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Life Cycle Assessment of Anaerobic Digestion Pathways for Winery Residues: Influence of Functional Unit Selection on Wastewater Treatment and Grape Pomace Valorization

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Abstract

Winery activities generate large amounts of residues requiring sustainable management. Anaerobic digestion offers opportunities for resource recovery while reducing the environmental burdens associated with these residues. This study presents a gate-to-gate Life Cycle Assessment (LCA) of two anaerobic digestion pathways: winery wastewater treatment (Scenario A) and grape pomace valorization (Scenario B). Inventory data were obtained from pilot-scale operation and complemented with the Ecoinvent 3.10 database. Environmental impacts were assessed using the ReCiPe 2016 Midpoint (H) method across seven impact categories. To ensure comparability, results were evaluated using both process-based functional units and an energy-normalized functional unit of 1 MJ of useful electricity, applied as an exploratory indicator of energy-recovery intensity under pilot-scale conditions. Although grape pomace digestion showed higher impacts per unit of substrate processed, it achieved lower impacts per MJ of electricity generated, with reductions of approximately 8–10 times across categories. Higher methane yields and lower electricity demand were contributors to this performance. However, both pilot-scale systems exhibited negative net electricity balances, indicating that the energy-normalized comparison represents energy-recovery intensity rather than net energy delivery. The findings highlight the importance of functional unit selection and the complementary role of both pathways in circular winery residue management.

Keywords: biogas; anaerobic digestion; grape pomace; winery wastewater; life cycle assessment

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1. Introduction

The wine industry is one of the largest agro-industrial sectors worldwide, generating substantial quantities of liquid and solid residues throughout the winemaking process. Among these, grape pomace and winery wastewater represent the two most abundant waste streams, posing significant environmental and economic challenges due to their high organic content and seasonal generation. If inadequately managed, these residues may contribute to greenhouse gas emissions, soil and water contamination, eutrophication, odor nuisance, and increasing waste management costs. Consequently, the transition towards more sustain-

able and circular production systems has stimulated growing interest in the recovery and valorization of winery by-products rather than their conventional disposal [1–3].

Grape pomace, consisting mainly of skins, seeds, and residual pulp remaining after grape pressing, accounts for approximately 15–25% of the processed grape mass and represents one of the largest solid by-products generated during vinification. Due to its high lignocellulosic and organic matter content, grape pomace has attracted considerable attention as a feedstock for the production of bioenergy, bio-based chemicals, and high-value compounds [4,5]. Winery wastewater, in contrast, originates primarily from equipment washing, tank cleaning, grape reception, and bottling operations. Its composition varies considerably throughout the production season but is typically characterized by high chemical oxygen demand (COD), biochemical oxygen demand (BOD), suspended solids, organic acids, and polyphenolic compounds, making wastewater treatment a major environmental challenge for wineries [2,6].

Among the available waste management technologies, anaerobic digestion (AD) has emerged as one of the most promising strategies for the sustainable management of winery residues. AD simultaneously stabilizes organic matter, reduces pollutant loads, and produces biogas, a methane-rich gas that can be converted into heat and electricity through combined heat and power (CHP) systems. In addition to renewable energy recovery, anaerobic digestion contributes to nutrient recycling through digestate production and supports the implementation of circular economy principles within the agri-food sector [7]. Numerous studies have demonstrated the technical feasibility of AD for both winery wastewater and grape pomace, either as mono-substrates or in co-digestion with complementary feedstocks to improve methane production and process stability [8–10].

Beyond technical feasibility, the environmental performance of anaerobic digestion has increasingly been evaluated through Life Cycle Assessment (LCA), widely recognized as one of the most robust methodologies for assessing the sustainability of waste management and bioenergy systems. By simultaneously accounting for upstream resource consumption, process emissions, and avoided environmental burdens, LCA provides a comprehensive framework for identifying environmental hotspots and supporting technology optimization [11–13]. Previous LCA studies have investigated anaerobic digestion of agricultural residues, food-processing wastes, and agro-industrial effluents, consistently identifying operational electricity demand and methane yield as key determinants of environmental performance [11,13]. Studies specifically addressing winery residues have similarly highlighted the influence of operational energy requirements, treatment efficiency, and biogas productivity on the overall environmental performance of anaerobic digestion systems. While wastewater-focused studies generally emphasize pollution abatement and organic load reduction [6], grape pomace studies tend to focus on resource recovery and energy generation [14], reflecting the distinct functions associated with each residue stream.

Despite the growing number of LCA studies addressing anaerobic digestion of winery residues, comparative environmental assessments directly evaluating winery wastewater and grape pomace within the LCA framework using harmonized methodological assumptions remain scarce. Most published studies focus on a single residue stream, typically assessing either wastewater treatment [2,15] or grape pomace valorization [8,16]. Furthermore, these studies often employ different system boundaries, inventory assumptions, and substrate-specific functional units, limiting the comparability of their environmental results [17,18]. To the best of our knowledge, no previous study has systematically compared these two major winery residue streams under identical LCA assumptions and evaluated both substrate- and energy-based functional units.

This limitation is particularly relevant because winery wastewater and grape pomace differ fundamentally in their physical characteristics, organic loading, biodegradability,

methane potential and operational requirements [3]. More importantly, the primary function of anaerobic digestion differs between the two systems: wastewater digestion is primarily designed to provide environmental treatment by reducing pollutant loads before discharge [19], whereas grape pomace digestion primarily aims to recover energy from a solid organic residue. Consequently, comparisons based solely on substrate mass or volume may lead to misleading conclusions regarding their relative environmental performance. Several methodological studies have highlighted functional unit selection as one of the most influential factors affecting the interpretation of comparative LCAs, particularly when systems provide different functions or levels of service [17,18,20]. This distinction motivates the evaluation of alternative functional units, as no single functional unit can fully capture the performance of systems that deliver different primary services [21]. Moreover, treatment-oriented performance indicators, such as COD removal, may be as relevant as energy-related indicators when assessing wastewater digestion systems. For this reason, treatment performance indicators are also reported and discussed to provide additional context regarding the wastewater-treatment function delivered by Scenario A.

The challenge becomes even more important when assessing pilot-scale anaerobic digestion systems, where operational energy requirements may be disproportionately high due to scale-related inefficiencies [13,22]. Under such conditions, systems designed for waste treatment and resource recovery may exhibit low or even negative net energy balances [23], raising important questions regarding the appropriateness of energy-based functional units and the interpretation of environmental performance results. Consequently, careful evaluation of functional unit selection is necessary to ensure meaningful comparisons between systems with fundamentally different objectives.

The objective of this study was to perform a comparative gate-to-gate Life Cycle Assessment of two anaerobic digestion pathways for winery residues: (i) treatment of winery wastewater and (ii) valorization of grape pomace. Environmental impacts were evaluated using the ReCiPe 2016 Midpoint (H) method and expressed using both process-based functional units and an energy-normalized functional unit (1 MJ of useful electricity) to investigate how functional unit selection influences the comparative interpretation of systems with different primary functions.

The inclusion of an energy-normalized functional unit was not intended to represent net energy performance alone, but rather to explore how the choice of functional unit influences the interpretation of environmental burdens associated with systems delivering different services.

In addition, contribution and sensitivity analyses were performed to identify the main environmental hotspots and evaluate the robustness of the comparative results. The findings provide methodological insights for the application of LCA to winery residues under consistent methodological assumptions, and support sustainable decision-making for circular waste management within the wine industry.

