Cleaner Engineering and Technology 25 (2025) 100914

Contents lists available at ScienceDirect

Cleaner Engineering and Technology

journal homepage: www.sciencedirect.com/journal/cleaner-engineering-and-technology

Reusable beverages packaging: A life cycle assessment of glass bottles for wine packaging

Justus Caspers *, Pauline Bade, Matthias Finkbeiner

Chair of Sustainable Engineering, Technische Universität Berlin, 10623, Berlin, Germany

ARTICLE INFO

Keywords:
Single-use
Reusable
Life cycle assessment
Wine packaging
Glass bottle

ABSTRACT

Bottle production constitutes up to 70% of the greenhouse gas emissions of wine consumption. However, a reuse system comes along with additional environmental burdens, namely via the impact of cleaning processes and increased transport distances for the return of packaging. Hence, the objective of this study is to assess the potential environmental implications associated with both reuse and single-use for wine bottles, by means of life cycle assessment (LCA).

Under the assumption based on wine consumption in Germany, the reusable bottle exhibits a reduced environmental impact in four out of five considered impact categories (climate change, fossil depletion, freshwater consumption, and freshwater ecotoxicity). Sensitivity analysis indicates that even one reuse cycle for wine bottles offers environmental benefit compared over single-use.

It is noteworthy that other studies, which also assess reusable beverage packaging, have reported smaller break-even points for the transport distances. This distinction arises from the study's exclusive focus on glass bottles, which dominate the wine market. In conclusion, a reusable wine bottle system holds the potential would significantly decrease the environmental footprint of wine consumption.

1. Introduction

Climate change poses a significant challenge to the wine production industry, with rising global temperatures impacting quality of wine grapes and leading to more frequent occurrences of water deficits in wine-producing regions (Ollat et al., 2016; Van Leeuwen and Darriet, 2016). Moreover, wine production itself contributes to climate change, with environmental assessments highlighting the significant share attributed to the production of glass bottles (Ferrara and De Feo, 2018; Jourdaine et al., 2020). Introducing reusable bottles could potentially mitigate the environmental impact of wine packaging. However, it's essential to recognize that the cleaning process and associated infrastructure required for a reusable system also entail environmental burden. Therefore, a thorough qualitative investigation is imperative to accurately assess the potential environmental advantages (Coelho et al., 2020).

Life Cycle Assessment (LCA) is a comprehensive analytical method used to evaluate the environmental impacts of a product, process, or system throughout its entire life cycle, from raw material extraction to end-of-life disposal. The ISO 14040 and 14,044 standards provide a standardized approach for conducting LCAs (Finkbeiner et al., 2006). Several LCAs have compared the environmental impact of single-use and reusable food and beverage packaging. Transport distances, for example, have been highlighted as crucial in an LCA comparing bread packaging (Koskela et al., 2014). Especially for wine packaging this factor needs to be considered, since about half of the wine consumed in Germany comes from abroad, which means long delivery distances. Of the wine consumed in Germany, 44% comes from Germany, and approximately 40% comes from southern European countries (16% from Italy, 14% from Spain, and 11% from France) (Münster, 2020; Deutsches Weininstitut, 2023).

Another significant factor in LCAs comparing single-use and reusable packaging for beverages is the choice of packaging material, as demonstrated by Simon et al. (2016). Although glass production is a significant source of greenhouse gas emissions, its properties, such as strength and durability, make it a valuable choice for beverage packaging (Colangelo, 2024). While lightweight materials like plastic or aluminum can potentially reduce emissions due to lower impacts of

This article is part of a special issue entitled: SDEWES24 published in Cleaner Engineering and Technology.

* Corresponding author.
E-mail address: j.caspers@tu-berlin.de (J. Caspers).

https://doi.org/10.1016/j.clet.2025.100914
Received 5 November 2024; Received in revised form 24 January 2025; Accepted 11 February 2025
Available online 12 February 2025
2666-7908/© 2025 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

production and long-distance transport, the market share of alternative packaging types, such as plastic bottles, aluminum cans or bag-in-box remains low (Thompson-Witrick et al., 2021). Additionally, the energy, water, and soap required for cleaning the reusable packaging must be considered when comparing single-use and reusable options. Studies on takeaway packaging have shown that the break-even point can vary significantly depending on cleaning behavior (Potting and van der Harst, 2015; Gallego-Schmid et al., 2018; Caspers et al., 2023).

The only LCA study dealing specifically with a comparison of a single-use and reusable wine glass bottles in Germany dates back to over 20 years. (Plinke et al., 2000). Environmental assessments of single-use and reusable wine packaging are available for other countries, such as Italy (Landi et al., 2019) and Canada (Cleary, 2013). However, these studies lack important aspects, such as environmental break-even point analyses, which are recommended for comparing single-use and reusable packaging (Cottafava et al., 2024) or don't include the complete life cycle (Landi et al., 2019). Further, these LCAs show the link between the environmental impact of different packaging options and the emissions associated with the electricity mix. This finding aligns with other LCAs, such as those comparing single-use and reusable coffee cups. (Woods and Bakshi, 2014). Further, the environmental impact of glass, is due to its energy intensive production, codetermined by the electricity mix (Platzbecker et al., 2022). Thus, a reconsideration of such comparisons is necessary given changes in the electricity grid mix (Eurostat, 2024; Holzapfel et al., 2023). As shown, the available LCAs comparing single-use and reusable glass wine bottles for consumption in Germany either lack some important aspects or are outdated. Therefore, we conducted a comparative LCA of a single-use glass bottle (SUB) and a reusable glass bottle (RB) with current grid mixes and addressing the identified factors for LCAs of single-use and reusable packaging.

The remainder of the paper is organized as follows: Section 2 describes the applied LCA method and the data used. Subsequently, Section 3 presents the results of the conducted LCA, including break-even and sensitivity analyses. Section 4 then Discusses and contextualizes the results. Finally, Section 5 presents the conclusions and provides an outlook on further research needs.

