



From Circular to Linear? Assessing the Life Cycle Environmental and Economic Sustainability of Steel and Plastic Beer Kegs

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Abstract

In the craft brewing industry, kegging solutions have changed dramatically in recent years. While steel kegs once dominated the draught beer market, single-use plastic kegs have increased in popularity due to their convenience, especially in the craft brewing sector. With the increasing importance of the circular economy and the introduction of policies in Europe to move away from single-use plastic systems, this study aims to assess and compare the sustainability of conventional steel and single-use plastic kegs. The environmental and economic performance are assessed through life cycle assessment and life cycle costing approaches. The results suggest that steel kegs have better environmental performance and life cycle costs. However, these are limited to the local markets, and with larger distances, plastic kegs may become the better option due to their lower weight, suggesting that both kegs are useful in certain situations. This is especially important in countries that have long distances between breweries and their markets. The importance of extending the lifetime of the keg fleet is also highlighted to improve the environmental performance as the results are influenced by the assumption on the lifetime of the steel kegs. To improve the environmental performance of plastic kegs, efficient closed-loop recycling systems should be developed. Careful decision-making is needed to ensure that more sustainable packaging options are chosen for draught beer and that sustainability aspects be taken into account beyond convenience.

Keywords Life cycle assessment · Beer · Packaging · Life cycle cost · Kegs · Circular economy

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Introduction

Activities related to food and beverage production and consumption account for 20–30% of anthropogenic greenhouse gas (GHG) emissions [1, 2]. As such, the food and beverage sector has received increased focus in recent years to mitigate these impacts through different interventions, e.g., changes in production systems, guidelines, packaging, and recommendations for diets [3, 4]. While much of the focus has been placed on food production and consumption, beverages have received less attention. Furthermore, most studies of the environmental impacts of dietary choices exclude alcoholic beverages, despite their large environmental impact [5].

Beer is the most widely consumed alcoholic beverage worldwide. It ranks as the fifth most consumed beverage globally, behind tea, carbonated beverages, milk, and coffee [6]. In 2018, roughly 1.94 billion hectoliters of beer were produced worldwide [7]. Recently, the beer production and packaging landscape has been changing with the expansion of the craft brewing industry [8–11]. Craft beer—also referred to as artisanal, micro, independent, specialty, and local—is broadly defined as beer brewed by small and independently owned breweries [12]. In Sweden, the empirical focus of this study, roughly 33 breweries represent approximately 90% of domestic alcohol production. Nonetheless, craft breweries have been growing extensively, from only a few in 2008 to over 400 in 2019, increasing their market share considerably [13].

Craft breweries have new challenges and logistic requirements, often struggling with limited labor and production capacity [12, 14]. For craft brewers, packaging continues to be an important economic factor for their financial viability. Thus, making the choice of packaging a critical business model factor and one which may entail different environmental sustainability impacts [15]. As such, over the past years, bottles have given way to cans, and traditional steel kegs have seen competition from plastic kegs. The Swedish Brewers Association [13] reports that roughly 12% of all beer produced is supplied in kegs, with the largest share of the beer provided primarily in cans (64%) and bottles (roughly 22%), although these shares have been changing the past few years. Plastic kegs have gained traction in the industry, and many craft brewers have taken to these kegs due to their lower investment cost, lighter weight, and ease of use [11, 13, 16, 17].

The shift from conventional reusable steel kegs to single-use plastic kegs raises several concerns regarding the sustainability of draught beer packaging systems. First, while the food and beverage packaging has been highlighted in many circular economy (CE) policy documents (see, e.g., [18–20]), brewers are increasingly using single-use plastic kegs. This marks a move away from the traditionally circular steel kegging system to a potentially linear system at a time when plastics and packaging, primarily single-use plastics, have attracted explicit policy attention [18, 19, 21] and with the circular economy gaining attention in the business sector [22, 23]. Second, despite a large number of studies reviewing and assessing the sustainability of beer packaging, the environmental performance of plastic keg solutions has not received critical scientific analysis, despite several recent reports and claims on their environmental performance [24–26]. Finally, while manufacturers of plastic kegs have developed systems to promote closed-loop recycling systems in some countries (such as the Netherlands, the UK, and Germany), no information about the recovery rate of the kegs is available. Furthermore, these closed-loop systems are absent in many countries throughout Europe, e.g., Sweden [27]. The recycling of plastics such as PET, outside of bottles in the deposit system, remains low in Sweden, with the majority being incinerated [28], due in part to regulations and a small market for recycled plastics [29].