2. Results

2.1. Biogas Yield and Energy Generation

Scenario A (SA) examines the anaerobic digestion of winery wastewater, with the functional unit defined as the treatment of 1 m^3 of wastewater, a composite stream generated from cleaning operations, residual wine losses, and fermentation by-products. Scenario B (SB) evaluates the anaerobic digestion of grape pomace, with a functional unit of 1 ton of substrate.

The two anaerobic digestion systems exhibited markedly different biogas production and energy recovery potentials owing to the contrasting characteristics of the processed substrates.

Table 1 shows the biogas yield and energy generation for the two scenarios.

Table 1. Biogas yield and energy generation performance of the two anaerobic digestion scenarios.

Parameter	Unit	SA	SB
Functional unit (FU)	–	1 m^3 wastewater treated	1 ton grape pomace processed
Biogas production	m^3 biogas per FU	2.0	76.6
Methane content	% CH_4	64	70
Methane yield	m^3 CH_4 per FU	1.28	53.6
Chemical energy potential (LHV)	MJ per FU	45.8	1920
Chemical energy equivalent	kWh per FU	12.7	533
Electrical conversion efficiency (CHP)	%	35	35
Useful electricity generated	kWh per FU	4.4	187
Operational electricity demand	kWh per FU	96.7	500
Electricity intensity *	kWh consumed per kWh generated	22.0	2.7

* Electricity intensity = operational electricity demand/useful electricity generated.

In SA, biogas production of 2.0 m^3 per m^3 of wastewater was obtained, with an average methane content of approximately 64%, corresponding to 1.28 m^3 of CH_4 under normal temperature and pressure conditions. This yield translates into an energy potential of about 45.8 MJ, equivalent to 12.7 kWh of chemical energy, or 16.0 MJ of useful electricity, assuming a combined heat and power (CHP) electrical conversion efficiency of 35%.

By contrast, SB, based on grape pomace digestion, achieved a biogas yield of 76.6 m^3 per ton of pomace, with a methane content of approximately 70%, corresponding to 53.6 m^3 CH_4. Consequently, the system produced approximately 1920 MJ of chemical energy, equivalent to 533 kWh, or 672 MJ of useful electricity.

The substantially higher energy recovery observed for SB reflects the greater organic loading and methane potential of grape pomace compared with the more dilute winery wastewater. However, these values should be interpreted in light of the different operational modes of the two systems. SA represents a continuous wastewater treatment process with daily feeding and energy production, whereas SB corresponds to a batch digestion process operating over a 33-day retention period. Therefore, the absolute energy outputs reported here describe the performance of each process under its respective operating cycle and should not be interpreted as a direct measure of process productivity over time.

To compare process efficiency, operational electricity demand was related to the useful electricity generated. Scenario A consumed 96.7 kWh of electricity while generating 4.4 kWh of useful electricity, corresponding to an electricity intensity of 22.0 kWh consumed per kWh generated. Scenario B consumed 500 kWh while generating 187 kWh of useful electricity, corresponding to an electricity intensity of 2.7 kWh consumed per kWh generated. These values reflect the pilot-scale nature of the systems and should not be interpreted as representative of commercial-scale anaerobic digestion facilities.

These results demonstrate that the two systems fulfill complementary rather than competing roles within winery residue management. Anaerobic digestion of winery wastewater primarily serves as an environmental treatment process by reducing the effluent's organic load while recovering a limited amount of energy. In contrast, grape pomace digestion primarily serves as an energy-recovery pathway, achieving substantially higher methane yields and lower electricity demand per unit of useful electricity generated.

Similar behavior has been reported in other agro-industrial anaerobic digestion systems, where diluted wastewater is primarily treated for pollution control, while solid organic residues are preferentially valorized for bioenergy production [24].

The energy performance indicators obtained in this study provide the basis for the subsequent environmental comparison. Because the two systems generate substantially dif-

ferent amounts of useful electricity from their respective functional units, life cycle impacts are presented both per original process-based functional units and after normalization to 1 MJ of useful electricity.

2.2. Comparative Environmental Performance

Life cycle impact assessment (LCIA) results were first analyzed using the original process-based functional units defined for each system, namely 1 m^3 of winery wastewater treated (SA) and 1 ton of grape pomace processed (SB). When results were expressed using the original process-based functional units, Scenario B exhibited higher absolute environmental impacts across all evaluated categories (Table 2). Climate change impacts increased from 27.9 kg CO_2 eq per m^3 of wastewater treated in SA to 141.8 kg CO_2 eq per ton of grape pomace processed in SB. Similar trends were observed for all other impact categories, reflecting the larger amount of biomass processed and the higher resource requirements associated with the pomace digestion pathway.

Table 2. LCIA results using the original process-based functional units.

Impact Category	Unit	SA (1 m^3 WW Treated)	SB (1 t Grape Pomace Processed)
Climate change (GWP100)	kg CO_2 eq	27.89	141.79
Terrestrial acidification	kg SO_2 eq	0.088	0.430
Freshwater eutrophication	kg P eq	4.49×10^{-3}	1.99×10^{-2}
Marine eutrophication	kg N eq	5.81×10^{-4}	2.55×10^{-3}
Fossil resource scarcity	kg oil eq	8.36	43.01
Particulate matter formation	kg $PM_{2.5}$ eq	3.10×10^{-2}	0.148
Human toxicity (carcinogenic)	kg 1,4-DCB eq	3.74	18.75

However, after normalization to 1 MJ of useful electricity (Table 3 and Figure 1), Scenario B consistently presented lower impacts than Scenario A.

Table 3. LCIA results normalized per 1 MJ of useful electricity. The SA/SB ratio represents the relative environmental impacts of Scenario A and Scenario B. Values greater than 1 indicate higher impacts for Scenario A.

Impact Category	Unit	SA	SB	SA/SB Ratio
Climate change (GWP100)	kg CO_2 eq	1.739	0.211	8.2
Terrestrial acidification	kg SO_2 eq	0.00549	0.00064	8.6
Freshwater eutrophication	kg P eq	2.80×10^{-4}	2.97×10^{-5}	9.4
Marine eutrophication	kg N eq	3.62×10^{-5}	3.80×10^{-6}	9.5
Fossil resource scarcity	kg oil eq	0.521	0.064	8.1
Particulate matter formation	kg $PM_{2.5}$ eq	0.00193	0.00022	8.8
Human toxicity (carcinogenic)	kg 1,4-DCB eq	0.233	0.0279	8.4

This outcome reflects the larger amount of biomass processed, higher total electricity consumption throughout the digestion cycle, and the inclusion of transportation processes in the inventory. In contrast, Scenario A presents lower impacts when expressed per cubic meter of wastewater treated. However, because the original process-based functional units represent different functions and reference flows, these results should be interpreted as environmental profiles of the individual systems rather than as a direct ranking of environmental performance.

These results demonstrate that comparisons based exclusively on substrate quantity primarily reflect differences in system function, substrate characteristics, and processing

requirements. Consequently, the original process-based functional units provide valuable information regarding the environmental profile of each system individually, but they do not constitute a common basis for direct comparison.

