from larger production areas. However, a constant quality over time and a strong territorial identity can allow a DOC wine to qualify for the DOCG status. Both classifications serve to guarantee the authenticity and typicality of Italian wines, supporting the preservation of the oenological heritage and giving consumers security. In the Northern region of Italy, 66% of production is related to high quality wine with DOP certification. According to the National Confederation of Voluntary Consortia for the Protection of Italian Wine Denominations [10], Piedmont, a region in Northwest Italy, has the highest number of DOCG wine labels, i.e., 41 DOC and 19 DOCG certifications in 2023, representing one-quarter of the total national DOCG labels [8]. Therefore, red wine produced in Piedmont can be globally considered a representative and significant example of high-quality wine.

Wine production involves multiple phases, including viticulture, winemaking, bottling, and packaging [12–15]. Grape cultivation implicates phytosanitary defence and plant nutrition [16]. After grapes are harvested, vinification starts right away, and the residues are composted and usually applied on the vineyard as fertilizer [17]. Bottling is environmentally significant, not for the operation itself but rather for the glass bottle (61% of CF) and label (35% of CF) [18]. In detail, using lighter glass bottles (−10% bottle weight) can save up to 0.43 kg CO2eq/bottle [16], and other materials such as PET [19] can reduce the associated environmental impacts by 21% [20]. The production and transport of the bottles to the winery also contribute to the overall environmental impacts [18]. Also, an increase in the use of recycled glass from 60% to 85% might result in an 11.1% reduction in the CF [16].

Literature extensively investigated the environmental aspects associated with wine production. A literature review performed on Scopus database with the keywords "wine" and "environmental assessment" in the period 2013–2024 provided 378 documents. A screening based on the consistency of the abstracts allowed to select 45 references. These have been categorized (Table 1) according to the type of publication (scientific article or review), geographical location, environmental assessment tool, functional unit, system boundaries applied, and main findings. About the type, there are 37 scientific articles and

8 review papers. These review papers focus on CF calculation applied to case studies in Europe, mostly in Italy, and show that red wine production is more impactful than white wine [21], and that environmental certifications can improve the sustainability of the wine sector [22]. With respect to WF, according to these review papers, the green component is prevalent [23,24].

Table 1. Categorization of the references selected in the literature review (R: review paper, SA: scientific article, CF: carbon footprint, FU: functional unit, na: not available).

Reference	Type	Tool	Geographic Location	FU	Main Findings
[25]	R	WF	na	na	Water management policies on consumptive WF and supply chain profitability
[23]	R	WF	Italy	na	The total WF of national production in Italy: 81% associated with green WF, 8% to blue WF and 11% to grey WF
[26]	SA	WF	Spain	na	Very fast increase in the blue WF from 1995
[27]	SA	CF	na	na	Viticulture contributes to >50% of the CF
[28]	SA	CF	Italy	na	In the global wine market firms' sustainable strategies through activities aimed at improving CF performance.
[29]	SA	WF	Italy	1 bottle 0.75 L	WF is 632.2 L, due to green water (98.3%) and with minor contributions (1.2% and 0.5%) given by grey and blue water, respectively.
[30]	SA	CF, WF	Italy	1 bottle 0.75 L	The CF is 1.07 ± 0.09 kg CO_2eq and the WF is 580 ± 30 L
[31]	SA	WF	Italy	1 bottle 0.75 L	The blue WF corresponding to the 15%, the grey WF contributes only to the 2% and the green WF contributes to the 83% of the overall WF.
[32]	SA	CF, WF	Italy	1 ha vineyard	Organic management in viticulture can be applied without having economic losses and with the benefit of better preserving the natural capital.
[12]	R	LCA	Italy	1 bottle 0.75 L	The temporal aspects were treated only in 78% of cases, the specific geographical location was indicated for 97% of the studies.
[17]	SA	CF	Italy	1 bottle 0.75 L	The CF is 0.79 ± 0.14 kg CO_2eq, with 15% related to viticulture and 85% to the vinification.
[33]	SA	CF, WF	Italy	1 bottle 0.75 L	CF is 1.47 kg CO_2eq, while the WF is 666.7 L (86.75% green water, 1.92% blue and 11.34% grey).
[34]	SA	CF	Italy	1 bottle 0.75 L	The main contributors of GHGs emissions are the glass bottle (29%), electricity used in the winery stage (14%), transport and distribution of the final product (13%), heat used in the winery phase (9%) and fossil fuels used in vineyard (8%).
[35]	SA	WF	Romania	1 bottle 0.75 L	99% of the total WF is related to the supply-chain water use, out of which 82% is green, 3% blue and 15% grey.
[36]	SA	LCA,	Italy	0.75 L of packaged wine	Italian still wines showed impacts 30% higher compared to the European reference value, the opposite trend was observed for sparkling wines.
[28]	SA	CF	Italy	1 bottle 0.75 L	CF is 2.2 kg CO_{2eq}.

Table 1. *Cont.*

Reference	Type	Tool	Geographic Location	FU	Main Findings
[37]	SA	LCA, LCC	Spain	1 bottle 0.75 L	The weight of the glass bottle should be minimized as it has a great impact on environmental (−40%) and production costs.
[38]	SA	CF	Spain	na	CO_2 alcoholic fermentation process strategy offers a new pathway toward a greener wine-making production with a 16.79% reduction in the CF.
[39]	R	LCA	Italy, Spain	1 bottle 0.75 L	Wine type (red or white) and grape variety are less significant in determining the CF than the production strategies employed.
[40]	SA	WF	New Zealand	1 bottle 0.75 L	The volumetric WF quantifies the water based on consumption along the product life cycle; in this way the comparisons of impacts between products of different regions are limited.
[41]	SA	CF	Italy	1 bottle 0.75 L	Red high quality wine CF in the range 0.99 to 0.05 kg CO_2eq.
[42]	SA	CF	Greece	na	Focus on CF related to vineyard practices link to pesticides, fertilizers and fuel use. Results show that fuel is the main contributor to CO_2eq compared to pesticides and fertilizers.
[43]	SA	CF	Greece	na	The CF is due 32% to viticulture (328.27 t CO_2eq) and 68% to vinification (1000.87 t CO_2eq). The annual CF in 2020 was 1383.14 t CO_2eq.
[44]	SA	WF	Italy	1 bottle 0.75 L	Green water represents 81% of the WF, ranging between 704.5 and 915.9 L of green water/L wine produced.
[20]	SA	LCA	Chile	1 bottle 0.75 L	The environmental impacts are associated with viticulture (39%), bottling (12%), and distribution (42%).
[45]	SA	LCA	Cyprus	1 bottle 0.75 L	CF is 1.31 kg CO_2eq (46% due to electrical energy consumption, 18% to packaging, 16% to viticulture, and 10% each to fuel and waste management).
[46]	SA	CF	Italy	1 bottle 0.75 L	The contributions of CF are 29% distribution, 25% canteen activities, 25% packaging and 16% vineyard activities.
[47]	SA	CF	Italy	na	Recovery of biogenic CO_2 from alcoholic fermentation of grapes could be seen as a new strategy to consolidate the status of carbon neutrality (approximately capture more than 6000 t CO_2 in the territory of Siena.
[48]	SA	CF	Italy	1 kg of grape yield	CF is 0.39 kg CO_2eq, mostly related to fossil fuel use and soil management.
[49]	SA	LCA	Italy	1 bottle 0.75 L	The packaging materials stage accounted for 71.3% of the contribution for each impact category of LCA study.
[19]	SA	LCA, LCC	Italy	1 glass 0.125 L	The glass bottle is the most impactful packaging, followed by the PET keg and the steel keg; the higher quantity of raw material used for the glass bottles and the total weight of each batch led to a greater environmental impact.