Thus, little is known of the environmental implications of an increased influx of single-use plastic kegs in the beverage sector.

In order to assess the sustainability of brewing packaging, life cycle assessment (LCA) is widely applied for food and beverage packaging [30–32]. A number of studies have focused on comparisons of beer packaging, e.g., cans and bottles [8, 33, 34], where packaging has been found to contribute to a large share of the impacts from a life cycle perspective. However, few studies address the use of kegs and other forms of retail packaging for beer [34]. Additionally, only a limited number of academic studies have assessed the life cycle costs of beverage packaging solutions [33], despite their share of brewing expenses, accounting for over 20% of costs from breweries [11]. While many of these studies focus on the environmental impacts of packaging, to the best of our knowledge, no studies have combined life cycle costing with environmental impacts to support beer packaging decisions, with few studies explicitly focusing on beer kegs.

Given the knowledge gaps, this paper aims to assess the life cycle environmental impacts and costs associated with conventional steel and single-use plastic keggling solutions. Our findings are especially relevant to the expanding craft brewing industry, providing information to aid in their choice of keggling solutions. In the following sections, we outline the methods employed to assess the environmental and economic performance of the keggling solutions as well as details on the modeling (“[Methodology](#)” section), followed by an assessment and discussion of the results (“[Results](#)” and “[Discussion](#)” sections) and our conclusions (“[Conclusions](#)” section).

Methodology

This analysis is based on a case study of a craft brewery producing roughly 100 000 l of kegged beer annually. This is a hypothetical scenario, which provides generalizable results applicable to many craft beer producers in Sweden. It is assumed that the brewery is located in Stockholm, Sweden, with a market for kegged beer within 100 km. For both the environmental and economic assessments, all material and energy inputs are based on this size and the specified outputs. The subsections below provide further detail on the keggling solutions, life cycle assessment, and life cycle costing methods.

Life Cycle Assessment

Life cycle assessment is a widely employed environmental assessment tool for assessing the potential environmental impacts and resource use of products and services throughout their life cycle. This includes all impacts from raw material extraction via production and use phases to waste management and transportation [35].

The LCA was conducted employing OpenLCA (v 1.10). All life cycle inventory (LCI) data was obtained from the LCI database Ecoinvent v. 3.6 (see also [Table S2](#) in the Supplementary Material for further details on the datasets employed). For this study, the ReCiPe Midpoint (H) life cycle impact assessment (LCIA) method was employed. While this method includes many impact categories, this study focuses on four impact categories—i.e., greenhouse gas emissions (GWP) and material depletion (water, fossil, and metal)—to provide relevant indicators for resource consumption for comparing choices of plastic and steel kegs, although a more comprehensive listing of other impact categories is provided in the Supplementary Material (Sect. 5).