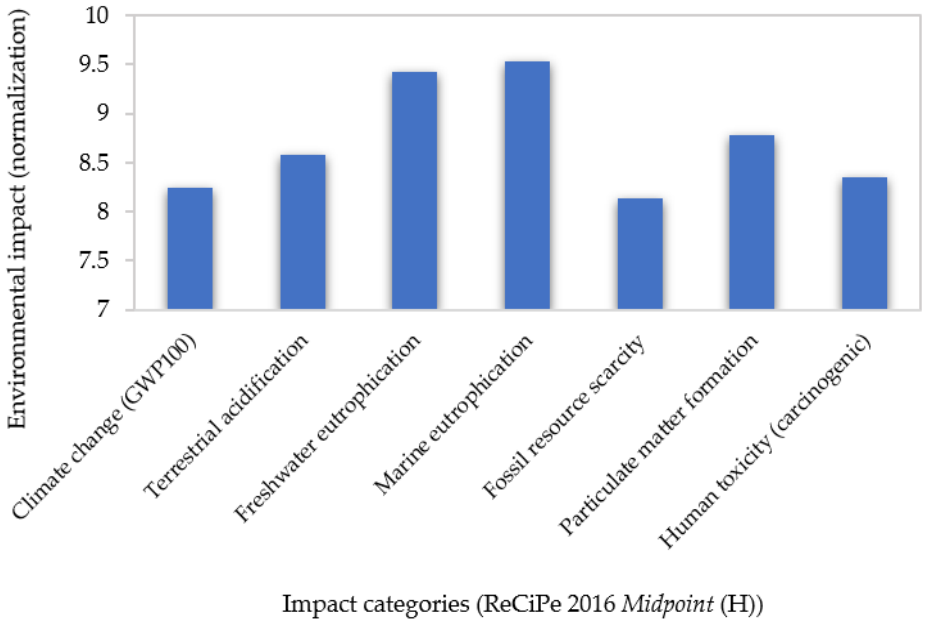


Figure 1. Relative comparison (SA/SB ratio) of normalized environmental impacts per 1 MJ of useful electricity.

2.2.1. Environmental Impacts Normalized by Useful Electricity

To compare both anaerobic digestion pathways according to their common function of electricity generation, environmental impacts were normalized to 1 MJ of useful electricity.

This normalization substantially changes the comparative interpretation of the two systems. Whereas Scenario B presented higher impacts when expressed per ton of substrate, it consistently exhibited the lowest impacts across all impact categories after normalization (Table 3). This inversion reflects considerably higher methane yield and lower electricity demand per unit of useful electricity generated during grape pomace digestion.

Climate change impacts decreased from 1.74 kg CO_2 eq MJ^{-1} in Scenario A to 0.21 kg CO_2 eq MJ^{-1} in Scenario B, representing an approximately eightfold reduction. Similar trends were observed for terrestrial acidification, freshwater and marine eutrophication, fossil resource scarcity, particulate matter formation, and human toxicity, for which normalized impacts in Scenario A remained between eight and ten times higher than those obtained for Scenario B.

The consistency of this pattern across all impact categories indicates that the observed differences are not limited to a single environmental mechanism but rather stem from fundamentally different energy recovery efficiencies between the two anaerobic digestion systems. As demonstrated in Section 2.1, wastewater digestion requires substantially higher operational electricity consumption per unit of useful electricity generated, resulting in higher normalized environmental burdens.

2.2.2. Contribution Analysis by Process Stage

Contribution analysis, shown in Figure 2, identified operational electricity consumption as the dominant environmental hotspot in both anaerobic digestion systems, confirming the trends observed in the normalized LCA results.

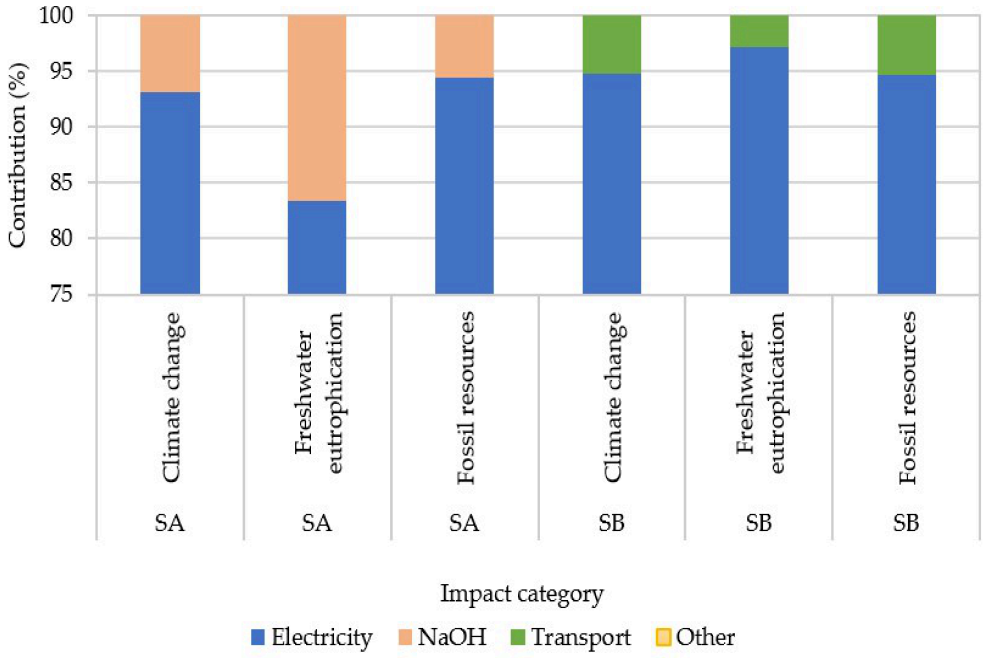


Figure 2. Contribution analysis of the main inventory flows to environmental impacts per MJ of useful electricity for scenarios SA and SB.

In SA, electricity consumption accounted for 93.2% of climate change impacts and 94.4% of fossil resource scarcity, while sodium hydroxide used for pH correction represented the second most relevant contributor, accounting for 6.8% of climate change and up to 16.6% of freshwater eutrophication. Other inventory flows, including tap water consumption and digestate production, showed negligible contributions.

Similarly, electricity remained the principal contributor in SB, representing 94.8% of climate change impacts, 97.1% of freshwater eutrophication, and 94.6% of fossil resource scarcity. Transportation of grape pomace contributed between 2.9% and 5.4%, whereas digestate generation had only a marginal influence on the overall environmental profile.

Although transport was included only in SB, its contribution remained relatively small compared with the environmental burden associated with electricity consumption. This finding indicates that improvements in process energy efficiency are likely to achieve substantially greater environmental benefits than optimization of transport logistics under the conditions investigated.

Only three impact categories are presented in the contribution analysis for clarity, as they were representative of the dominant environmental patterns identified across all evaluated categories.

Overall, the contribution analysis confirms that operational electricity demand is the primary driver of environmental performance in both scenarios, while secondary inputs, such as pH-correction chemicals or transport, influence only specific impact categories and do not alter the overall environmental ranking.

2.3. Sensitivity Analysis

A sensitivity analysis was performed to evaluate the robustness of the comparative environmental assessment by varying the operational parameters identified as the main contributors to environmental performance in the hotspot analysis. Based on the contribution analysis presented in Section 2.2, operational electricity demand and methane yield were investigated in both scenarios, while transportation distance was additionally evaluated for SB because transport was included only in the grape pomace system.

The results (Figures 3–5) indicate that operational electricity demand and methane yield were the parameters exerting the greatest influence on comparative environmental performance within the evaluated scenarios. Despite these variations, the relative environmental ranking of the two anaerobic digestion pathways remained unchanged across all scenarios investigated, indicating that the comparative conclusions are robust within the evaluated range of uncertainty.