Table 1. *Cont.*

Reference	Type	Tool	Geographic Location	FU	Main Findings
[50]	SA	WF	Italy	na	Policy planning of wine production, integrating the notion of WF, land use and prices, represents the potential to reach the objective of an integrated and durable sustainability.
[24]	R	WF	Italy	na	Water sustainability assessment (including WF) of wine production in Italy. Crop water use (i.e., green water) is the main contributor to the WF.
[18]	SA	LC, LCC	Italy	1 bottle 0.75 L	The GHG emissions that resulted from the LCA analysis of packaging activities were 0.55 kg CO_2eq (57% related to the glass bottle, 32% to the label).
[51]	SA	LCA,	Brazil	1 bottle 0.75 L	CF is 287.5 g of CO_2eq for red wine and 29.2 g of CO_2eq for white wine.
[22]	R	CF	Italy	1 bottle 0.75 L	Utilizing environmental certification programmes is a useful strategy for raising standards in the food and wine industry.
[52]	SA	CF, WF	Australia	na	Water use occurred mainly in the vineyard (97%), and this was the main contribution to the WF (97%).
[53]	SA	CF, WF	na	1 bottle 0.75 L	For red wine CF is 1.427 kg CO_2eq and WF is 497.7 L; for white wine CF is 1.374 kg CO_2eq and WF is 539.7 L.
[54]	SA	CF	na	na	The average CF values collected for 29 literature studies: the CF for a generic bottle of wine is 2.2 ± 1.3 kg CO_2eq.
[55]	SA	CF, WF	Portugal	1 bottle 0.75 L	WF ranged from 366 to 899 L, with green water representing >50% of the total WF. The winery stage is responsible for >75% of the CF.
[56]	SA	CF	na	na	An increase in price proportional to the CF of the wine is associated with wine choices that have lower levels of emissions. Specifically, the price increase is associated with an average reduction of approximately 0.1 kg CO_2eq emitted per purchased wine bottle.
[21]	R	CF	Europe	1 bottle 0.75 L	The average CF were 1.02, 1.25, and 1.62 CO_2eq for red wine from organic cultivation, and for red wine and white wine from conventional cultivation, respectively.
[57]	SA	LCA	Italy	1 bottle 0.75 L	Average value of GWP for four production years is 1.2 ± 0.18 kg CO_2eq/bottle of wine.
[16]	SA	LCA	Italy	1 bottle 0.75 L	CF is 1.1 kg CO_2eq (55% due to the packaging, and 30% due to agricultural fuel use for grape production and harvesting activities).
[58]	R	LCA	Italy, Spain, Portugal	1 bottle 0.75 L	CF is 1.37 ± 0.91 kg CO_2eq (35% due to agricultural practices and 53% to vinification and packaging phase)

Almost all references in Table 1 considered "cradle to gate" system boundaries [16,33,48,49,55,56,58], i.e., the environmental impacts were accounted from the vineyard to the wine bottles ready to be shipped to vendors or clients. Examples of the designated functional unit (FU) were a 0.75 L bottle of wine (58% of references) [19,33,34,50,52,57], 1 hectare of vineyard (3%) [32], 1 kg of grape (3%) [48], and a 0.125 L glass of wine (3%) [19], while in 14 references the FU was not disclosed. About localization, Italy hosted 53% of the analyzed case studies [13,24,28,36,45,46,58–61], few were reported in France [42], Spain [26,37,38], Portugal [55], Greece [43], Romania [35], and other countries [40,51], and 15% did not specify the localization [27,54].

A total of 40% of the references performed a Carbon Footprint (CF) analysis [21,37,42,53,55,58], 27% a Water Footprint (WF) assessment [23,29,40,50], and 15% both [30,32,55]. For instance, the CF and WF of 15 red wine production case studies in Italy have been assessed [33] obtaining an average value of 1.47 kg CO2eq/FU for CF and 666.7 L/FU for WF. In Brazil, white wine production has lower impact (−6%) than red wine [51]; conversely, in southern Europe, the production of white wine had a bigger impact than that of red wine [21]. Other studies compared the organic and traditional viticulture operations [62–64], achieving better performances for the organic one in C F (−16%) and WF: a reduction is observed for blue and grey water (respectively, −28% and −96%), while an increase is shown for green water (+6%)—implying a better use of the soil moisture along the growing period—compared to conventional agriculture.

The geographical context of the studies is a key factor [51], as the CF depends on energy consumption and the local energy mix [61]. CF and WF were the most used methodologies (82% of the references), and Life Cycle Assessment (LCA) methodology was applied in 18% of the case studies [20,45,49,57], while only 7% also applied Life Cycle Costing (LCC), showing a medium value of 1.75 €/bottle [33] or 2.48 €/bottle [18].

Based on the performed literature review, some knowledge gaps can be highlighted about the environmental assessment of wine as a product, as follows. Firstly, just few review papers have been published in the last 11 years, and most research articles applied single environmental assessment tools (mainly CF, WF, and LCA), providing specific and non-harmonized points of view to the topic. Secondly, none of the selected references applied the EF methodology, leaving unexplored the impacts of wine production on natural resources.

The main aim of this study is the preliminary investigation on the environmental performance of red wine produced in Piedmont (Northwest), an excellence in the global market. Based on a literature overview, the novelty of this work is (i) the application of EF tool within a cradle to gate system, from the vineyard to a 0.75 L bottle of wine; and (ii) the simultaneous application of carbon, water, and ecological footprint to the same case studies of red wine producers. The objective is to provide the outcomes of this environmental evaluation of CF, WF, and EF on red wine growers, offer different and complementing viewpoints, and, if feasible, compare them with existing literature to highlight bottlenecks and future trends to improve the sustainability of wine production.

2. Materials and Methods

2.1. Description of Case Studies

The analysis was based on 12 case studies of wine producers located in Piedmont, Italy (Figure 1). Specifically, the case studies are in the area defined Langhe and Roero and involved producers of DOC and DOCG red wines: Barolo, Barbera, Barbaresco, and Nebbiolo.