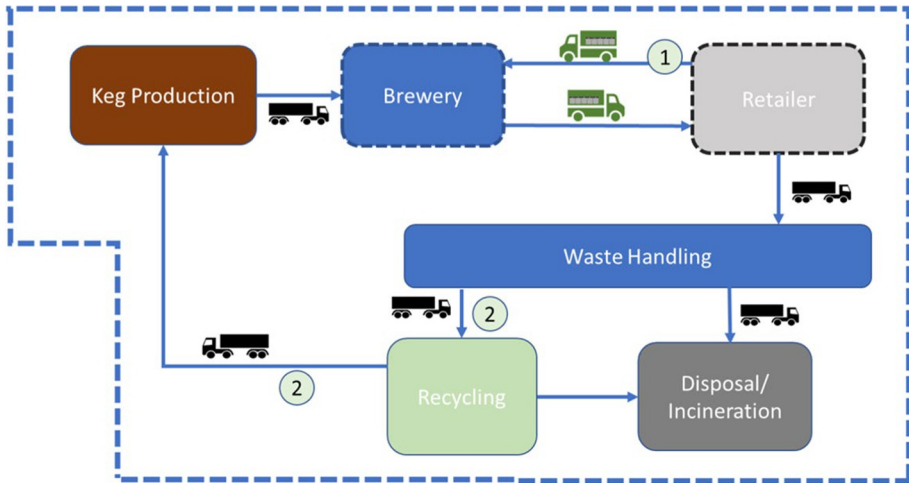


Fig. 1 System boundaries of study, where (1) denotes the steel keg “loops” back to the brewery. (2) denotes extra transportation and processes for recycling plastic in the closed-loop scenarios for the plastic kegs. The brewery and retail/bar have dashed lines as impacts associated with these processes are only partly included in the assessment as outlined in the text

The functional unit of this study is the safe packaging of 1 l of kegged beer in a 30-l keg. A conventional reusable stainless steel keg and single-use plastic keg are compared (see further information about these systems in the following subsection). The system boundaries include a cradle-to-grave assessment consisting of the production of the kegs, their transportation, use, and the final disposal (i.e., end-of-life phase) (see Fig. 1).

This study is limited to the use of the kegs in the brewing industry (i.e., only when filled with beer) despite the use of kegs in other beverage sectors. For the assessment, it is assumed that the beer is produced and packaged in kegs by a producer in the Stockholm area and that the beer is shipped to an end-user (assumed to be a bar) 100 km away, where it is served with no losses in either system. The assumption on distance is analyzed in the sensitivity analysis. The production of the beer is assumed to be the same for both kegs and therefore excluded from the study; note the dashed line around the brewery in Fig. 1. This is also motivated by the fact that the production processes and types of beer are largely divergent among brewers in the region. Furthermore, the energy required for refrigeration, in addition to other processes, infrastructure, and tapping equipment, was not included in the study as they are assumed to be similar in both the steel and plastic kegs¹. However, carbon dioxide and compressed air needed for dispensing are included, as the beer kegs can use different serving gases.

¹ While the thermal conductivity for steel and plastic kegs may differ, the kegs are often stored in large refrigerators, and as such, the differences in refrigeration and allocation to the studied kegs were considered out of the scope of the assessment.

Table 1 Overview of the components of a steel keg and their weight, derived from [34]

| Component | Material | Weight (g) |
|----------------------------|----------------|------------|
| Steel for keg | Steel | 9 600 |
| Ink | Ink | 0.002 |
| Keg coupler (plastic ball) | Polyamide (PA) | 5 |
| Bar code label | Paper | 5.4 |

Assessed Kegs and Scenarios

Steel Keg

A conventional 30-l steel keg was included in this study as it is widely used across the industry. Information on the components and manufacturing of a steel keg were obtained from [34]. Table 1 presents an overview of the steel keg and its components. Further details on the LCI datasets and modeling of the manufacturing of the steel keg are available in the Supplementary Material, Table S1–2.

The steel kegs are assumed to be produced in Italy². At the brewery, the steel keg is then filled and sent to a retail point, assumed to be a bar within 100 km of the brewery. Once emptied of beer, the steel keg is returned to the brewery by a light commercial vehicle in connection with a new delivery of beer. The keg is then cleaned by the brewery and refilled for transportation back to a bar. This is assumed to be repeated roughly 80 times. In a study by Cimini et al. [34], the lifetime of the steel kegs is 80 uses, with a reuse³ rate of roughly 3.6 times per year. In this study, the reuse rate was assumed to be higher, where the reuse rate was 5.5 times a year, based on upon discussions with several craft breweries and highlighted by a steel keg manufacturer [36]. As the assumption of the keg lifetime, in addition to the distance to market, were considered to be sensitive choices, their influence is tested in the sensitivity analysis.