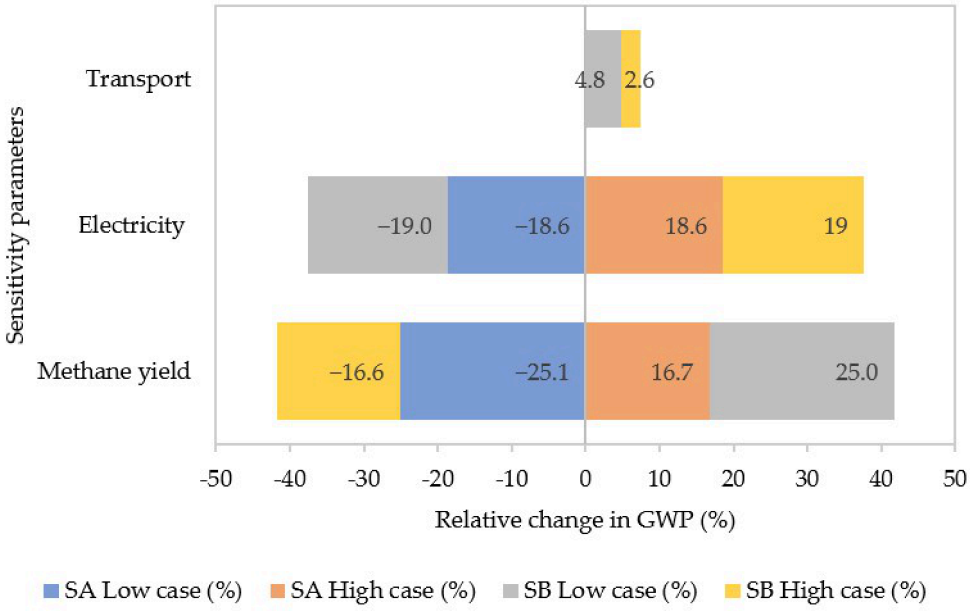


Figure 3. Sensitivity analysis for SA and SB for GWP impact category. Low case and high case correspond to the minimum and maximum values evaluated for each parameter (−20% and +20% for electricity demand and methane yield; −50% and +50% for transport distance). Results are expressed as percentage variation relative to the baseline scenario.

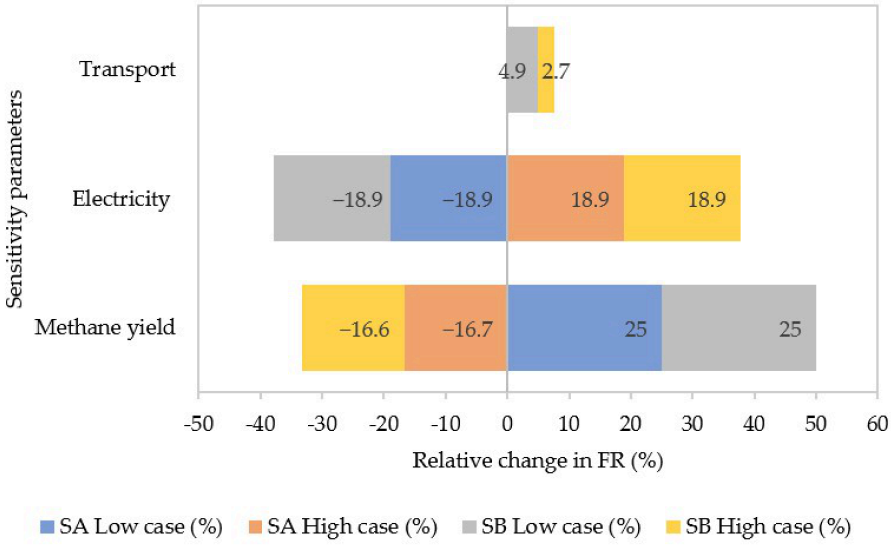


Figure 4. Sensitivity analysis for SA and SB for fossil resources impact category. Low case and high case correspond to the minimum and maximum values evaluated for each parameter (−20% and +20% for electricity demand and methane yield; −50% and +50% for transport distance). Results are expressed as percentage variation relative to the baseline scenario.

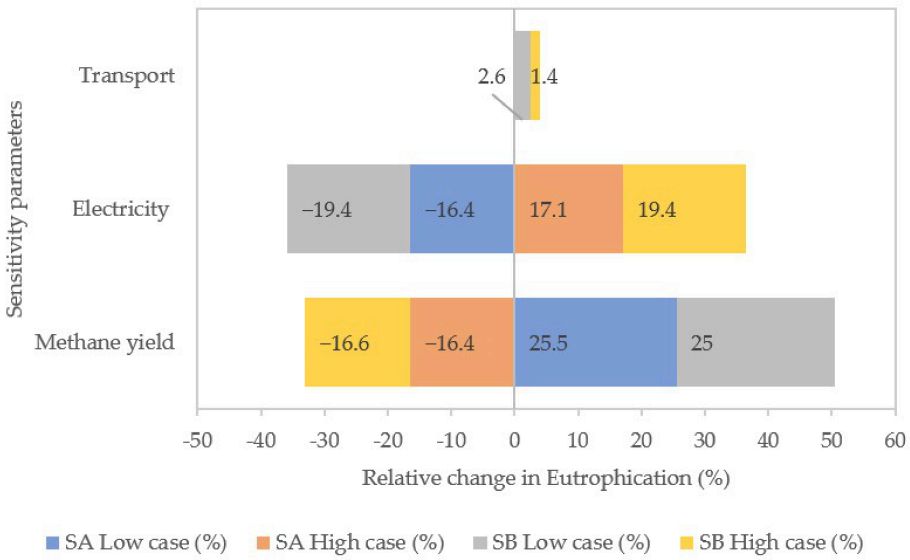


Figure 5. Sensitivity analysis for SA and SB for freshwater eutrophication impact category. Low case and high case correspond to the minimum and maximum values evaluated for each parameter (−20% and +20% for electricity demand and methane yield; −50% and +50% for transport distance). Results are expressed as percentage variation relative to the baseline scenario.

Electricity demand exhibited an almost proportional relationship with the environmental impacts. A variation of ±20% resulted in changes of approximately ±19% for climate change, ±19% for fossil resource scarcity, and ±16–19% for freshwater eutrophication in both scenarios. This behavior is consistent with the contribution analysis, which identified operational electricity consumption as the dominant hotspot across all impact categories.

Methane yield showed the highest sensitivity among all evaluated parameters. Because the functional unit remained fixed at 1 MJ of useful electricity, reductions in methane yield required proportionally greater substrate consumption and operational inputs to generate the same amount of useful energy. Consequently, a 20% decrease in methane yield increased environmental impacts by approximately 25%, whereas a 20% increase reduced impacts by approximately 17%. The asymmetric response reflects the non-linear effect of energy normalization, whereby decreases in methane productivity require proportionally larger increases in resource consumption per unit of useful electricity generated.

Transportation exhibited the lowest influence on the environmental profile of SB. Varying transport demand by ±50% produced changes generally below 5% for climate change and fossil resource scarcity and below 3% for freshwater eutrophication. These results indicate that, under the transport distances considered in this study, logistics represent only a secondary contributor compared with operational electricity demand and methane productivity.