The information used for the analysis was collected through the submission of a questionnaire (Table 2) (data collected from the different case studies are in Appendix A) to producers to collect primary data about the phases of the life cycle of wine production: (i) viticulture (hectares of vineyard cultivated, type of cultivation—i.e., conventional or organic, use of chemicals as copper oxide, nitrogen fertilizers, and pesticides, use of water for irrigation and of fuel for the agricultural machines), (ii) vinification (use of sulphur and sulphur dioxide, use of water and electricity in the cellar), and (iii) bottling (number of bottles produced per year, type and volume of the bottle, materials employed for the cap, e.g., aluminum and cork, and paper label). To ensure data consistency and comparability across producers, the questionnaire was designed with strict methodological standards. All quantitative responses were structured with mandatory units of measurement, such as litres, kilograms, grams, kilowatt-hours (kWh), hectares, and bottles per year, thereby avoiding ambiguities in data interpretation. Furthermore, a clear temporal reference was established for all questions, requiring respondents to report values corresponding to a specific production period. To minimize errors and facilitate subsequent data processing, open text fields were avoided for numerical inputs, which were instead constrained to predefined formats. In addition, several questions used categorical closed-ended responses, particularly for variables such as cultivation practices (e.g., conventional, organic), ensuring uniformity in classification and facilitating the analysis.

Figure 1. Geographical location of the case studies.

Table 2. Questionnaire submitted to producers for data collection for analysis CF, WF, EF.

Input	Unit
Hectares cultivated	ha
Quantity of grapes harvested	kg
Number of bottles produced annually	-
Applied agricultural practice (organic/conventional)	-
Quantity of copper oxide	kg/ha
Quantity of sulphides	kg/ha
Quantity of sulphur dioxide	kg
Quantity of nitrogen fertilisers applied	kg
Weight of the glass bottle	kg
Weight of the bottle cap	g
Weight of the PVC capsule	g
Weight of the aluminum capsule	g
Weight of the label	g
Fuel used	L
Electricity consumption	kWh
Number of pesticide applications	-
Average volume of water used for pesticide dilution	m^3
Water consumption in the cellar	m^3

Conventional viticulture involves the use of synthetic agrochemicals such as fertilizers, herbicides, and systemic pesticides to optimize grape yield and manage biotic and abiotic stresses. In contrast, organic viticulture avoids the use of synthetic inputs and instead employs organic soil amendments, mechanical or manual weed control, and natural pest management strategies [63]. This approach aims to preserve soil biodiversity, enhance ecosystem services, and promote long-term sustainability in vineyard management. For instance, it has been detected that organic farming provides higher levels of polyphenols than conventional farming when it comes to wine manufacturing [64,65].

2.2. Methodologies Applied

Based on the results of the literature review (Section 1), this study adopted a 0.75 L wine bottle as FU and “cradle to gate” system boundaries (Figure 2).

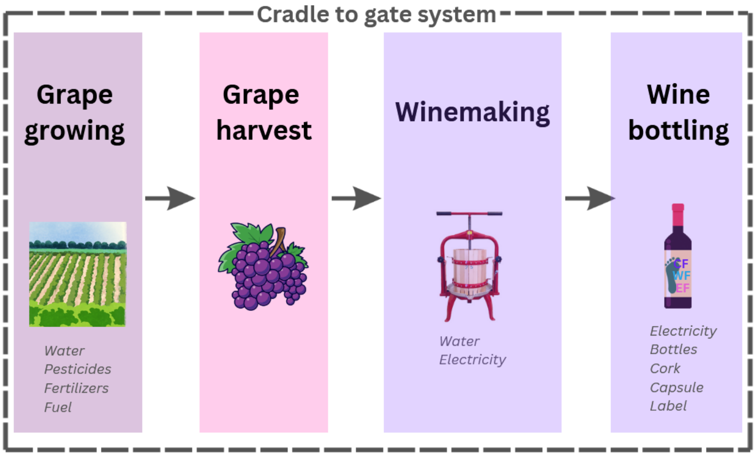

Figure 2. System boundaries of the case studies.

The environmental assessment was performed through simultaneously application of CF, WF, and EF methodologies at all twelve case studies, as follows. CF is based on international standard ISO 14067 [66] and quantifies as CO_{2eq} both the direct and indirect Green House Gases (GHG) emissions associated with a specific product. CF calculation was based on the life cycle phases of wine production and the related materials mentioned in Section 2.1 and on the emission factors (Table 3) reported in the literature for an Italian case study [17] and followed Equation (1).

$$\mathrm{CF} = \sum_{i=1}^{n} \mathrm{A_i} * \mathrm{EF_i} \tag{1}$$

A_i represents the activity data, such as the quantity of a material used or energy consumed, and EF_i is the corresponding emission factor, expressing the amount of CO_2eq emitted per unit of that activity. The calculation of the Carbon Footprint includes all three emission contributions: biogenic, fossil, and land use change, in order to provide a complete assessment in line with current international guidelines.

WF is based on the international standard ISO 14046 [67] and measures water consumption throughout the entire production cycle [31,45] as sum of three sub-indicators: green (Green WF), blue (Blue WF) and grey (Grey WF) water footprints. Green WF accounts the rainwater stored in the soil through the roots of the plants and consumed through evapotranspiration ($ET_{a,i}$) as in Equation (2) [30]:

$$\mathrm{ET_{a,i}} = \mathrm{K_{s,i}} * \mathrm{K_{c,i}} * \mathrm{ET_{0,i}} \tag{2}$$

based on the water stress coefficient ($K_{s,i}$), wine crop coefficient ($K_{c,i}$), and on daily reference evapotranspiration ($ET_{0,i}$). The average value of $ET_{0,i}$, for the examined area in Piedmont considered in this study is 480 mm/year [68]. Blue WF includes the surface and groundwater involved in the whole production process, from the vineyard to vinification and corresponds to water used for irrigation and to wash the machinery [29]. It should be mentioned that strict irrigation regulations are in force in high-quality certified wine production in Italy [69], e.g., irrigation is allowed only for young vines and in mature vineyard only in emergency conditions or more recently for causes associated with the drought brought on by climate change.

Table 3. Emission factors applied in the Carbon Footprint analysis [17].

Input	Unit	Emission Factor (kg CO_2eq/Input Unit)
Copper oxide	kg	1.94
Sulphur	kg	1.39
Iron wire	kg	1.48
Diesel for farming (fuel production)	kg	0.51
Diesel for farming (fuel combustion)	kg	3.1
Italian energy mix	kWh	0.65
Yeast and nutrient for the yeast	g	0.001
Sulphur dioxide	g	0.0004
Glass bottle	kg	0.67
Cork	g	0.001
Polyvinyl chloride	g	0.003
Recycled paper,	g	0.002
Aluminum	kg	0.84

Grey WF is the amount of freshwater needed to retain the contaminants produced by human activities, considering both natural background concentrations and current environmental water quality regulations [24], as in Equation (3) [32]:

$$WF_{Grey} = \frac{\alpha * A_{appl}}{C_{max} - C_{min}} \tag{3}$$

accounting for the Runoff coefficient (α), characteristic of the zone based on slope lithology and type of vegetation; the applied chemical rate (A_{appl}) referred to the viticulture stage; and the contaminants' concentration in the receiving water body where C_{max} is the environmental quality water standard and C_{min} is the baseline concentration present in the water body. Given the nature of the lithotypes present in the considered specific territory (very compact and poorly permeable soil) and the fact that the slopes of the vines were almost always found to be more than 10%, a Runoff coefficient of 0.82 was attributed to all the case studies examined [70]. A nitrogen fertilizer with $C_{max} = 50$ mg/L of nitrate and $C_{min} = 0$ mg/L was applied.