Data and information for cleaning products employed for steel kegs were obtained from discussions with breweries and technical datasheets for common brewing cleaners and sanitizers used in the cleaning equipment [37]. Assumptions regarding energy and water use for the cleaning process of the kegs were obtained from [38, 39]. Furthermore, the cleaning infrastructure is included based on common equipment for keg cleaning for breweries of the size outlined [37].

At the end-of-life of the steel keg, it is assumed to be recycled by first being returned to the brewery before being shipped 250 km to a waste management facility. All data on energy requirements to crush and scrap the steel were obtained from [39]. Additionally, to repurpose the scrap for reuse in metal products, data on energy demand were obtained from [40]. Further details of all processes described above are provided in the Supplementary Material.

² Italian steel kegs are commonly found in Sweden based on input from regional breweries, although origins can vary.

³ Reuses are also referred to as “turns” in the brewing industry.

Table 2 Overview of the components of a 30-l plastic keg and their weight

| Component | Material | Weight (g) |
|-------------------------|-----------------------------|------------|
| Grip ring | Recycled PP | 268 |
| Outer container | PET | 382 |
| Closure | PA (glass fiber reinforced) | 43 |
| Inner ring | PP/SEBS | 19 |
| Spout | PE | 9 |
| Valve | PP/SEBS | 3 |
| Inner container | PET | 365 |
| Inner bag | PE/aluminum/PA laminate | 73 |
| Sleeve | PE | 19 |
| Base cup | Recycled PP | 160 |
| Dust cap | PE | 2 |
| Seal inner ring + valve | TPE | 3 |
| Evacuation foil | PE | 24 |
| Dip strip | PE | 19 |

PET polyethylene terephthalate, *PA* polyamide, *PP* polypropylene, *SEBS* styrene-ethylene-butylene-styrene, *PE* polyethylene, *TPE* thermoplastic elastomers.

Plastic Kegs

The 30-l plastic kegs analyzed are assumed to be produced in the Netherlands⁴, from where they are shipped to the brewery in Stockholm. The brewery fills the keg and transports it to a bar, once again assumed to be within 100 km of the brewery. Upon emptying the keg, the retail personnel then dispose of the keg. It is assumed that the plastic keg is shipped 100 km to a sorting facility, after which it travels another 100 km to an incineration plant, based on statistics available on plastic waste management in Sweden [41, 42]. As such, it is assumed that no recycling of the plastic fractions takes place in this scenario.

The plastic kegs are primarily composed of different plastic components. The materials and weights were obtained from communication with the manufacturer, technical specifications sheets, and information on the manufacturer's website [26, 27]. Table 2 outlines the share of different materials used in this study. Further details on the modeling of the plastic kegs and associated LCI datasets are available in the Supplementary Material (see Table S2).

Closed-Loop Scenarios

The *plastic keg closed-loop NL* scenario is similar to the previous plastic keg scenario. However, in this scenario, the kegs no longer enter the local waste management system for incineration. Instead, this scenario assumes that the kegs enter a closed-loop recycling system, similar to that available in the Netherlands and the UK, to recycle the PET [27]. In this scenario, it is assumed that there is a high recovery and recycling rate for the kegs, in

⁴ The majority of brewers in Stockholm employ single-use plastic kegs produced in the Netherlands based on input from regional breweries.

order to test the implications of a closed-loop system for the PET. However, in the current systems, in the Netherlands and the UK, the recovery rate for the plastic kegs may be much lower [43]. In this closed-loop recycling system, upon emptying the keg, it is sent to a sorting facility (100 km) to be crushed, collected, and sent back to the manufacturing factory in the Netherlands to be recycled into new kegs. Currently, there is no such closed-loop recycling plant in the Nordic region, and thus, the crushed kegs are assumed to be shipped back to the Netherlands to be recycled, a distance of 1 517 km. The parts of the keg that are not recycled are assumed to enter the local waste management system in the Netherlands for incineration.