2. Methods

A comparative environmental life cycle assessment (LCA) of a reusable and single-use wine bottle was conducted. Leaned on the guidelines of ISO 14040 and ISO 14044, the LCA consisted of four phases: goal and scope, life cycle inventory analysis, impact assessment and interpretation (ISO, 2006a, 2006b). LCA for Experts Database V2023.1 as well as Ecoinvent V3.8 database were applied to establish the life cycle models (Ecoinvent Center, 2021; Sphera, 2023).

2.1. Goals and scope definition

The goal of the study was to evaluate the potential environmental impact of SUBs (Single-Use Bottles) and RBs (Reusable Bottles) for wine produced and bottled in Europe, for consumption and the end-of-life (EoL) in Germany. The functional unit chosen was a 0.75 L green glass bottle weighing 548.5 g (Plinke et al., 2000).

The life cycle stages and system boundaries of the SUB are depicted in Fig. 1, and for the RB in Fig. 2. In the case of the SUB, the life cycle begins with the production of the wine bottle. The next step involves transportation to the winery, where the wine is bottled. After bottling, the wine is transported to the point of sale. The consumer's transport to the point of sale is not included in the assessment, as it depended by individual consumers and not the overall product systems. Following the use phase, the bottle and packaging are disposed of by the end user.

The initial stages of the RB's life cycle are identical to those of the SUB. After the use phase, a portion of the RB is disposed of, depending on assumptions about reuse cycles. As the reuse rate is often a key factor in LCAs comparing single-use and reusable packaging, two reuse rates

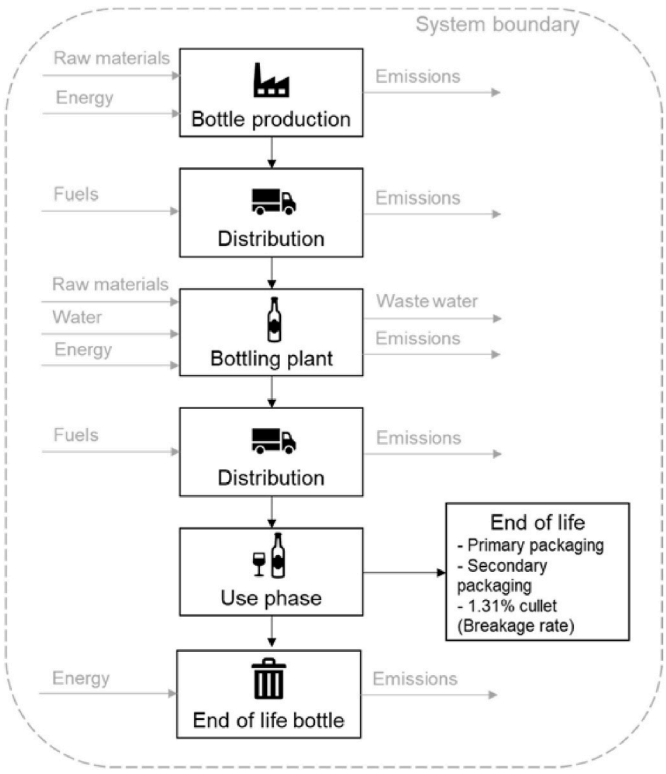

Fig. 1. Life cycle of a single-use wine bottle (SUB).

were assumed for the initial calculations. It is assumed that the reusable bottle (RB) is used, 50 times, in line with Plinke et al. (2000) as well as 15 times, as used by Cleary (2013). The remaining portion of the RB is transported to a reconditioning facility in Germany, where the bottle is cleaned and checked for suitability. Subsequently, it is transported to the bottling plant where new wine is bottled.

2.2. Life cycle inventory (LCI)

The constituent raw materials employed in the bottle production process were predominantly acquired from the LCA for Experts Database V2023.1 (Sphera, 2023), encompassing quartz sand, lime, soda, natural gas, and electricity. In instances where relevant data were unavailable, substitutes were derived from the Ecoinvent database V3.8 (Ecoinvent Center, 2021), incorporating materials such as feldspar, dolomite, and glass cullet. The share of each material was based on information provided by Schaeffer and Langfeld (2020). Other aggregates were cut off from the analysis, as the mass share is neglectable (0.4 %). An initial assumption was made with regard to a recycled glass cullet content of 90%. Energy consumption data were sourced from the study conducted by Platzbecker et al. (2022). An overview of all data used for the bottle production is given in Table 1.

The bottle production process is succeeded by the bottling plant operations, encompassing washing and bottle filling procedures. Within the washing process, the bottle undergoes cleansing with hot water, detergent, and disinfectant. Subsequently, in the filling process, the bottle is filled with wine (a parameter not considered in this Life Cycle Assessment), sealed using a cork closure and aluminum sleeve, labeled with a paper label, and encased in transport packaging, denoted as secondary packaging.

The secondary packaging comprises a cardboard box designed for six wine bottles each, accompanied by a polyethylene (PE) film for securement to a Euro pallet for transportation. Information pertaining to the Euro pallet is derived from Timber (2023) and (Wölfli, 2023). For the washing process, data from the Life Cycle Assessment study