Overall, the sensitivity analysis confirms that the environmental performance of both anaerobic digestion pathways is primarily governed by process energy efficiency rather than by transport-related assumptions. Most importantly, none of the tested scenarios altered the comparative ranking obtained in the baseline assessment. Grape pomace digestion consistently exhibited lower environmental impacts per MJ of useful electricity than winery wastewater digestion, demonstrating that the conclusions of this study are robust with respect to plausible variations in operational conditions.

3. Discussion

The present study demonstrates that the environmental performance of anaerobic digestion systems depends primarily on the balance between operational resource con-

sumption and useful energy recovery rather than on the amount of waste treated. Although winery wastewater digestion exhibits lower absolute impacts when environmental burdens are expressed per unit of treated substrate, grape pomace digestion consistently shows lower environmental impacts when results are normalized per unit of useful electricity. Importantly, this trend remained unchanged within the sensitivity ranges evaluated, indicating that the comparative ranking was robust under the assumptions considered in the present study.

Similar conclusions have been reported in LCAs comparing concentrated agro-industrial residues with dilute wastewater streams, where higher organic loading and methane productivity lead to improved environmental performance per unit of energy generated [13,25].

The contrasting environmental profiles observed between the two scenarios are primarily explained by differences in substrate composition, treatment objectives, and methane yield potential. Winery wastewater is characterized by low solids content and relatively dilute organic matter, which limits methane yield while requiring continuous electricity inputs for pumping, mixing and temperature control [26]. Consequently, anaerobic digestion of winery wastewater primarily delivers an environmental treatment service through pollutant removal, whereas energy recovery represents a secondary benefit. Pilot operation achieved COD removal efficiencies typically ranging between 80 and 91% under most operating conditions, confirming that wastewater treatment remained the primary function of Scenario A despite the additional energy-recovery benefit provided by biogas production.

In contrast, grape pomace is a solid residue with high organic content and methane potential, enabling substantially greater energy production per unit of processed material. Although its digestion requires additional handling operations, including transport and substrate conditioning, these burdens are largely offset by the considerably higher methane yield achieved. Similar behavior has been reported for food-processing residues and other lignocellulosic agro-industrial by-products [27–29]. Likewise, studies addressing food-processing and beverage-industry effluents consistently identify operational electricity demand as the dominant contributor to environmental impacts due to the relatively low biogas productivity of dilute substrates [30,31].

A practical limitation of grape pomace valorization is its highly seasonal production during harvest periods. Continuous anaerobic digestion throughout the year would therefore require temporary storage, preservation strategies, or integration with complementary substrates. These aspects were outside the scope of the present assessment but may influence the operational feasibility of full-scale implementation.

Beyond the comparison between substrates, one of the main methodological contributions of this study concerns the influence of functional unit selection on comparative LCA results. When environmental impacts are expressed using the original process-based functional units, winery wastewater digestion exhibits lower impacts per cubic meter of wastewater treated. However, because the functional units represent different services, these results should not be interpreted as demonstrating the environmental superiority of one system over the other. Instead, the process-based assessment should be viewed as a description of the environmental burdens associated with fulfilling each system's primary function, namely, wastewater treatment in Scenario A and residue valorization in Scenario B.

Once both systems are evaluated using a common functional unit based on useful electricity production, the comparative ranking across all impact categories is reversed. This finding clearly demonstrates that conclusions drawn from comparative LCAs can be strongly influenced by functional unit selection, particularly when systems provide different primary functions while simultaneously delivering energy recovery. These obser-

vations reinforce the recommendations of ISO 14044 and several methodological studies, which emphasize that the functional unit should represent the principal function delivered by the systems under comparison [20,32,33].

Contribution analysis further explains the environmental differences observed between the two scenarios by identifying operational electricity demand as the dominant environmental hotspot. In the present study, electricity consumption accounted for more than 93% of climate change impacts and over 94% of fossil resource scarcity in both systems, confirming that process energy requirements largely determine the overall environmental profile. These findings are consistent with previous LCAs of anaerobic digestion systems, where electricity demand has repeatedly been identified as the main contributor to climate change and fossil resource depletion, particularly under conditions of relatively low methane productivity [34,35].

The dominance of electricity consumption is closely linked to the operational characteristics of the pilot facilities. Maintaining reactor temperature, operating recirculation pumps for mixing, and compensating for heat losses represented a substantial fraction of the operational energy demand. This behavior is consistent with observations from pilot-scale anaerobic digestion systems, where thermal losses and unfavorable scale effects often result in considerably higher specific energy consumption than that observed in commercial facilities.

The results also highlight the distinction between technical feasibility and energetic viability. Project monitoring demonstrated that anaerobic digestion of winery wastewater was technically capable of achieving substantial pollutant removal, with COD removal efficiencies frequently exceeding 80%. However, under the pilot-scale conditions evaluated, the energy recovered through biogas production was insufficient to offset operational electricity requirements. This outcome reflects the scale of the installation and associated thermal inefficiencies rather than a fundamental limitation of anaerobic digestion as a wastewater-treatment technology.

Seasonality represents an additional challenge for winery wastewater treatment systems. The monitoring campaign revealed substantial variations in organic load and treatment performance throughout the production cycle. Influent COD concentrations ranged from approximately 1178 mg L^{-1} during pre-harvest periods to 10,920 mg L^{-1} during harvest, while methane content varied between 32% and 72% depending on operating conditions and season. These variations highlight the dynamic nature of winery wastewater and indicate that anaerobic digestion systems treating such effluents may require operational flexibility to maintain stable performance under changing organic loads and seasonal production patterns.

Although fugitive methane emissions were included in the inventory, their contribution remained substantially lower than the contribution associated with operational electricity consumption under the pilot-scale conditions evaluated. Consequently, electricity demand rather than methane leakage was identified as the dominant driver of environmental performance.

Additionally, the contribution analysis identified a hotspot specific to Scenario A. The sodium hydroxide used for pH adjustment accounted for up to 16.6% of freshwater eutrophication impacts, resulting in a more dispersed contribution profile than observed for the remaining impact categories. This result suggests that chemical consumption, although secondary in terms of climate-related impacts, may become environmentally relevant for nutrient-related categories due to upstream emissions associated with alkali production. Similar observations have been reported for wastewater treatment systems requiring pH control or coagulating chemicals, in which sodium hydroxide contributes significantly to eutrophication, toxicity, and ecotoxicity indicators [35,36].

The sensitivity analysis provides additional confidence in the robustness of the comparative assessment. Electricity demand and methane yield were confirmed as the parameters exerting the greatest influence on environmental performance, whereas transport had only a limited effect under the conditions evaluated. The pronounced influence of methane yield is expected because, under a fixed energy-based functional unit, reductions in methane productivity require proportionally greater substrate consumption and operational inputs to deliver the same amount of useful electricity. This behavior is consistent with previous studies identifying methane yield as one of the principal sources of uncertainty in LCAs of anaerobic digestion systems [37]. Conversely, transport contributed less than 5% to the analyzed impact categories, indicating that logistics play only a secondary role when transport distances remain short, and substrates exhibit high methane potential [38]. Most importantly, none of the evaluated sensitivity scenarios modified the environmental ranking obtained in the baseline assessment. These results indicate that the comparative conclusions were not affected by the operational variations considered in the present study, although broader uncertainty analyses could be explored in future work.