EF is an area-based indicator expressed in global hectares (gha) that quantifies the demand for resources from a population [71,72]. The ecological footprint of the vineyard (EF_V) is expressed in gha and based on the method of the calculated area [73] as in Equation (4).

$$EF_V = \frac{T}{Y_1} * YF * EQF \tag{4}$$

T is the annual grape production (tons), Y_1 is the local grape yield (t/ha), and YF is the global wine yield expressed by $\frac{Y_1}{Y_W}$, where y_w is the average Italian yield of wine cultivation [7]; EQF is the global equivalence factor, referring to different categories of the soil [73], and reflects the capacity of biological resources that each hectare of land can produce in relation to the relative productivity of the world average hectare [74,75]. A further contribution of the ecological footprint (EF_{CO_2}) is given by the area necessary to the assimilation of carbon dioxide produced in the total process and it is equivalent to the CO_2 emissions converted into the area of forest needed for its sequestration through the use of the world average carbon adsorption factor [71].

2.3. Sensitivity Analysis

The results obtained through the Carbon Footprint (CF), Water Footprint (WF), and Ecological Footprint (EF) analyses were subjected to statistical evaluation to explore potential relationships and interdependencies among the variables. Specifically, Pearson's bivariate correlation test was applied using Excel (Microsoft Office) to assess associations between these environmental impact indicators. This statistical approach allowed for the identification of significant correlations, providing insights into how changes in one parameter of footprint measure might influence the others. By leveraging Pearson's test, the study aimed to enhance the robustness of the data interpretation, ensuring a more comprehensive understanding of the environmental implications assessed.

Therefore, it was decided to perform a sensitivity analysis on the Carbon Footprint, given that most of the overall water footprint impact comes from the green WF contribution and that for EF, the impact is primarily determined by land use and the size of the vineyards themselves. The sensitivity analysis was specifically conducted using five scenarios that modify the elements that significantly affect the overall Carbon Footprint.

3. Results

The 12 wine producers involved in this study have different features (Table 4): the vineyard areas ranging from 2 ha (Case K) to 50 ha (Case C) and production levels between 12,000 bottles (Case K) and 300,000 bottles annually (Case C). The average vineyard size was 16.7 ± 12.8 ha, producing 108.4 ± 84.6 t of grapes and 100,000 ± 79.92 bottles/year. Cases A, C, F, H, I, and K used organic practices, while others (Case B, D, E, G, J, L) employed conventional methods.

Table 4. Features of considered case studies and results of the environmental footprints analysis referred to a 0.75 L red wine bottle (CF: carbon footprint, EF: ecological footprint, WF: water footprint, FU: functional unit, i.e., 0.75 L bottle).

Case Studies	Cultivated Hectares (ha)	Produced Bottles (No.)	Produced Grapes (t)	Type of Agriculture	CF (kg CO_2eq/FU)	WF (L/FU)	EF (gha/FU)
A	22	110,000	135	Organic	0.93	889.95	106.43
B	16	120,000	128.5	Conventional	0.63	666.58	77.56
C	50	300,000	320	Organic	0.65	855.29	231.19
D	5	28,000	30	Conventional	0.72	911.47	23.35
E	26	180,000	193	Conventional	0.75	722.53	129.43
F	20	120,000	128	Organic	0.85	835.85	99.17
G	9	76,000	81	Conventional	0.68	593.07	46.21
H	8	25,000	27	Organic	1.65	1574.38	39.78
I	10	60,000	64	Organic	0.72	832.43	47.35
J	12	85,000	91	Conventional	0.85	701.7	62.41
K	2	12,000	13	Organic	0.71	814.98	9.46
L	20	84,000	90	Conventional	1.4	1175.85	103.25

Considering the different contributions to the CF (Figure 3), bottling and specifically the glass bottle accounts for 44 ± 10% of the total footprint, and in viticulture, specifically the diesel fuel fed to agricultural equipment accounts for 20 ± 6%. Electric energy use during vinification accounts for 32 ± 7%, and other contributions (e.g., sulphides, copper oxide, sulphur dioxide) account for 4 ± 3%. Case studies using conventional agriculture, which is typified by a greater use of chemicals for agricultural techniques, had the greatest fertilizer content, like copper oxide. The average WF of the 12 case studies is 881 ± 252 L. This amount—considering the high standard deviation—is not unlike to literature data referred to Italy and a 0.75 L bottle of red wine, which are in the range 498–667 L [29,33,53], and consistent with the range 366–899 reported for Portugal [55]. About the various contributions to the WF (Figure 4), Green WF due to evapotranspiration is the prevalent component (98 ± 1.2%) compared to the sum of Blue and Grey WF (2 ± 1.7%) [23,24,29,31,35,45,55].

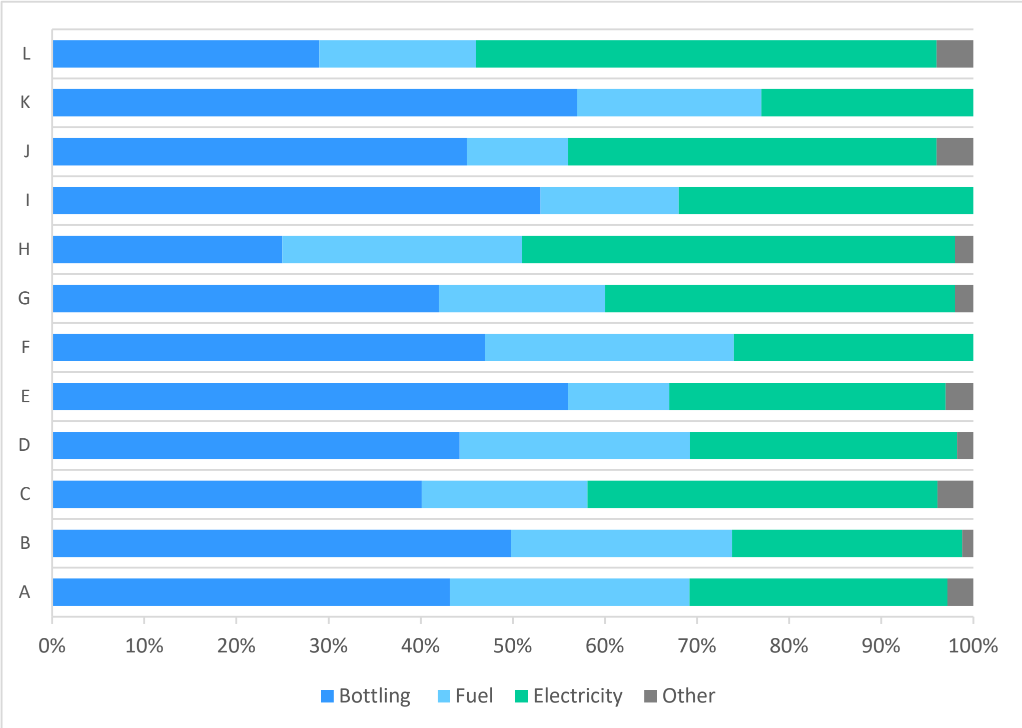

Figure 3. Contributions to the Carbon Footprint of the 12 case studies associated with bottling, fuel fed to agricultural machines during viticulture, electricity used during vinification, and others (sulphides, copper oxide, sulphur dioxide).