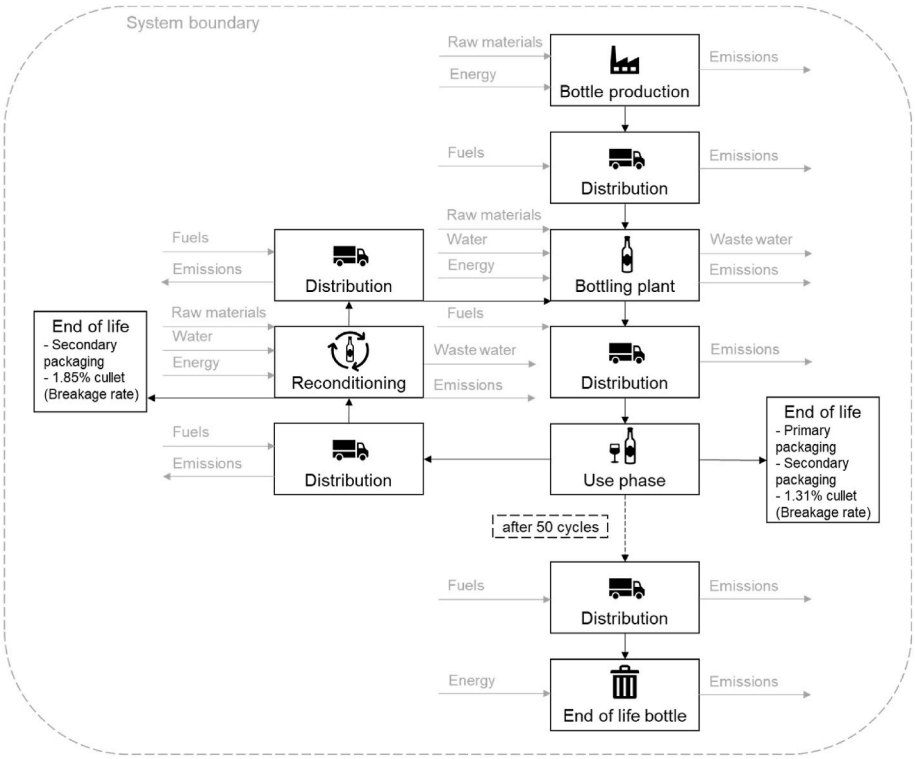

Fig. 2. Life cycle of a reusable wine bottle (RB Fig. 2).

Table 1
Inputs and Outputs of the bottle production process.

Process	Type of flow	Name of flow	Value	Unit	Reference
Bottle production	Input	Glass cullet	4.94E-01	kg	Schaeffer and Langfeld (2020)
	Input	Quartz sand	2.74E-02	kg	
	Input	Soda	1.1E-02	kg	
	Input	Lime	5.49E-03	kg	
	Input	Dolomite	4.39E-03	kg	
	Input	Feldspar	4.64E-03	kg	
	Input	Electricity	2.21E-01	kWh	Platzbecker et al. (2022)
	Input	Fuel	8.98E-01	kWh	
	Output	Glass bottle	5.49E-01	kg	Plinke et al. (2000)

conducted by Tua et al. (2020) concerning the reuse of glass bottles in Italy were employed, assuming the extrapolation of these data to the European level. In the case of the filling process, data from the LCA study conducted by Meneses et al. (2016) focusing on Spanish red wine were utilized.

Various transport distances are considered for both reusable and single-use systems. In the modeling process, transportation is generally represented using a truck. Given that Italy is the primary source of wine imported to Germany in terms of quantity, a distance of 1200 km is assumed—this corresponds to the distance from the center of Germany to the largest wine-producing region in Italy, namely Tuscany. Furthermore, an additional 200 km is accounted for in the transport from bottle production to the bottling plant. For the reusable bottle system, the round-trip journey (2400 km) and the distance from the local distributor to the reconditioning plant (200 km) are included in the transportation considerations.

The reconditioning of reusable glass bottles consists of a washing process (including disinfection) and repackaging for transport back to the winery (bottling plant). The data for this process is also sourced from the LCA study by Tua et al. (2020). For the subsequent packaging process, data for secondary packaging from the LCA study by Meneses et al. (2016) was used.

The EoL distribution for the various disposal pathways (recycling, incineration, and landfill) was derived from the UBA study by Burger et al. (2021) for waste generated in Germany, and from Eurostat, 2020 for waste generated in Europe (PE and cardboard). A credit is given for the EoL, depending on the material and EoL treatment.

2.3. Life cycle impact assessment (LCIA)

The ReCiPe method has been selected for impact assessment, as it offers a harmonized implementation of cause-effect pathways, facilitating the calculation of both midpoint and endpoint characterization factors. Recognized for its comprehensive development and widespread application, ReCiPe is considered a well-established method in the field (Dekker et al., 2020). The study considers the following midpoint impact categories: climate change excluding biogenic carbon, fossil depletion, freshwater consumption, freshwater ecotoxicity, and freshwater eutrophication. Climate change was chosen due to expected emissions from transport as well as the bottle production. The same reasoning applies to the choice of fossil depletion, as both processes are currently fossil fuel dependent. Freshwater consumption was chosen to investigate the impact of water used for cleaning of reusable packaging. Similarly, freshwater ecotoxicity and freshwater eutrophication were selected due to the expected impacts from the detergent used for cleaning of reusable packaging.

3. Results

In four of the five considered impact categories, the reusable bottle

(RB) demonstrates a smaller potential environmental impact. However, for freshwater eutrophication, the single-use bottle (SUB) indicates a lower potential environmental impact than the RB. An overview of the results of the base scenario (1200 km distance between winery and place of use; 50 and 15 reuse cycles) is provided in Table 2.

The potential reduction of environmental impacts varies across different impact categories and productsystems. The highest reduction, at 39%, is observed for fossil depletion between SUB and RB 50. Following closely are freshwater consumption and climate change, with reduction potentials of 36% and 35%, respectively. In contrast, the reduction potential for freshwater eutrophication is notably lower, at 22% to RB 50 and 17% to RB 15, when a SUB is utilized. The relative values are illustrated in Fig. 3. As the results for RB 50 and RB 15 point in the same direction, the detailed analysis will be limited to a comparison of RB 50 and SUB.

For climate change impact, the transport phase (51%) constitutes the dominant contribution in the case of the RB. Conversely, for the SUB, bottle production (59%) represents the largest share of the life cycle stages. On overview of the emissions of all life cycle stages is given in Fig. 4. Transport exerts a higher impact (50%) in the case of the RB compared to the SUB. As transport emissions are, among other factors, dependent on the weight of the transported goods, the emissions of the return journey are approximately 50% of that on the outward journey, given that the bottle roughly weighs the same as the wine filled in.

With 0.1 kg CO2 eq., the bottling plant contributes equally to both product systems. The reconditioning plant contributes 0.08 kg CO2 eq., which are observable in the emissions of the RB. However, in comparison to the new production of bottles, this contribution is considerably smaller. The credit for end-of-life disposal is higher in the case of the RB, as the return journey also necessitates packaging material.