As the inventory was based on pilot-scale operation, the reported electricity demands may not be fully representative of commercial-scale facilities, where process efficiencies are often higher. Project monitoring indicated that both pilot systems had negative net electricity balances, with operational electricity consumption exceeding the useful electricity generated from the recovered biogas. Consequently, the energy-normalized functional unit of 1 MJ of useful electricity should not be interpreted as representing net electricity delivery or energy self-sufficiency. Instead, it was used as an exploratory indicator to compare the environmental intensity of energy recovery from two winery residue streams that serve different primary functions. The results, therefore, describe the environmental burdens associated with energy recovery potential under pilot-scale conditions rather than the performance of commercially optimized anaerobic digestion facilities.

An additional limitation of the study concerns the uncertainty in pilot-scale operational data. Although the inventory was derived from multiple monitoring campaigns covering different seasonal conditions, the assessment relied on average values rather than on probabilistic distributions. Consequently, the sensitivity analysis should be interpreted as an evaluation of the influence of parameters rather than as a full uncertainty propagation analysis.

Monte Carlo simulation was not performed because the available operational dataset lacked sufficient information to define robust probability distributions for all inventory parameters. Nevertheless, the sensitivity analysis enabled identification of the parameters exerting the greatest influence on environmental performance and confirmed that the comparative ranking remained unchanged within the evaluated ranges.

Additional factors, such as alternative electricity mixes, digestate management pathways, CHP performance, or alternative residue management scenarios, may also influence environmental outcomes and should be investigated in future studies. However, these aspects were outside the scope of the present attributional gate-to-gate assessment.

An additional strategy deserving further investigation is the co-digestion of winery wastewater and grape pomace. Combining liquid and solid winery residues may improve substrate balance, increase methane productivity, reduce operational variability, and enhance overall resource recovery. Although co-digestion was not evaluated in the present work, it represents a promising pathway for improving both environmental and operational performance in winery-based anaerobic digestion systems.

From a practical perspective, the results support differentiated yet complementary circular management strategies for winery residues. Anaerobic digestion of winery wastewater should primarily be regarded as an environmental treatment technology that reduces

organic pollution while recovering part of the embedded energy. Conversely, grape pomace is a more energy-dense substrate with greater potential for electricity generation. Rather than considering these residues as competing resources, integrated management strategies could exploit their complementary functions within a circular bioeconomy framework. In this approach, the higher energy recovery potential of grape pomace digestion could help reduce the overall energy demand of integrated winery residue management systems. However, under the pilot-scale conditions evaluated, both pathways remained net electricity consumers; therefore, the proposed integration should be interpreted as a conceptual circular management strategy rather than a demonstrated solution for energy self-sufficiency. Similar integrated approaches have been proposed as effective strategies to reduce greenhouse gas emissions and enhance resource efficiency in agro-industrial systems [4,5,10,24,39–41]. These findings reinforce the role of anaerobic digestion as a circular resource management option that combines organic waste treatment with energy recovery from winery residues.

Digestate management was excluded from the system boundary to ensure methodological consistency between scenarios and because post-treatment pathways are highly dependent on site-specific practices. Nevertheless, the inclusion of credits for digestate transport, storage, agricultural application, or fertilizer substitution could influence the overall environmental profiles of both pathways. In particular, digestate management may generate additional emissions from ammonia volatilization or nitrous oxide formation, while nutrient recovery could provide environmental credits by displacing synthetic fertilizers. These aspects deserve further investigation in future studies.

Overall, this study contributes to the current literature by providing one of the first comparisons of anaerobic digestion pathways for liquid and solid winery residues, based on harmonized methodological assumptions and conducted under consistent methodological conditions. The results suggest that energy-normalized assessment may provide a more appropriate basis for comparing systems with different primary functions and reinforce the importance of combining robust methodological choices with process-specific interpretation when evaluating waste-to-energy technologies within the circular economy framework.

4. Materials and Methods

4.1. System Description

This study evaluates the environmental performance of two anaerobic digestion pathways applied to winery residues using a common gate-to-gate Life Cycle Assessment. The assessment is based on a case study representative of winery operations in the Douro wine region (Portugal), where anaerobic digestion is considered as a strategy for both wastewater treatment and organic residue valorization (Figure 6).

Scenario A (SA) examines the anaerobic digestion of winery wastewater, with the functional unit defined as treating 1 m^3 of wastewater, a composite stream generated from cleaning operations, residual wine losses, and fermentation by-products. Scenario B (SB) evaluates the anaerobic digestion of grape pomace, with a functional unit of 1 ton of substrate.

Although both scenarios rely on the same anaerobic digestion technology, they fulfill different primary functions. SA primarily represents a wastewater treatment process in which biogas production provides an additional environmental benefit through energy recovery. Conversely, SB represents a residue valorization pathway in which anaerobic digestion is primarily intended to generate renewable energy from grape pomace. This distinction motivated the adoption of both process-based and energy-normalized functional units, allowing comparison of the systems according to both their individual functions and their common function of electricity generation.

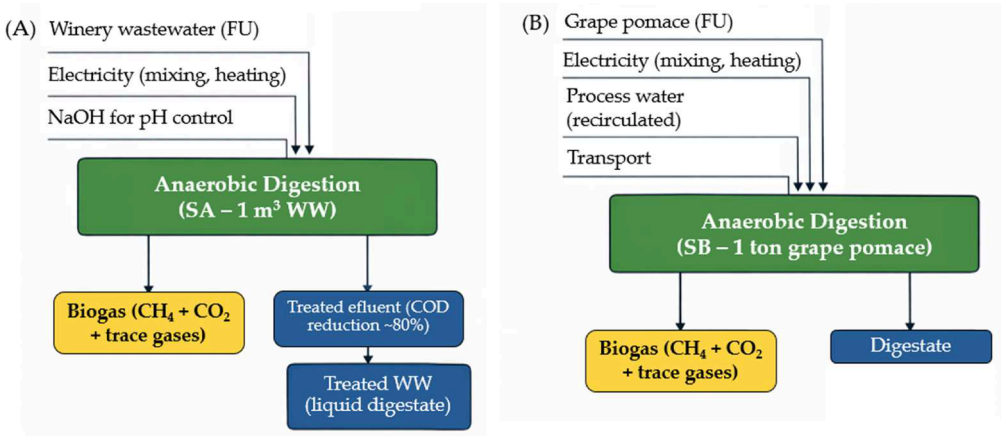


Figure 6. Gate-to-gate process flow diagram. (**A**) SA—Biogas from Winery Wastewater; (**B**) SB—Biogas from Grape Pomace.

SA models the treatment of liquid effluents generated during wine production, including washing tap water, cleaning residues, and soluble organic matter. Winery wastewater typically presents strong seasonal variability associated with winemaking operations. During harvest and fermentation, wastewater primarily originates from washing crushers, presses, and tanks, containing grape juice residues, sugars, suspended solids, and yeast biomass, resulting in an average COD of approximately 11,000 mg L^{-1} measured during pilot operation. Outside the harvest season, wastewater is generated mainly from routine cleaning of tanks, pipelines, floors, and equipment, resulting in a lower COD concentration of approximately 4200 mg L^{-1}.

Throughout the monitoring period, the anaerobic digestion system achieved COD removal efficiencies ranging from 48% to 91%, with most operational periods exceeding 80%. These results, shown in Table 4, indicate that the system effectively fulfilled its wastewater-treatment function while simultaneously recovering energy through biogas production. Variations in treatment performance were mainly associated with changes in organic load, hydraulic retention time, and seasonal operating conditions.

Table 4. Main operational and treatment performance parameters for SA.