In a second scenario, the *plastic keg closed-loop SE* assumes that the empty kegs are sent to a sorting facility (100 km) upon which they are transported to a recycling plant in Sweden (250 km) to collect the PET before sending the sorted PET to the keg manufacturer in the Netherlands. It is assumed that the recycling plant is located in Motala, Sweden, due to its central location and as it is home to Sweden's largest plastic recycling plant [44]. Similar to the previous scenario, the parts of the keg that do not enter the reuse process enter the local waste management system, i.e., the local municipal incineration plant in Sweden. Thereafter, the sorted PET is sent 1 300 km to the Netherlands to be used in the kegs again.

In both closed-loop scenarios, only the parts made of PET enter the closed-loop recycling process. These scenarios assume an 80% recycling efficiency, requiring therefore 20% virgin PET material. The material undergoes a cleaning process before being mixed with virgin PET granulate for new keg production. The process also includes the transport of the virgin granulate to the facility. Both scenarios assume that the non-recycled components of the keg are ultimately incinerated. Further details are provided in the Supplementary Material (Sect. 1).

General Transportation Assumptions

Transportation of the kegs in all scenarios is assumed to be conducted using a EURO5 truck for shipping the new kegs from their production facilities to the breweries, in addition to the transportation of the discarded empty kegs to the waste management and sorting facilities. However, for shipments between the breweries and bars to deliver the beer and return the steel kegs to the breweries, a light commercial vehicle is employed. Associated LCI datasets are outlined in Table S2 in the Supplementary Material.

Life Cycle Costs

As the economic viability of packaging has been highlighted as an important aspect in the economics of brewing, life cycle costing was also conducted. The application of LCC is often connected with LCA in order to provide decision support in product design and alternative approaches [45–47]. In this study, the life cycle costs (LCC) for the packaging is conducted employing the following costs in Eq. (1):

$$LCC_{\text{keg}} = C_{\text{keg}} + C_{\text{trans-distr}} + C_{\text{serv}} + C_{\text{cleaning}} + C_{\text{waste-recyc}} \quad (1)$$

In Eq. (1), the different costs include:

- LCC_{keg} : total life cycle costs of using keg
- C_{keg} : costs of the initial keg, including raw materials and transportation costs

- $C_{\text{trans distr}}$: costs for shipping from producer to user (and back again)
- C_{serv} : costs for serving beer from the kegs
- C_{cleaning} : costs for cleaning kegs, including all machinery, materials, and labor
- $C_{\text{waste recyc}}$: costs for waste disposal and recycling

The costs of the kegs (C_{keg}) include the retail prices for breweries, which is assumed to include all upstream costs for transportation to the retailer [48]. The cost for beer production is not included in the LCC.

For the steel kegs, again, the lifetime of the kegs is assumed to be 80 uses, which with an average of 5.5 reuses per year, amounts to a lifetime of roughly 14 years. Furthermore, to account for losses (such as stolen kegs), roughly 4% more kegs are required in the steel keg fleet, i.e., 577 kegs. The plastic kegs are single use. As such, to fill 100 000 l, it is assumed that 3 333 kegs are purchased each year.

Transportation and distribution ($C_{\text{trans distr}}$) costs include all costs for distributing the filled kegs to the bars. For the steel kegs, this also includes transportation back to the brewery. Assumptions were based on data provided from distribution costs for private-label beers [48].

Costs for cleaning of the steel kegs (C_{cleaning}) are also included in the assessment. This includes the cleaning machinery for kegs [37], which is assumed to have a lifetime of 10 years, where the total cost of roughly 120 000 SEK is distributed over these 10 years. All water, electricity, detergents, and sanitizers are included in the cleaning costs and are obtained from brewing suppliers [37, 49]. Labor costs for cleaning are also included in this overarching cleaning cost. Kegs are assumed to be cleaned in 12 min.

For serving the beer (C_{serv}), only the costs for serving are included. This includes the costs for carbon dioxide and the tank for the steel keg, in addition to the costs for a compressor and electricity to compress air for the plastic kegs. Other costs for taps and other equipment are not included as they are assumed to be similar for both kegging systems (see the Supplementary Material (Sect. 4) for further information).

Finally, costs associated with the respective waste handling and recycling for the different kegging systems ($C_{\text{waste recyc}}$) are included. This also includes credits for recycled materials and costs for transportation to the different facilities for the steel and plastic keg scenarios assessed as outlined above.