The impact category freshwater eutrophication is dominated by the bottling stage of the wine life cycle in both product systems (42% for RB and 62% for SUB), including the rebottling process (41%) in the case of the RB. The bottle production (21%) also contributes significantly to the case of the SUB, but the difference compared to the RB is not as pronounced as in other impact categories. Conversely, for the transport phase, the RB exhibits a higher freshwater eutrophication. The main contributors to freshwater eutrophication are wastewater treatment (31 % of impacts of the bottling plant for RB) and the production of cardboard for transport packaging (60 %. of impacts of the bottling plant for RB). This also explains the higher credit given for the EoL of the RB compared to the SUB, as more cardboard volume is returned for recycling. An overview of the results for the life cycle states is given in Fig. 5.

The analysis reveals that bottle production significantly influences the results of the impact categories. As the number of reuses increases, the influence of bottle production diminishes. Therefore, we examined the results of the impact categories based on the number of reuse cycles. Freshwater eutrophication is not considered, as the impact of the RB at the maximum reuse cycle of 50 already surpasses that of the SUB. An overview of the analysis is provided in Fig. 6.

For a single-use, the environmental impact potential of the RB is equivalent to that of the SUB. However, this changes as the number of uses exceeds two. The results for climate change, fossil depletion, and freshwater consumption exhibit notable similarity. When the RB is used twice, its impact is, on average, approximately 19% lower than that of the SUB. If the RB is used five times, its impact potential decreases by approximately 30% compared to the SUB. Beyond approximately 15 reuse cycles, the impact of the RB decreases only marginally.

In the freshwater ecotoxicity impact category, the impact of the RB is lower even from the second bottle cycle onwards. However, as the overall reduction for this impact category is smaller, the decrease is comparatively slighter compared to the other three impact categories.

Depending on the distance between the bottling of the wine and the sale point, either the SUB or the RB demonstrates a smaller potential environmental impact. The break-even distances are outlined in Table 3. Notably, for freshwater eutrophication, the environmental impact is consistently smaller for the SUB, irrespective of the transport distance.

For instance, with a break-even at around 2200 km, the RB would exhibit a similar environmental impact as the SUB for wines originating from Spain or Sicily, given that this distance roughly corresponds to the driving distance from the center of Germany to the center of these locations. However, for the other studied impact categories, the break-even distances are significantly higher. Consequently, for all wines sourced from mainland Europe, the RB would yield smaller environmental impacts than the SUB.

Table 2
Impact assessment results of the RB and SUB.

Impact categories	RB 15	RB 50	SUB	Unit
Climate change, excl biogenic carbon	0.3761	0.3523	0.5394	kg CO2 eq.
Fossil depletion	0.1254	0.1251	0.2063	kg oil eq.
Freshwater Consumption	0.0008	0.0009	0.0014	m3
Freshwater ecotoxicity	6.8264E-05	6.1799E-05	6.8984E-05	kg 1,4 DB eq.
Freshwater Eutrophication	2.1674E-05	2.6258E-06	2.0456E-06	kg P eq.

4. Discussion

In addition to the more detailed analyzed five midpoint impact categories, reveals an examination of all midpoint impact categories of ReCiPe that this outcome is not attributable to the choice of impact categories (See supplementary information A). Out of the 18 midpoint indicators included in ReCiPe, 15 demonstrate a smaller potential environmental impact for the RB. Apart from freshwater eutrophication, the categories land use and human toxicity, non-cancer, also indicate a lower potential environmental impact for the SUB. A similar observation can be made when analyzing the results of endpoint categories of ReCiPe (Damage to human health, ecosystems, and resource availability). For these categories, the RB demonstrates the lowest potential environmental impact when used 50 times. Even when the RB is used only twice, the potential environmental impacts are lower than those of the SUB. However, as the difference in the endpoint categories is not significant, caution is warranted (See supplementary information A for results). Overall, it can be argued that the calculated results demonstrate that with the introduction of an RB, the potential environmental impacts can be decreased overall.

Depending on the impact category and the product system, different hotspots in the life cycle of the products can be identified. For the SUB, the bottle production emerges as the hotspot, accounting for over 50% of the impacts in categories such as climate change, fossil depletion, and freshwater consumption. It also represents 43% of the impact in freshwater ecotoxicity. Conversely, for freshwater eutrophication, the bottling phase is the primary hotspot of potential environmental impact for the SUB. In contrast, for the RB, the transport phase emerges as the hotspot in categories such as climate change, fossil depletion, and freshwater ecotoxicity. Additionally, the bottling plant and reconditioning process become the hotspots for freshwater consumption and eutrophication for the RB.

Other LCAs of wine yield comparable results regarding the potential environmental impact of single-use wine bottles. For instance, Neto et al. (2013) reported a result of 0.54 kg CO_2 eq. for the wine bottle, which exhibits only a slight variance from the result obtained in this study. In other investigations, values slightly higher than the aforementioned were recorded, with 0.56 kg CO_2 eq. (Fusi et al., 2014), 0.67 kg CO_2 eq (Meneses et al., 2016). and 0.93 kg CO_2 eq. (Benedetto, 2013), although remaining within a comparable range. Despite minor discrepancies, these findings collectively suggest consistent trends in the environmental impact of wine bottling across various LCAs. The results from other comparative LCAs of single-use and reusable glass bottles cannot be directly compared with the calculated results. In one case, only a part