Parameter	Range Observed
Reactor working volume	20 m^3
Operating temperature	31–36 °C
pH	6.6–7.3
HRT	9–28 d
Influent COD	1178–10,920 mg/L
Effluent COD	159–3226 mg/L
COD removal efficiency	48–91%
Methane content	32–72%

The system includes wastewater handling (including pH correction), anaerobic digestion in a 20 m^3 reactor, biogas storage, and the generation of treated wastewater and liquid digestate. The reactor was initially inoculated with 7 m^3 of WWTP sludge, corresponding to approximately 35% of the reactor working volume. As the inoculum was required only during reactor commissioning and was not replenished during operation, it was not included as an operational input in the foreground inventory.

Owing to the absence of solid–liquid separation, digestate was modeled as a single liquid output stream.

SB represents the anaerobic digestion of grape pomace, consisting mainly of skins, seeds, and residual pulp. The process was carried out in a pilot-scale anaerobic digester with a working volume of 3 m^3. The system includes transportation of grape pomace and inoculum, substrate feeding, anaerobic digestion in a pilot-scale reactor, biogas storage, and digestate production. Digestate was modeled as a single output stream without explicit solid–liquid separation. Recovered process water was considered internal recirculation and therefore remained within the system boundaries. Consequently, the digestate output reflects not only residual grape pomace solids but also retained moisture and water present within the digestion mixture. For this reason, digestate mass exceeded the initial mass of grape pomace supplied to the system.

Transportation assumptions differed across scenarios based on each system's operational configuration. In SA, transportation of winery wastewater and inoculum was excluded because the pilot plant was assumed to operate on-site within the winery, representing an integrated wastewater treatment configuration. Only grape pomace transport was included in the foreground inventory. Inoculum transport was excluded because the inoculum was considered a start-up requirement rather than an operational input to the system.

Although the study adopts a gate-to-gate perspective, transportation was included when it constituted an operational requirement of the assessed configuration. In Scenario B, external collection and delivery of grape pomace were necessary steps to enable anaerobic digestion and were therefore considered part of the foreground system. Inoculum transport was excluded because the inoculum was treated as a start-up requirement rather than an operational input.

A common gate-to-gate system boundary was adopted for both scenarios to ensure methodological consistency. The assessment includes substrate handling, pH correction (when applicable), anaerobic digestion, biogas production and storage, digestate generation, and treated wastewater production. Downstream processes, including biogas upgrading, electricity distribution, digestate utilization, wastewater discharge, infrastructure construction, and equipment end-of-life, were excluded from the base-case assessment because they are highly site-specific and could compromise the comparability of the two systems. The use of a fixed CHP electrical efficiency represents an additional simplification of the assessment. Because CHP operation was not explicitly modeled, variations in conversion efficiency would affect the magnitude of the normalized results but would not alter the underlying comparison of methane recovery performance between the two systems. Future studies could investigate the influence of alternative conversion technologies and CHP efficiencies on energy-normalized environmental indicators.

Digestate post-treatment was not quantitatively assessed and is discussed qualitatively.

Both winery wastewater and grape pomace were treated as waste streams entering the system using a cut-off approach. Consequently, no environmental burdens associated with grape cultivation, wine production, or prior waste generation were allocated to the assessed substrates. The study, therefore, evaluates the environmental burdens associated exclusively with the anaerobic digestion processes within the defined gate-to-gate system boundaries. Digestate utilization was not included in the assessment, and no substitution credits were assigned because potential agricultural applications, nutrient replacement efficiencies, and local management practices are highly site-specific. Excluding digestate valorization ensured methodological consistency between scenarios and avoided introducing additional uncertainty into comparative analysis.

The present study was designed as an attributional gate-to-gate assessment. Therefore, the avoidance of conventional wastewater treatment, grape pomace disposal, electricity substitution, digestate substitution credits, and other consequential effects was not included. The results should consequently be interpreted as operational environmental burdens associated with the assessed anaerobic digestion systems rather than as net environmental consequences relative to alternative management pathways.

4.2. Life Cycle Inventory (LCI)

The Life Cycle Inventory combined pilot-scale operational data obtained during biodigester operation, industrial information provided by the winery, and peer-reviewed literature on the anaerobic digestion of winery residues. The pilot-scale operational data were obtained from multiple monitoring campaigns conducted between 2024 and 2025, covering pre-harvest, harvest, and post-harvest periods. The inventory, therefore, reflects average operating conditions observed over extended periods rather than isolated measurements. A summary of the sources of the principal foreground inventory parameters is provided in Supplementary Table S1.

Background processes, including electricity generation, sodium hydroxide production, and freight transport, were modeled using Ecoinvent version 3.10, adopting the cut-off system model. The Portuguese medium-voltage electricity supply was used to represent operational electricity consumption. The cut-off approach was selected because both winery wastewater and grape pomace were considered waste streams entering the system without upstream environmental burdens, in accordance with the attributional gate-to-gate scope of the study.

Foreground inputs included the respective substrates (1 m^3 of winery wastewater for SA and 1 t of grape pomace for SB), electricity consumption, and sodium hydroxide (NaOH) for pH correction. NaOH consumption is reported as the mass of active sodium hydroxide.

For Scenario A, operational electricity demand was mainly associated with water heating (90 kWh/FU), followed by digester agitation (4 kWh/FU), water circulation (1.6 kWh/FU), and effluent transfer operations (1.1 kWh/FU in total). These values were obtained from pilot operational records and explain the relatively high electricity demand observed under pilot-scale conditions. The relatively high electricity requirements observed in both scenarios were largely attributable to maintaining mesophilic operating conditions, particularly during colder periods of the year, as well as to heat losses typical of small-scale pilot installations. These energy requirements are therefore representative of the pilot configurations evaluated and should not be interpreted as typical values for commercial anaerobic digestion facilities.

The start-up inoculum was not included as an operational input, as described in Section 4.1.

Transportation inventories were modeled only for Scenario B, reflecting the logistics associated with pomace and inoculum supply. In Scenario A, transport was excluded according to the on-site treatment configuration described above.

Direct emissions associated with anaerobic digestion included residual COD and fugitive methane emissions. A baseline methane leakage rate of 2% of methane production was assumed, consistent with values reported in the anaerobic digestion literature. Sensitivity scenarios evaluated the influence of variations in methane productivity and other key operational parameters.

Methane yield and biogas composition were obtained from pilot-scale measurements and verified against literature values for winery residues. The measured methane yields therefore represent the effective biological performance of the pilot systems under realistic operating conditions rather than theoretical methane potentials.

4.3. Life Cycle Impact Assessment (LCIA)

Environmental impacts were assessed using the ReCiPe 2016 Midpoint (H) method. The impact categories selected were those considered most relevant for anaerobic digestion and bioenergy systems, namely climate change, terrestrial acidification, freshwater eutrophication, marine eutrophication, fossil resource scarcity, particulate matter formation, and human toxicity. According to the ReCiPe 2016 methodology, biogenic CO_2 emissions were considered climate-neutral, whereas fossil CO_2 emissions associated with background processes such as electricity production were fully accounted for.

These categories were selected because they capture both direct emissions associated with anaerobic digestion and indirect environmental burdens related to electricity consumption, chemical production, and transport activities.

All modeling and impact calculations were performed using OpenLCA version 2.1.1.

4.4. Functional Units and Energy Normalization

Two complementary functional units were adopted to evaluate the environmental performance of the systems according to their distinct primary functions, while enabling a comparison grounded in consistent methodological assumptions regarding energy recovery.