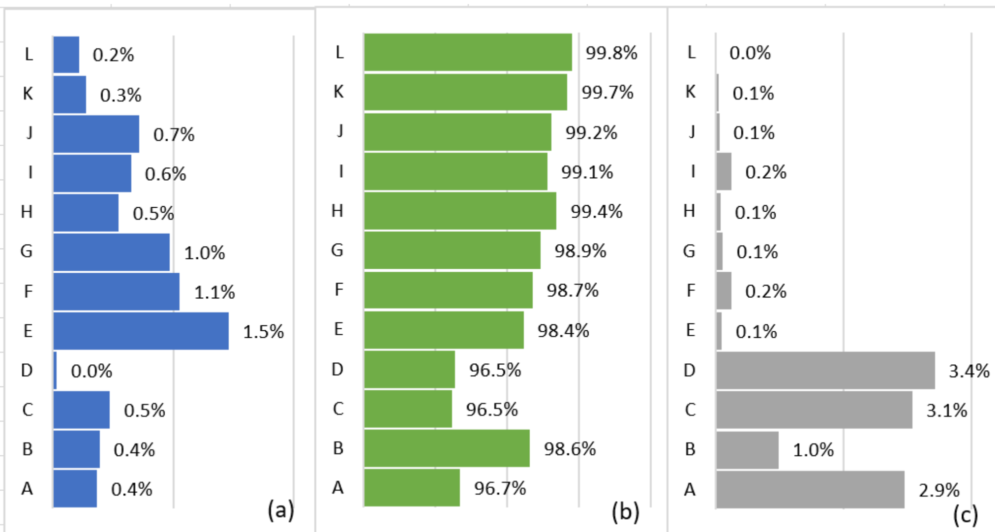

Figure 4. Contributions to the Water Footprint (WF) of the 12 case studies: (**a**) Blue WF, (**b**) Green WF and (**c**) Grey WF.

The average EF was 81.3 ± 59.2 gha, with a range spanning from 9.46 to 231.2 gha (Figure 5). These results cannot be compared with literature data, as they are previously unknown. The average, 73 ± 3%, of the EF can be ascribed to the land assigned to the vineyard, while the 27 ± 3% to the area necessary for the assimilation of CO_2 emissions. The minimum EF values calculated for Cases D and K are related with the small area of cultivated land, respectively, 5 and 2 hectares.

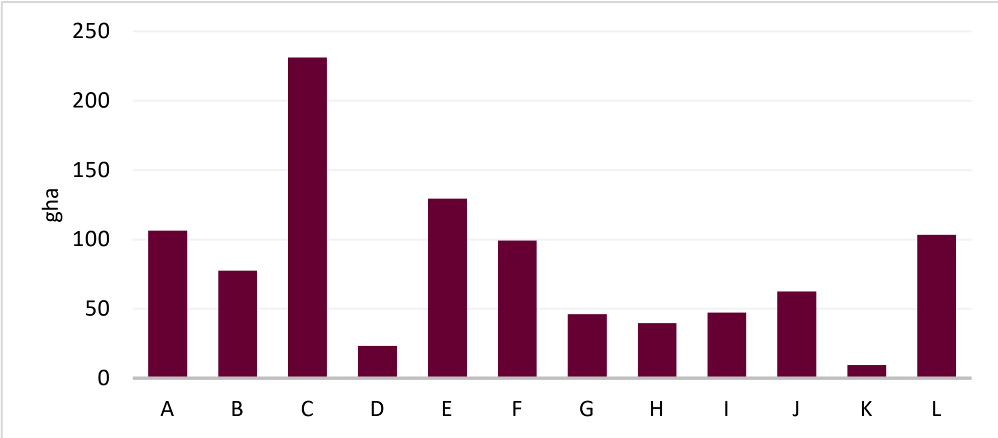

Figure 5. Ecological Footprint (expressed in global hectars, gha) calculated for the 12 case studies.

About the cultivation practices, the organic method (applied in 6 case studies out of 12) employs natural pesticides and plant growth regulators, produced through natural processes. The average CF calculated for the case studies implementing conventional agriculture operations (0.84 ± 0.3 kg CO_2eq/bottle) is slightly lower than the CF calculated for the wine producers applying organic agriculture (0.92 ± 0.3 kg CO_2eq/bottle) (Figure 6). On the other hand, even if the values are similar the ones presented in this study, another study [21] calculated for a 0.75 L red wine bottle derived from conventional agriculture a higher CF (1.25 kg CO_2eq/bottle) compared to a bottle produced via organic agriculture (1.02 kg CO_2eq/bottle). Overall, the results of the footprints analyses did not show any substantial variation based on the applied cultivation practices (Figures 3–5). This is likely due to the dominant contributions identified through the footprints analyses, namely the production of the glass bottle for the CF, the Green WF due to evapotranspiration for the WF, and the significant requirement of land for vines cultivation for the EF.

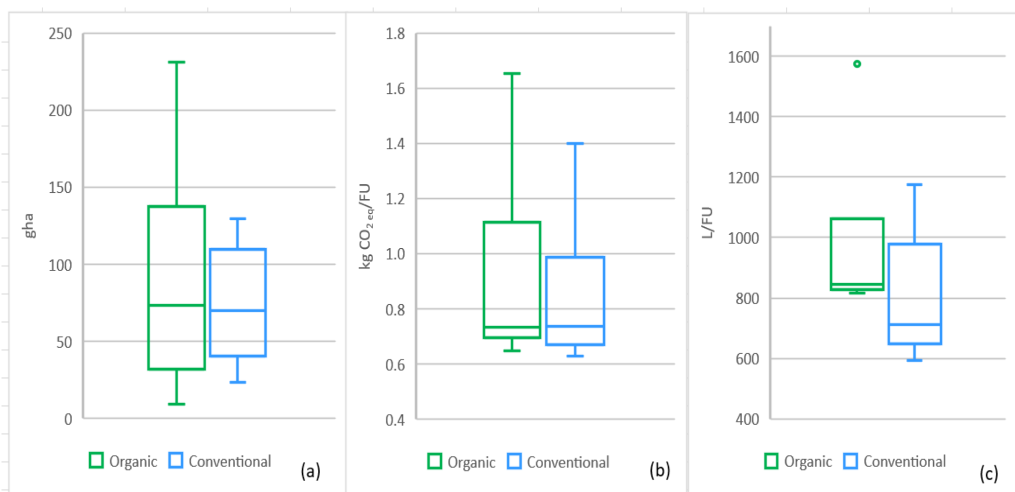

Figure 6. Overall trend of (**a**) Ecological Footprint (EF), (**b**) Carbon Footprint (CF), and (**c**) Water Footprint (WF) within the 12 case studies comparing organic and conventional agricultural practices.