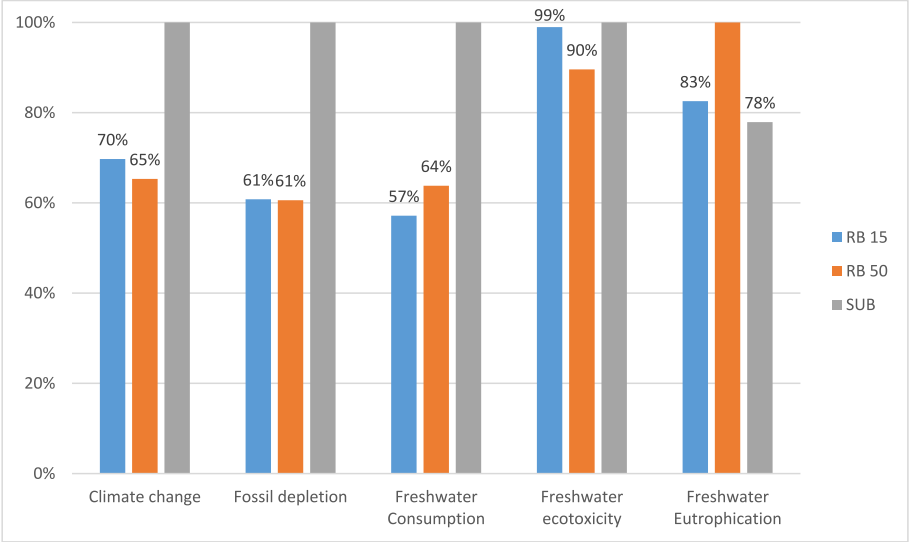

Fig. 3. Impact assessment results of the RB 50 and SUB in relative values.

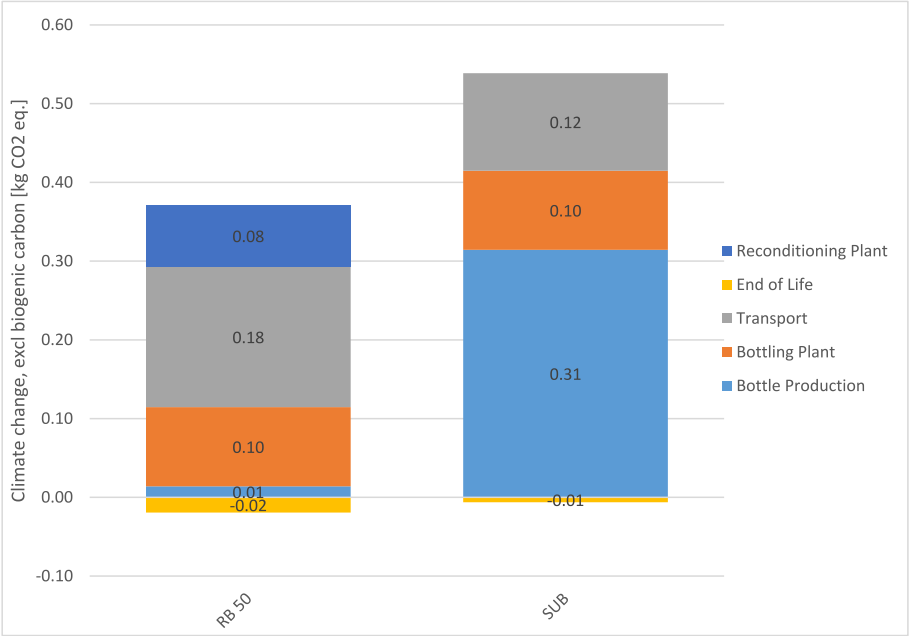

Fig. 4. Impact assessment in the category Climate Change, excl. biogenic carbon by life cycle stages.

of the life cycle is assessed (Landi et al., 2019), while in the other, only endpoint results are provided in absolute numbers (Cleary, 2013). Nevertheless, the conclusion that reusable wine bottles have the potential to reduce environmental emissions is consistent with both studies and the energy demand as a main driver of the environmental emissions. The results of a carbon footprint, while the scope of the study was the complete wine life cycle, underscores this two conclusions (Ponstein et al., 2019).

The observed variance in results can be attributed to several factors. Firstly, differences in bottle weights contribute significantly. Across the studies discussed, bottle weights for a standard 0.75 L bottle range from 516 to 580 g. Another influential factor is the bottle colour. Studies conducted by Benedetto, Fusi, and Neto primarily focused on white glass bottles, while this study and the investigation by Meneses considered green glass bottles. Notably, the production of white glass typically entails higher consumption of primary raw materials and consequently greater energy requirements. Such distinctions underscore the nuanced nature of environmental impact assessments in the context of wine packaging.

As the wine bottle is a major contributor to the overall life cycle of wine, the introduction of the RB could significantly decrease the impacts of the complete wine production system. In this study, only the bottle emissions are calculated, and an example calculation with the results of Fusi et al. (2014) was conducted. The share of the bottle in this study is 56% of the total 1 kg CO_2 eq. emitted for one wine bottle. With the saving potential calculated the potential emissions of the bottle would decrease from 0.56 kg CO_2 eq. to 0.36 kg CO_2 eq. Therefore, the total GHG emissions would decrease to 0.8 kg CO_2 eq., resulting in a reduction of 20%.

As the comparison of single-use and reusable packaging is a widely discussed topic, the result needs to be compared with other similar studies. That the transport distance is the main driver of the environmental impacts in case of glass packaging is consistent with other studies (Plinke et al., 2000; Tua et al., 2020). Also the determining factor for the