The primary process-based functional units were:

- treatment of 1 m^3 of winery wastewater (SA);
- anaerobic digestion of 1 ton of grape pomace (SB).

Since the two systems provide different primary services (wastewater treatment versus residue valorization), direct comparison based exclusively on substrate quantity could lead to misleading conclusions. Therefore, an additional energy-normalized functional unit of 1 MJ of useful electricity was introduced to compare the two systems on a per-unit energy basis.

Useful electricity was calculated according to:

$$E_{\text{useful}} = V_{CH_4} \times 35.8 \times \eta_{\text{el}}$$

where V_{CH_4} is the specific methane yield (m^3 CH_4 per functional unit), 35.8 MJ m^{-3} is the LHV (Lower Heating Value) of methane, η_{el} is the electrical conversion efficiency of the CHP system. A value of 35% was adopted, consistent with commonly reported electrical efficiencies for biogas-fueled CHP units [42].

The CHP unit was not modeled as an inventoried process within the system boundaries. Instead, the electrical conversion efficiency was used exclusively as a harmonization factor to convert methane yield into useful electricity, thereby enabling comparison of both anaerobic digestion pathways using a common energy-based functional unit. As the objective of the study was to evaluate the influence of functional unit selection rather than the environmental performance of downstream energy-conversion technologies, CHP infrastructure and operational burdens were intentionally excluded from the gate-to-gate assessment. Consequently, the energy-normalized functional unit should be interpreted as a methodological reference basis rather than as a representation of a fully modeled electricity-generation system.

The resulting electricity production was 16.0 MJ for Scenario A and 672 MJ for Scenario B. All foreground inventory flows were subsequently normalized by the corresponding electricity production, allowing direct comparison of environmental impacts per unit of useful energy generated.

Tables 5 and 6 summarize the normalized LCI for SA and SB, respectively.

Table 5. Life Cycle Inventory for scenario SA. Operational data is reported for the pilot system and normalized per 1 MJ of useful electricity produced.

Flow	Type	Value (per 1 m^3 WW)	Value (per 1 MJ)	Unit
Winery wastewater	Reference flow	1	0.062	m^3
Electricity (operation)	Input	96.7	6.03	kWh
NaOH	Input	1.3	0.078	kg
Biogas	Output	2	0.125	m^3
Methane produced (CH_4)	Output	1.28	0.0798	m^3
Liquid digestate	Output	990	61.7	kg

Note: 1 kWh = 3.6 MJ.

Table 6. Life Cycle Inventory for scenario SB. Operational data are reported for the reference system (1 t of grape pomace) and normalized to 1 MJ of useful electricity produced.

Flow	Type	Value (per 1 t Pomace)	Value (per 1 MJ)	Unit
Grape pomace	Reference flow	1000	1.49	kg
Electricity (operation)	Input	500	0.744	kWh
Transport—pomace	Input	25.8	0.0384	tkm
Biogas	Output	76.6	0.114	m^3
Methane (CH_4)	Output	53.6	0.0798	m^3
Digestate (including retained moisture and inoculum)	Output	2550	3.79	kg

Note: Digestate mass does not correspond exclusively to the grape pomace fraction. The reported value includes retained moisture and water present within the digestion mixture. Consequently, digestate mass cannot be directly compared with the initial mass of grape pomace supplied to the system.

4.5. Sensitivity Analysis Approach

A sensitivity analysis was performed to evaluate the influence of key operational parameters on the comparative environmental results and to identify the variables exerting the greatest influence on environmental performance.

Based on the hotspot analysis of the base-case scenarios, three parameters were identified as the principal sources of uncertainty: operational electricity demand, methane yield, and transportation of grape pomace.

Operational electricity demand was varied by ±20% to account for uncertainties related to pumping, mixing, reactor heating, and auxiliary energy consumption. The selected variation ranges were intended to represent plausible operational deviations commonly encountered in pilot-scale anaerobic digestion systems and were not intended to represent statistical confidence intervals or probability distributions.

Methane yield was varied by ±20% in both scenarios, while the functional unit was held fixed at 1 MJ of useful electricity. This was implemented by proportionally scaling the substrate requirements, along with all foreground inputs and outputs necessary to produce the same amount of useful electricity. Consequently, lower methane yields required proportionally higher resource consumption per MJ generated, whereas higher methane yields reduced the inventory requirements.

For Scenario B, transportation distances were additionally varied by ±50% to evaluate the influence of logistical assumptions on environmental performance.

The sensitivity analysis was performed for climate change, fossil resource scarcity, and freshwater eutrophication because these categories were considered representative of the overall environmental trends observed in the study and encompass climate-related,

resource-depletion, and nutrient-related environmental mechanisms. Similar comparative patterns were observed across the remaining impact categories.

Methane leakage was not varied independently because its contribution was substantially lower than the contribution associated with operational electricity demand. Nevertheless, fugitive methane emissions were included in the baseline inventory using a conservative leakage assumption.

The purpose of the sensitivity analysis was to assess the influence of key operational assumptions on comparative outcomes rather than to provide a comprehensive uncertainty assessment. Consequently, the results should be interpreted as scenario-based evaluations of the influence of parameters.

5. Conclusions

This study performed a comparative gate-to-gate Life Cycle Assessment of two anaerobic digestion pathways for major winery residues, namely winery wastewater and grape pomace. The results demonstrated that the environmental performance of these valorization pathways depends not only on substrate characteristics and methane yield potential, but also on the functional unit adopted for comparison.

When impacts were expressed per unit of treated substrate, the digestion of winery wastewater exhibited lower environmental burdens. However, when environmental impacts were normalized per unit of useful electricity generated, grape pomace digestion consistently achieved lower impacts across all assessed categories because of its substantially higher methane yield and lower operational electricity demand per unit of energy recovered.

The results further highlighted the different roles of the two residues within winery waste management systems. Anaerobic digestion of winery wastewater primarily serves an environmental treatment function by reducing pollutants, whereas grape pomace digestion offers high energy recovery potential under the pilot-scale conditions evaluated.

These findings reinforce the importance of selecting functional units that adequately reflect the intended function of the systems being evaluated. Contribution and sensitivity analyses identified operational electricity demand and methane yield as the main factors influencing environmental performance, although electricity demand was strongly affected by pilot-scale operation and associated thermal inefficiencies.

From a circular economy perspective, the results suggest that winery wastewater and grape pomace should be regarded as complementary resources rather than competing waste streams. Integrated anaerobic digestion strategies could simultaneously support wastewater treatment, energy recovery, and resource valorization within winery residue management systems.

Overall, this work contributes to the growing body of knowledge on winery residue valorization by providing a consistent environmental assessment of two important anaerobic digestion pathways. The proposed framework supports more informed decision-making on waste management and resource recovery strategies in the wine industry and highlights the role of anaerobic digestion in advancing circular and sustainable agro-industrial systems. Future work should incorporate larger operational datasets and probabilistic uncertainty analysis to further improve the robustness of comparative assessments.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/recycling11090155/s1, Table S1: Source of foreground inventory data.

Author Contributions: Conceptualization, M.S.; methodology, M.S. and J.P.; software, M.S.; validation, M.S., V.C.B. and A.C.F.; formal analysis, M.S.; investigation, M.S. and J.P.; resources, M.S. and J.P.; data curation, M.S.; writing—original draft preparation, M.S.; writing—review and editing,

V.C.B.; visualization, A.C.F.; supervision, A.C.F.; project administration, A.C.F.; funding acquisition, A.C.F. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The original contributions presented in this study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

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