4. Discussions

Among the case studies, the largest Carbon Footprint value associated with bottling and electricity consumption during vinification are related to Cases E, I, and K. The Carbon Footprint values associated with fuel used during viticulture are related to Cases A, B, F and H, probably because the used farm equipment is most likely older and requires more energy. Literature reports highly variable data on the contributions to the Carbon Footprint of a 0.75 L bottle of red wine: packaging (18–25% of the total Carbon Footprint) [45,46], viticulture (15–50%) [17,27,45,46], and vinification (25–85%) [17,43,46], with detailed data about the contributions to the Carbon Footprint of agricultural fuel (8–19%) and of the chemicals applied in viticulture and vinification (4%) [16,33,45]. The only Carbon Footprint value obtained in this study that is higher than literature data is related to the glass bottle. This may be due to the type of bottle used by the considered producers, which is commonly associated in Italy with high-wine quality.

Out of all the many factors that contribute to the water footprint, evapotranspiration's Green Water Footprint is the most common (98 $\pm$ 1.2%), while the combined Blue and Grey WF (2 $\pm$ 1.7%) are the least common. Case studies A, B, C, and D exhibit the largest share of Grey WF. Case study E displays the largest contribution to Blue WF, as a significant cellar phase contribution. The values calculated as contributions to the WF are consistent with literature, reporting shares of the Green WF in the range 81–98% [23,24,29,31,35,44,55].

A previous study [51] investigated the correlation between the results obtained applying CF and WF to red wine production in Portugal and found a linear correlation between the CF and the Blue WF, suggesting that an increase in the impact of global warming is correlated to a rise in volume of freshwater used and then its blue water footprint. A correlation analysis of the Carbon Footprint, Water Footprint, and Ecological Footprint values obtained for the 12 case studies considered in this study revealed a moderate correlation (Pearson's r-index r = 0.54) between the contribution of the bottling phase and the total CF, and a strong correlation between the contribution of electricity and fuel consumption and the total CF (r = 0.83 and r = 0.97, respectively). Regarding the Water Footprint, the analysis shows a very strong linear correlation (r = 0.99) between the Green WF and the total Water Footprint. For the Ecological Footprint assessment, all components showed a strong correlation with an index r > 0.9.

Sensitivity Analysis

Since the main impact of the total water footprint comes from the green WF contribution, while for EF, land management and vineyard extent play a dominant role, a sensitivity analysis was conducted on the carbon footprint. By examining the factors that have the greatest influence on the overall impact of the same CF—fuel consumption and electricity—the sensitivity analysis of the CF has been carried out. France was specifically selected for two reasons: France's energy mix differs greatly from Italy's, and France is the second-largest producer of wine in Europe, with quantitatively equivalent production [7]. The Italian energy mix [76] in the year analyzed in this study is equal to 42% renewable sources, 43% natural gas, 8% natural coal, 4% nuclear, and 3% other sources [77] represented as follows: 71% nuclear, 21% renewable sources, and 8% fossil. This leads to a varied emission factor value, which in turn affects the overall effect in terms of electricity-related kg CO_2 equivalent.

Precisely, five possible scenarios (Table 5) were used to conduct the sensitivity analysis: the baseline scenario calculation of CF of this study, (i) the same production process of this study located in France; (ii) process located in Italy using recycled glass and electric tractor for agricultural practices; (iii) process located in France using recycled glass and electric tractor for agricultural practices; (iv) use of recycled glass for the production of the glass bottle; (iii) process using recycled glass with the process in France. Figure 7 illustrates the results of the sensitivity analysis. The scenarios associated with the case studies in Italy (Baseline, Scenario ii, and Scenario iv) are shown with a dashed texture, while those related to France (Scenario i, Scenario iii, and Scenario v) are depicted in with a full-colour texture. The graph clearly indicates that the overall carbon footprint is consistently lower in the French scenarios compared to the Italian ones. This difference is primarily attributed to the distinct national energy mixes, which influence the emission factors used in the carbon footprint calculation. Notably, a substantial reduction, with respect to the baseline scenario, in impact is observed when recycled glass is used (scenario iv and scenario v): −22.0 ± 4.7% for Italy and −49.9 ± 3.4% for France. The environmental benefit becomes even more pronounced when the use of electric agricultural machinery is introduced, eliminating emissions associated with diesel fuel consumption. In fact, in the most favourable scenarios (scenario ii and scenario iii)—combining recycled glass and electric vehicles—the total carbon footprint is reduced by an average of −46.6 ± 6.7% in Italy and −70.6 ± 4.5% in France compared to the baseline scenario.

Table 5. Definition of different scenarios for sensitivity analysis of Carbon Footprint.

Scenario	Grape Growing	Grape Harvest	Winemaking	Wine Bottling	Localization
Baseline scenario			Electricity mix		Italy
Scenario i			Electricity mix		France
Scenario ii	Electric tractor	Electric tractor	Electricity mix	Recycled glass, electricity mix	Italy
Scenario iii	Electric tractor	Electric tractor	Electricity mix	Recycled glass, electricity mix	France
Scenario iv			Electricity mix	Recycled glass, electricity mix	Italy
Scenario v			Electricity mix	Recycled glass, electricity mix	France