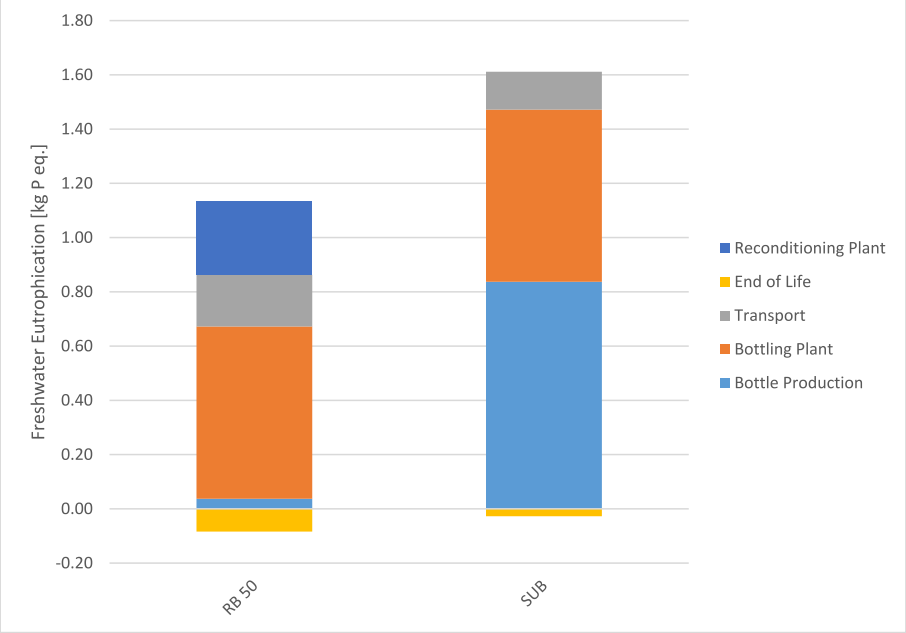

Fig. 5. Impact assessment in the category Freshwater Eutrophication by life cycle stages.

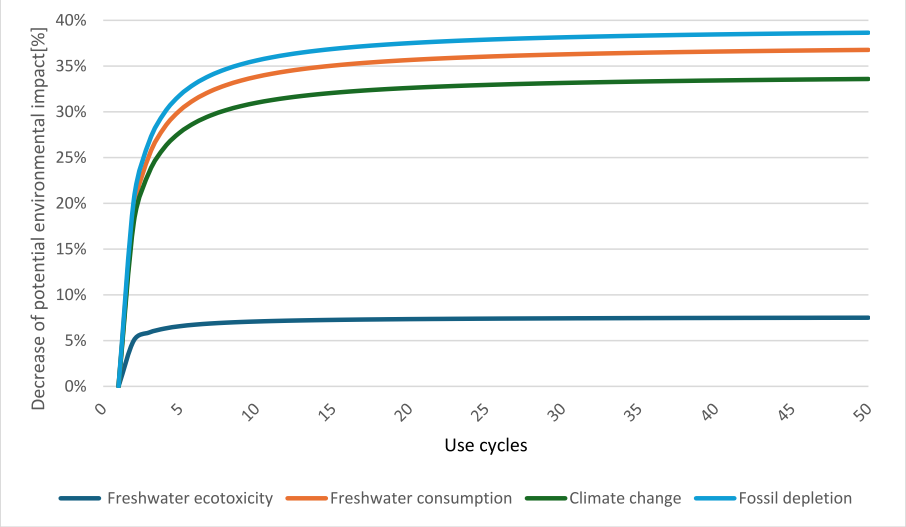

Fig. 6. Decrease of potential environmental impact of RB with reuse cycles.

Table 3
Break-even distance of SUB and RB.

Impact category	Climate change	Fossil depletion	Freshwater Consumption	Freshwater ecotoxicity	Freshwater Eutrophication
Break-even distance [km]	5.907	7.701	13.757	2.186	−2.872

environmental impact of a single-use bottle, the bottle production, were found in similar LCAs (Plinke et al., 2000; Benedetto, 2013; Boutros et al., 2021). The calculated break-even between a reusable and single-use depending on the transport distance is in other LCAs significantly smaller. For example, for water bottles in Italy, depending on reuses cycles, between 200 and 800 km (Tua et al., 2020) or for boxes for food catering between 350 and 450 km (Accorsi et al., 2014). The explanation for that is that in the presented study only glass bottles are analyzed. The reason for that is the dominant role of the glass bottle in the wine market. Packaging such as bag-in-box, aluminum cans or bottles from polyethylene terephthalate could be an alternative type of packaging (Thompson-Witrick et al., 2021). Another packaging system, with potential smaller environmental impacts, could be that the wine is filled in tanks at the winery and bottled considerably closer to the location of the consumer.

As the bottle production significantly drives the environmental impact of the SUB, it is crucial to critically analyze the assumption about the bottle weight. Technologically, a bottle weight as light as 330 g is now possible, representing almost a halving of the assumed bottle weight (Robinson, 2009; Thompson-Witrick et al., 2021). This reduction

would likely lead to a significant decrease of the potential environmental impacts of the SUB. However, it would also reduce the potential environmental impacts of the RB, as a lighter bottle would lead to decreased transport emissions. Another implication of weight reduction is that technical aspects of the bottle could change, such as the number of possible reuses. However, given that the RB already exhibits lower environmental impacts in most impact categories, this change can likely be neglected. Regardless of the environmental impacts, wine producers may oppose a switch to a lightweight bottle, as consumers often associate heavier wine bottles with better quality and higher value (Soares et al., 2022).

The recycling glass content, at 90%, is almost at the current maximum share of recycling content for green glass bottles in Germany, which stands at 95% (Leisin, 2020). Since the input flow of recycled material is modeled without an environmental burden, it can be argued that the SUB is modeled as a best-case approach. While an increase in recycling content could potentially decrease the environmental impact of the SUB, the main driver of bottle production remains energy demand. Therefore, a significant reduction cannot be expected. Specifically, for the impact category of climate change, thermal energy demand and electricity usage are responsible for 93% of the total CO_2 eq. of the modeled bottle production.

As demonstrated in the results, cardboard packaging emerges as a significant driver of freshwater eutrophication, the only impact category where the RB impact surpasses that of the SUB. To further reduce the environmental impact of the RB, an option could be the implementation of reusable transport packaging, such as plastic crates widely used for beer. These crates are already available, and there are existing reusable wine bottle pool systems that utilize similar packaging (Mayer, 2023). Indeed, implementing reusable transport packaging could also potentially reduce the environmental impacts of the SUB, given that cardboard packaging contributes to its environmental impact as well. However, it's important to note that using reusable transport packaging for the SUB would necessitate additional reverse logistics, which in turn would introduce additional environmental burden. Therefore, while reusable transport packaging may offer environmental benefits, a comprehensive assessment of its overall impact, including logistics considerations, is crucial.