Table 3 provides an overview of the costs for the different kegging solutions. Further details on the costs and assumptions employed in the life cycle costing are provided in the Supplementary Material.

Results

The sections below outline the results from the LCA and LCC for the steel and plastic keg scenarios and provide analyses of their sensitivity to assumptions and data. Further results and details, including further environmental impact categories, are also outlined in the Supplementary Material (Tables S5–S8).

Life Cycle Assessment

Figure 2 illustrates the GHG emissions of the steel and plastic keg scenarios. As shown, the manufacturing, waste handling, and transportation phases contributed to a

Table 3 Costs for different keg solutions per keg (all costs shown in Swedish kronor (SEK) in 2020)

| Costs | Description | Steel keg | Plastic keg | Plastic keg closed-loop NL | Plastic keg closed-loop SE |
|----------------------------|---|-----------|-------------|----------------------------|----------------------------|
| Initial costs of keg | Retail (inclusive transport) | 885 | 170 | 170 | 170 |
| Distribution costs | | 223 | 150 | 150 | 150 |
| Cleaning costs for brewery | Equipment, detergents, sanitizers | 44 | - | - | - |
| Serving costs | Gas and air regulation | 1.8 | 0.5 | 0.5 | 0.5 |
| Waste handling costs | Waste handling logistics, energy, and credits | 0.3 | 6.1 | 69 | 71 |

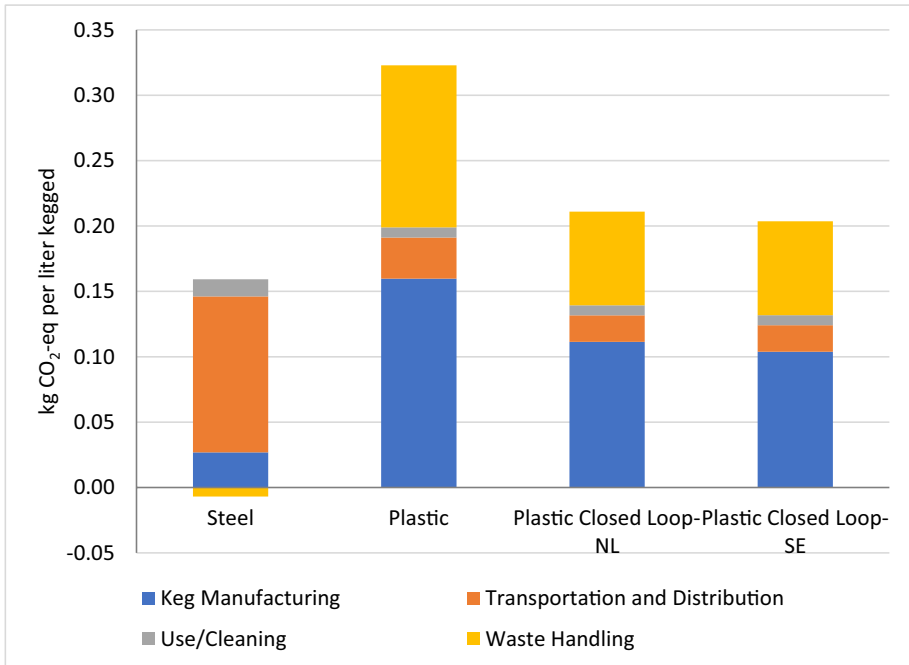


Fig. 2 GHG emissions for life cycle phases for the different keg scenarios. Results are shown in kg CO₂-eq per liter kegged

large share of the environmental impacts of the different kegging solutions. The results suggest that the steel kegs have lower GHG emissions than the plastic keg scenarios, despite larger transportation and distribution impacts. This is partly due to lower GHG emissions allocated to the keg, as it is assumed to be reused 80 times. Furthermore, the steel kegs have a net negative GHG emission for the waste handling process due to credits from the avoided use of virgin steel.