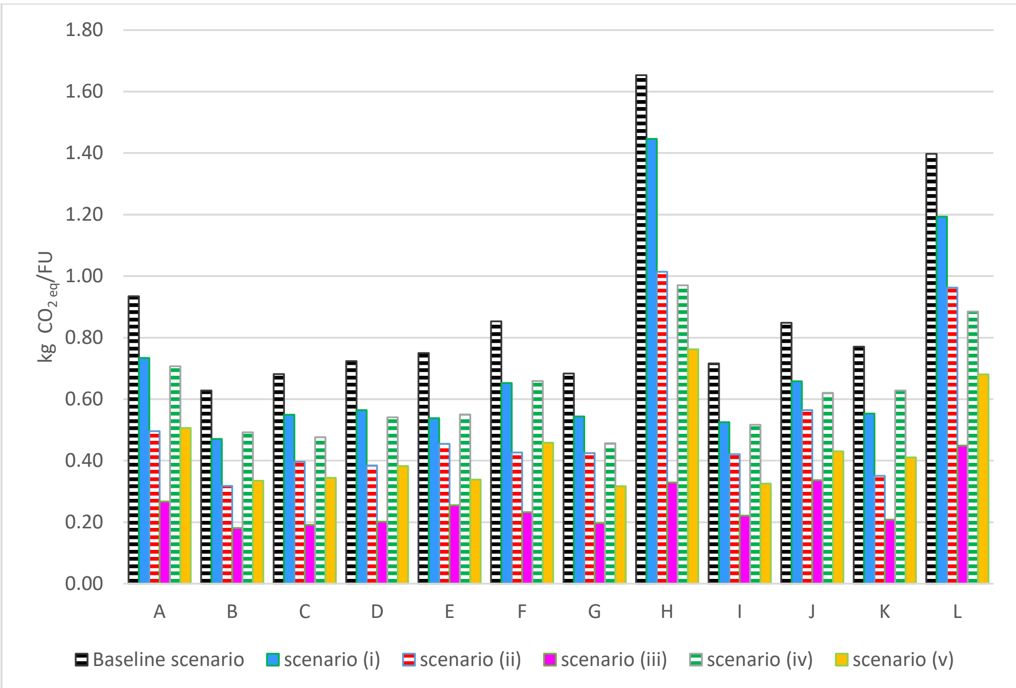

Figure 7. Overall trend of different scenarios assumed for all case studies of the analysis: baseline scenario: calculation of the CF of this study; (i) the same production process of this study located in France; (ii) process located in Italy using recycled glass and electric tractor for agricultural practices, (iii) Process located in France using recycled glass and electric tractor for agricultural practices; (iv) use of recycled glass for the production of the glass bottle; (v) process using recycled glass with the process in France.

5. Conclusions

The wine industry plays a significant role in both the global food distribution market and wines are increasingly being examined from an environmental perspective. Within this study, every single 0.75 L bottle of red wine is associated with an average Carbon Footprint equal to 0.88 ± 0.3 Kg CO_{2eq}, a Water Footprint equal to 881.2 ± 263.6 L, and an Ecological Footprint equal to 81.3 ± 59.7 gha. The major contributor of the Carbon Footprint is the bottling phase, e.g., the production of the glass bottle accounts for 39–69% of CO_{2eq} emissions per bottle. The glass bottle associated with quality wine has a long history that is deep-rooted in the Italian culture, and as of now, there is unfortunately no viable substitute for preserving properly the wine's quality. To cut the overall carbon footprint emission by up to 40%, a possible solution would be using a thinner glass bottle [16]. A recent study [37] confirmed this perspective, evidencing that the Carbon Footprint of a 0.42 kg bottle (0.513 kg CO_{2eq}) is lower compared to a 0.65 kg bottle (0.721 kg CO_{2eq}). In relation to the Water Footprint analysis, the Green Water contribution is prevalent (98 ± 1.2%) of the total Water Footprint) compared to the Blue and Grey Water inputs. This is due to the amount of water used by the vines through evapotranspiration, and this finding is consistent with the results of the Ecological Footprint analysis. Only 27% of the Ecological Footprint is related to the area needed for the assimilation of carbon dioxide emissions, while the remaining 73% is associated with the land area hosting the vineyard. The Carbon and Water Footprint results achieved in this study align with the existing literature. However, any other Ecological Footprint results are available in the literature for a comparison with the data presented in this study. In conclusion, the wine sector has great significance for the history and traditions of a country and for its economy. From an environmental point of view there are operations that can be implemented to mitigate the environmental impacts of the wine sector (e.g., adopting glass bottles made of recycled glass and electric agricultural machines and using electric energy deriving from renewable energy sources) without sacrificing the intrinsic characteristics of all small producers of high-quality wine.

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Abbreviations

The following abbreviations are used in this manuscript:

CAP	Common Agricultural Policy
UE	European Union
CF	Carbon Footprint

WF	Water Footprint
EF	Ecological Footprint
FU	Functional Unit
SQNPI	System of National Integrated Quality Production
OIV	International Organization of Vine and Wine
ISTAT	Italian Institute for Statistics
DOC	Controlled Designation of Origin
DOCG	Controlled and Guaranteed Designation of Origin
R	Review paper
SA	Scientific article

Appendix A

Table A1. Questionnaire produced by the different case studies.

Case Study A	Quantity	Unit
Hectares cultivated	22	ha
Quantity of grapes harvested	135,000	kg
Number of bottles produced annually	110,000	-
Applied agricultural practice (organic/conventional)	organic	-
Quantity of copper oxide	3.5	kg/ha
Quantity of sulphides	110	kg/ha
Quantity of sulphur dioxide	25	kg
Quantity of nitrogen fertilisers applied	8000	kg
Weight of the glass bottle	0.55	kg
Weight of the bottle cap	4.4	g
Weight of the PVC capsule	na	g
Weight of the aluminum capsule	3.3	g
Weight of the label	2	g
Fuel used	7281.2	L
Electricity consumption	44,100	kWh
Number of pesticide applications	9	-
Average volume of water used for pesticide dilution	36	m^3
Water consumption in the cellar	323.1	m^3
Case Study B	**Quantity**	**Unit**
Hectares cultivated	16	ha
Quantity of grapes harvested	128,500	kg
Number of bottles produced annually	120,000	-
Applied agricultural practice (organic/conventional)	conventional	-
Quantity of copper oxide	4.6	kg/ha
Quantity of sulphides	30.7	kg/ha
Quantity of sulphur dioxide	71	kg
Quantity of nitrogen fertilisers applied	0.48	kg
Weight of the glass bottle	0.45	kg
Weight of the bottle cap	4.4	g
Weight of the PVC capsule	na	g
Weight of the aluminum capsule	3.3	g
Weight of the label	2	g
Fuel used	5100	L
Electricity consumption	28,594	kWh
Number of pesticide applications	14	-
Average volume of water used for pesticide dilution	1.9	m^3
Water consumption in the cellar	28.4	m^3

Table A1. *Cont.*

Case Study C	Quantity	Unit
Hectares cultivated	16	ha
Quantity of grapes harvested	128,500	kg
Number of bottles produced annually	120,000	-
Applied agricultural practice (organic/conventional)	conventional	-
Quantity of copper oxide	4.6	kg/ha
Quantity of sulphides	30.7	kg/ha
Quantity of sulphur dioxide	71	kg
Quantity of nitrogen fertilisers applied	0.48	kg
Weight of the glass bottle	0.45	kg
Weight of the bottle cap	4.4	g
Weight of the PVC capsule	na	g
Weight of the aluminum capsule	3.3	g
Weight of the label	2	g
Fuel used	5100	L
Electricity consumption	28,594	kWh
Number of pesticide applications	na	-
Average volume of water used for pesticide dilution	105	m^3
Water consumption in the cellar	1100	m^3
Case Study D	**Quantity**	**Unit**
Hectares cultivated	5	ha
Quantity of grapes harvested	30,000	kg
Number of bottles produced annually	28,000	-
Applied agricultural practice (organic/conventional)	conventional	-
Quantity of copper oxide	5	kg/ha
Quantity of sulphides	50	kg/ha
Quantity of sulphur dioxide	15	kg
Quantity of nitrogen fertilisers applied	1.25	kg
Weight of the glass bottle	0.45	kg
Weight of the bottle cap	4.4	g
Weight of the PVC capsule	3.3	g
Weight of the aluminum capsule	no	g
Weight of the label	2	g
Fuel used	1600	L
Electricity consumption	9000	kWh
Number of pesticide applications	2	-
Average volume of water used for pesticide dilution	0.4	m^3
Water consumption in the cellar	8	m^3
Case Study E	**Quantity**	**Unit**
Hectares cultivated	26	ha
Quantity of grapes harvested	193,000	kg
Number of bottles produced annually	180,000	-
Applied agricultural practice (organic/conventional)	conventional	-
Quantity of copper oxide	3	kg/ha
Quantity of sulphides	90	kg/ha
Quantity of sulphur dioxide	15	kg
Quantity of nitrogen fertilisers applied	0.78	kg
Weight of the glass bottle	0.6	kg
Weight of the bottle cap	4.4	g
Weight of the PVC capsule	3.3	g
Weight of the aluminum capsule	no	g
Weight of the label	2	g
Fuel used	5000	L
Electricity consumption	63,831	kWh
Number of pesticide applications	8	-