5. Conclusion and outlook

The results of the LCA conducted for this paper indicate that, based on the data and assumptions utilized, the implementation of a reusable bottle (RB) system for wine would result in a reduction in environmental impacts across several midpoint categories. Moreover, the quasi weighting with endpoint indicators suggests an overall decrease in potential environmental impacts, even with just one reuse of the wine bottle. The calculated break-even distances demonstrate that the introduction of RB in mainland Europe could potentially decrease the environmental impacts of the current wine production system. It has been shown that the packaging of the wine represents a significant share of the overall wine product system, and with the decrease in the potential environmental impact of the wine packaging, the GHG emissions of the total product system can be reduced by 20%. Nevertheless, the results of the environmental impacts are constrained by the assumptions made in conducting this LCA. Furthermore, the economic costs associated with the introduction of a reusable wine bottle system are beyond the scope of LCA and, therefore, not considered in this study.

Both product systems, single-use and reusable wine packaging, can further be improved in terms of their environmental impact. In the case of single-use packaging, alternative materials such as plastic and aluminum should be explored. For reusable packaging, options such as reusable secondary packaging and different modes of transport, such as train transport, offer potential avenues to decrease environmental impact.

CRediT authorship contribution statement

Justus Caspers: Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Pauline Bade:** Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Matthias Finkbeiner:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clet.2025.100914.

Data availability

Data will be made available on request.

References

Accorsi, R., Cascini, A., Cholette, S., Manzini, R., Mora, C., 2014. Economic and environmental assessment of reusable plastic containers: a food catering supply chain case study. Int. J. Prod. Econ. 152, 88–101. https://doi.org/10.1016/j.ijpe.2013.12.014.

Benedetto, G., 2013. The environmental impact of a Sardinian wine by partial Life Cycle Assessment. Wine Economics and Policy 2, 33–41. https://doi.org/10.1016/j.wep.2013.05.003.

Boutros, M., Saba, S., Manneh, R., 2021. Life cycle assessment of two packaging materials for carbonated beverages (polyethylene terephthalate vs. glass): case study for the lebanese context and importance of the end-of-life scenarios. J. Clean. Prod. 314, 128289. https://doi.org/10.1016/j.jclepro.2021.128289.

Burger, A., Cayé, N., Jaegermann, C., Schüler, K., 2021. Aufkommen und Verwertung von Verpackungsabfällen in Deutschland im Jahr 2019.

Caspers, J., Süßbauer, E., Coroama, V.C., Finkbeiner, M., 2023. Life cycle assessments of takeaway food and beverage packaging: the role of consumer behavior. Sustainability 15, 4315. https://doi.org/10.3390/su15054315.

Cleary, J., 2013. Life cycle assessments of wine and spirit packaging at the product and the municipal scale: a Toronto, Canada case study. J. Clean. Prod. 44, 143–151. https://doi.org/10.1016/j.jclepro.2013.01.009.

Coelho, P.M., Corona, B., ten Klooster, R., Worrell, E., 2020. Sustainability of reusable packaging–Current situation and trends. Resour. Conserv. Recycl. X 6, 100037. https://doi.org/10.1016/j.rcrx.2020.100037.

Colangelo, S., 2024. Reducing the environmental footprint of glass manufacturing. Int. J. Appl. Glass Sci. 15, 350–366. https://doi.org/10.1111/ijag.16674.

Cottafava, D., Brussa, G., Cavenago, G., Cespi, D., Rigamonti, L., Bala, A., Beigbeder, J., Refalo, P., Sazdovski, I., 2024. Requirements for comparative life cycle assessment studies for single-use and reusable packaging and products: recommendation for decision and policy-makers. Int J Life Cycle Assess s11367-024-02291–0. https://doi.org/10.1007/s11367-024-02291-0.

Dekker, E., Zijp, M.C., Van De Kamp, M.E., Temme, E.H.M., Van Zelm, R., 2020. A taste of the new ReCiPe for life cycle assessment: consequences of the updated impact assessment method on food product LCAs. Int. J. Life Cycle Assess. 25, 2315–2324. https://doi.org/10.1007/s11367-019-01653-3.

Deutsches Weininstitut, 2023. '23/'24 Deutscher Wein Statistik. Deutsches Weininstitut, Bodenheim.

Ecoinvent Center, 2021. Ecoinvent 3 LCI database [WWW document]. https://www.ecoinvent.org/, 1.8.21.

Eurostat, 2024. SHARES (renewables) - energy - Eurostat. 599 [WWW document]. https://ec.europa.eu/eurostat/web/energy/data/shares, 2.7.24.

Eurostat, 2020. Statistics | Eurostat [WWW document]. https://ec.europa.eu/eurostat/databrowser/view/ENV_WASTRT_custom_7179913/bookmark/table?lang=de&bookmarkId=c23397cb-c7db-4b04-8a0e-fa495f710859&page=time:2020, 1.30.24.

Ferrara, C., De Feo, G., 2018. Life cycle assessment application to the wine sector: a critical review. Sustainability 10, 395. https://doi.org/10.3390/su10020395.

Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K., Klüppel, H.-J., 2006. The new international standards for life cycle assessment: ISO 14040 and ISO 14044. Int. J. Life Cycle Assess. 11, 80–85. https://doi.org/10.1065/lca2006.02.002.

Fusi, A., Guidetti, R., Benedetto, G., 2014. Delving into the environmental aspect of a Sardinian white wine: from partial to total life cycle assessment. Sci. Total Environ. 472, 989–1000. https://doi.org/10.1016/j.scitotenv.2013.11.148.

Gallego-Schmid, A., Mendoza, J.M.F., Azapagic, A., 2018. Improving the environmental sustainability of reusable food containers in Europe. Sci. Total Environ. 628–629, 979–989. https://doi.org/10.1016/j.scitotenv.2018.02.128.

Holzapfel, P., Bach, V., Finkbeiner, M., 2023. Electricity accounting in life cycle assessment: the challenge of double counting. Int. J. Life Cycle Assess. 28, 771–787. https://doi.org/10.1007/s11367-023-02158-w.

ISO, 2006a. ISO 14040: 2006 Environmental Management. Life Cycle Assessment. Principles and Framework. International Organization for Standardization (ISO), Genf, Switzerland.

ISO, 2006b. ISO 14044: 2006-Environmental Management. Life Cycle Assessment. Requirements and Guidelines. International Organization for Standardization (ISO), Genf, Switzerland.

Jourdaine, M., Loubet, P., Trebucq, S., Sonnemann, G., 2020. A detailed quantitative comparison of the life cycle assessment of bottled wines using an original harmonization procedure. J. Clean. Prod. 250, 119472. https://doi.org/10.1016/j.jclepro.2019.119472.

Koskela, S., Dahlbo, H., Judl, J., Korhonen, M.-R., Niininen, M., 2014. Reusable plastic crate or recyclable cardboard box? A comparison of two delivery systems. J. Clean. Prod. 69, 83–90. https://doi.org/10.1016/j.jclepro.2014.01.045.

Landi, D., Germani, M., Marconi, M., 2019. Analyzing the environmental sustainability of glass bottles reuse in an Italian wine consortium. Procedia CIRP 80, 399–404. https://doi.org/10.1016/j.procir.2019.01.054.

Leisin, M., 2020. Branchensteckbrief der Glasindustrie. Navigant Energy Germany GmbH.

Mayer, M., 2023. 0,75 Liter Mehrweg-Flasche für Wein vorgestellt [WWW Document]. Weinheimat Blog. https://blog.weinheimat-wuerttemberg.de/frontpage-subteaser/weinheimat-württemberg-stellt-075-liter-mehrweg-flasche-fuer-wein-vor/.

Meneses, M., Torres, C.M., Castells, F., 2016. Sensitivity analysis in a life cycle assessment of an aged red wine production from Catalonia, Spain. Sci. Total Environ. 562, 571–579. https://doi.org/10.1016/j.scitotenv.2016.04.083.

Münster, D., 2020. Kein trockenes thema: deutsche weinstatistik » weinfreunde magazin. Weinfreunde magazin. https://www.weinfreunde.de/magazin/weinwissen/kein-trockenes-thema-deutsche-weinstatistik/, 2.7.24.

Neto, B., Dias, A.C., Machado, M., 2013. Life cycle assessment of the supply chain of a Portuguese wine: from viticulture to distribution. Int. J. Life Cycle Assess. 18, 590–602. https://doi.org/10.1007/s11367-012-0518-4.

Ollat, N., Touzard, J.-M., Van Leeuwen, C., 2016. Climate change impacts and adaptations: new challenges for the wine industry. J Wine Econ 11, 139–149. https://doi.org/10.1017/jwe.2016.3.

Platzbecker, E., Schwarz, M., Rhiemeier, J.-M., Fleischmann, B., 2022. Prozesskettenorientierte Ermittlung der Material- und Energieeffizienzpotenziale in der Glas- und Mineralfaserindustrie. Dessau-Roßlau.

Plinke, E., Schonert, M., Meckel, H., Detzel, A., Giegrich, J., Fehrenbach, H., Ostermayer, A., Schorb, A., Heinisch, J., Luxenhofer, K., Schmitz, S., 2000. Ökobilanz für Getränkeverpackungen II - Hauptteil -. Dessau-Roßlau, Umweltbundesamt.

Ponstein, H.J., Meyer-Aurich, A., Prochnow, A., 2019. Greenhouse gas emissions and mitigation options for German wine production. J. Clean. Prod. 212, 800–809. https://doi.org/10.1016/j.jclepro.2018.11.206.

Potting, J., van der Harst, E., 2015. Facility arrangements and the environmental performance of disposable and reusable cups. Int. J. Life Cycle Assess. 20, 1143–1154. https://doi.org/10.1007/s11367-015-0914-7.

Robinson, J., 2009. Red, white and green [WWW Document]. https://www.jancisrobinson.com/articles/red-white-and-green.

Schaeffer, H.A., Langfeld, R., 2020. In: Auflage, 2 (Ed.), Werkstoff Glas: alter Werkstoff mit großer Zukunft, Technik im Fokus. Springer, Berlin [Heidelberg].

Simon, B., Amor, M.B., Földényi, R., 2016. Life cycle impact assessment of beverage packaging systems: focus on the collection of post-consumer bottles. J. Clean. Prod. 112, 238–248. https://doi.org/10.1016/j.jclepro.2015.06.008.

Soares, J., Ramos, P., Poças, F., 2022. Is lightweighting glass bottles for wine an option? Linking technical requirements and consumer attitude. Packag. Technol. Sci. 35, 833–843. https://doi.org/10.1002/pts.2680.

Sphera, 2023. Sphera LCA data - most reliable LCA data | Sphera (GaBi). Sphera. https://sphera.com/life-cycle-assessment-lca-database/ accessed 9.19.23.

Thompson-Witrick, K.A., Pitts, E.R., Nemenyi, J.L., Budner, D., 2021. The impact packaging type has on the flavor of wine. Beverages 7, 36. https://doi.org/10.3390/beverages7020036.

Timber, K., 2023. Euro-palette | KLAUS timber a.s. [WWW document]. https://www.klaustimber.cz/de/euro-palette, 1.24.24.

Tua, C., Grosso, M., Rigamonti, L., 2020. Reusing glass bottles in Italy: a life cycle assessment evaluation. Procedia CIRP 90, 192–197. https://doi.org/10.1016/j.procir.2020.01.094.

Van Leeuwen, C., Darriet, P., 2016. The impact of climate change on viticulture and wine quality. J Wine Econ 11, 150–167. https://doi.org/10.1017/jwe.2015.21.

Wölfli, M., 2023. 1 container – 22 176 weinflaschen: itj. Transport Journal [WWW Document]. https://www.transportjournal.com/de/home/news/artikeldetail/1-container-22176-bottles-of-wine.html, 1.24.24.

Woods, L., Bakshi, B.R., 2014. Reusable vs. disposable cups revisited: guidance in life cycle comparisons addressing scenario, model, and parameter uncertainties for the US consumer. Int. J. Life Cycle Assess. 19, 931–940. https://doi.org/10.1007/s11367-013-0697-7.