Table A1. *Cont.*

Case Study E	Quantity	Unit
Average volume of water used for pesticide dilution	0.2	m^3
Water consumption in the cellar	1900	m^3
Case Study F	**Quantity**	**Unit**
Hectares cultivated	20	ha
Quantity of grapes harvested	128,000	kg
Number of bottles produced annually	120,000	-
Applied agricultural practice (organic/conventional)	organic	-
Quantity of copper oxide	3.8	kg/ha
Quantity of sulphides	4	kg/ha
Quantity of sulphur dioxide	0.15	kg
Quantity of nitrogen fertilisers applied	15,000	kg
Weight of the glass bottle	0.58	kg
Weight of the bottle cap	4.4	g
Weight of the PVC capsule	3.3	g
Weight of the aluminum capsule	no	g
Weight of the label	2	g
Fuel used	9000	L
Electricity consumption	60,616	kWh
Number of pesticide applications	14	-
Average volume of water used for pesticide dilution	5.6	m^3
Water consumption in the cellar	1049	m^3
Case Study G	**Quantity**	**Unit**
Hectares cultivated	9	ha
Quantity of grapes harvested	81,000	kg
Number of bottles produced annually	76,000	-
Applied agricultural practice (organic/conventional)	conventional	-
Quantity of copper oxide	3.6	kg/ha
Quantity of sulphides	4.2	kg/ha
Quantity of sulphur dioxide	na	kg
Quantity of nitrogen fertilisers applied	7000	kg
Weight of the glass bottle	0.54	kg
Weight of the bottle cap	4.4	g
Weight of the PVC capsule	3.3	g
Weight of the aluminum capsule	no	g
Weight of the label	2	g
Fuel used	3500	L
Electricity consumption	35,000	kWh
Number of pesticide applications	6	-
Average volume of water used for pesticide dilution	6.4	m^3
Water consumption in the cellar	500	m^3
Case Study H	**Quantity**	**Unit**
Hectares cultivated	8	ha
Quantity of grapes harvested	27,000	kg
Number of bottles produced annually	25,000	-
Applied agricultural practice (organic/conventional)	organic	-
Quantity of copper oxide	1.5	kg/ha
Quantity of sulphides	36	kg/ha
Quantity of sulphur dioxide	na	kg
Quantity of nitrogen fertilisers applied	3210	kg
Weight of the glass bottle	0.4	kg
Weight of the bottle cap	4.4	g
Weight of the PVC capsule	3.3	g
Weight of the aluminum capsule	no	g

Table A1. *Cont.*

Case Study H	Quantity	Unit
Weight of the label	2	g
Fuel used	3000	L
Electricity consumption	37,899	kWh
Number of pesticide applications	2	-
Average volume of water used for pesticide dilution	1	m^3
Water consumption in the cellar	486	m^3
Case Study I	**Quantity**	**Unit**
Hectares cultivated	10	ha
Quantity of grapes harvested	64,000	kg
Number of bottles produced annually	60,000	-
Applied agricultural practice (organic/conventional)	organic	-
Quantity of copper oxide	3.8	kg/ha
Quantity of sulphides	39	kg/ha
Quantity of sulphur dioxide	na	kg
Quantity of nitrogen fertilisers applied	2000	kg
Weight of the glass bottle	0.57	kg
Weight of the bottle cap	4.4	g
Weight of the PVC capsule	3.3	g
Weight of the aluminum capsule	no	g
Weight of the label	2	g
Fuel used	3000	L
Electricity consumption	30,000	kWh
Number of pesticide applications	2	-
Average volume of water used for pesticide dilution	1	m^3
Water consumption in the cellar	200	m^3
Case Study J	**Quantity**	**Unit**
Hectares cultivated	12	ha
Quantity of grapes harvested	91,000	kg
Number of bottles produced annually	85,000	-
Applied agricultural practice (organic/conventional)	conventional	-
Quantity of copper oxide	354	kg/ha
Quantity of sulphides	na	kg/ha
Quantity of sulphur dioxide	na	kg
Quantity of nitrogen fertilisers applied	520	kg
Weight of the glass bottle	0.55	kg
Weight of the bottle cap	4.4	g
Weight of the PVC capsule	no	g
Weight of the aluminum capsule	3.3	g
Weight of the label	2	g
Fuel used	2600	L
Electricity consumption	34,000	kWh
Number of pesticide applications	2	-
Average volume of water used for pesticide dilution	na	m^3
Water consumption in the cellar	400	m^3
Case Study K	**Quantity**	**Unit**
Hectares cultivated	2	ha
Quantity of grapes harvested	13,000	kg
Number of bottles produced annually	12,000	-
Applied agricultural practice (organic/conventional)	organic	-
Quantity of copper oxide	3.5	kg/ha
Quantity of sulphides	2.4	kg/ha
Quantity of sulphur dioxide	na	kg
Quantity of nitrogen fertilisers applied	na	kg

Table A1. *Cont.*

Case Study K	Quantity	Unit
Weight of the glass bottle	0.54	kg
Weight of the bottle cap	4.4	g
Weight of the PVC capsule	3.3	g
Weight of the aluminum capsule	no	g
Weight of the label	2	g
Fuel used	500	L
Electricity consumption	3000	kWh
Number of pesticide applications	2	-
Average volume of water used for pesticide dilution	0	m^3
Water consumption in the cellar	0.05	m^3
Case Study L	**Quantity**	**Unit**
Hectares cultivated	20	ha
Quantity of grapes harvested	90,000	kg
Number of bottles produced annually	84,000	-
Applied agricultural practice (organic/conventional)	conventional	-
Quantity of copper oxide	2.5	kg/ha
Quantity of sulphides	50	kg/ha
Quantity of sulphur dioxide	0.5	kg
Quantity of nitrogen fertilisers applied	na	kg
Weight of the glass bottle	0.58	kg
Weight of the bottle cap	4.4	g
Weight of the PVC capsule	3.3	g
Weight of the aluminum capsule	no	g
Weight of the label	2	g
Fuel used	6500	L
Electricity consumption	75,000	kWh
Number of pesticide applications	11	-
Average volume of water used for pesticide dilution	22	m^3
Water consumption in the cellar	190	m^3

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