The plastic kegs have large impacts from the manufacturing phase while also having relatively large impacts for waste handling. In the manufacturing phase, the GHG emissions of the plastic kegs are over five-fold larger than the steel keg per liter of kegged beer, while the GHG emissions for the closed-loop plastic kegs are roughly four-fold compared to the steel kegs.

Additionally, the results illustrate that including closed-loop recycling can improve the associated GHG emissions of the plastic kegs compared to the baseline single-use plastic keg. While the transportation emissions are increased due to the logistics to deliver recycled plastic to the Netherlands, the waste handling and manufacturing emissions are both reduced. The waste handling emissions are reduced due to less incineration. The GHG emissions for manufacturing the closed-loop kegs are also reduced due to a lower requirement of virgin plastic material. The closed-loop scenario in the Netherlands is slightly higher than that of the scenario in Sweden. This is due to lower emissions from sorting the PET of the crushed kegs at the sorting facility in Sweden, due to better efficiency and lower impacts from energy carriers.

Table 4 Results per impact category, shown in respective impacts per liter of kegged beer normalized to 100% for the steel kegs for comparison

| Impact category | Steel keg | Plastic keg | Plastic keg closed-loop NL | Plastic keg closed-loop SE |
|--|-----------|-------------|----------------------------|----------------------------|
| Water depletion (m ³) | 100% | 44% | 41% | 44% |
| GHG emissions (kg CO ₂ -eq) | 100% | 212% | 144% | 140% |
| Metal depletion (kg Fe-eq) | 100% | 32% | 13% | 13% |
| Fossil depletion (kg oil-eq) | 100% | 196% | 139% | 136% |

Table 5 Contribution of different life cycle phases to the impact categories reviewed, where each lifecycle stage is taken as a fraction of the total impact for each scenario

| | | Keg manuf | Trans./distr | Use/clean | Waste hand | Total |
|------------------|------------------------|-----------|--------------|-----------|------------|-------|
| GHG | Steel | 18% | 78% | 9% | – 5% | 100% |
| | Plastic | 49% | 10% | 2% | 38% | 100% |
| | Plastic closed-loop NL | 51% | 21% | 4% | 25% | 100% |
| | Plastic closed-loop SE | 49% | 22% | 4% | 26% | 100% |
| Water Depletion | Steel | 4% | 6% | 90% | 1% | 100% |
| | Plastic | 33% | 3% | 47% | 16% | 100% |
| | Plastic closed-loop NL | 35% | 5% | 51% | 9% | 100% |
| | Plastic closed-loop SE | 39% | 5% | 48% | 9% | 100% |
| Metal depletion | Steel | 106% | 25% | 3% | – 35% | 100% |
| | Plastic | 36% | 13% | 10% | 41% | 100% |
| | Plastic closed-loop NL | 23% | 52% | 24% | 1% | 100% |
| | Plastic closed-loop SE | 23% | 52% | 24% | 1% | 100% |
| Fossil depletion | Steel | 14% | 83% | 6% | – 4% | 100% |
| | Plastic | 82% | 11% | 1% | 5% | 100% |
| | Plastic closed-loop NL | 75% | 23% | 2% | 0.3% | 100% |
| | Plastic closed-loop SE | 74% | 24% | 2% | 0.3% | 100% |

As outlined in Table 4, beyond GHG emissions, fossil resource depletion was lower for the steel kegs compared to all plastic keg systems. However, the plastic kegs are shown to have lower water use and metal resource depletion. The difference in the results for the metal and fossil depletion is a direct result of the materials used in the steel and plastic kegs, respectively.

As shown in Table 5, the added water resource depletion for the steel kegs is derived predominantly from the use phase, which includes cleaning the keg for reuse. The plastic kegs are illustrated to have larger fossil resource use, with over 80% of the total impact originating from the manufacturing of the plastic keg. Around 50% of the total GHG emissions for the plastic keg originate from its manufacturing, with the remaining impacts being borne from transportation and waste handling. The introduction of a closed-loop recycling scheme for the plastic kegs can improve the environmental performance across many of the environmental impact categories. Both the closed-loop scenarios for the plastic kegs improve the GHG emissions and reduce the fossil resource depletion and metal depletion

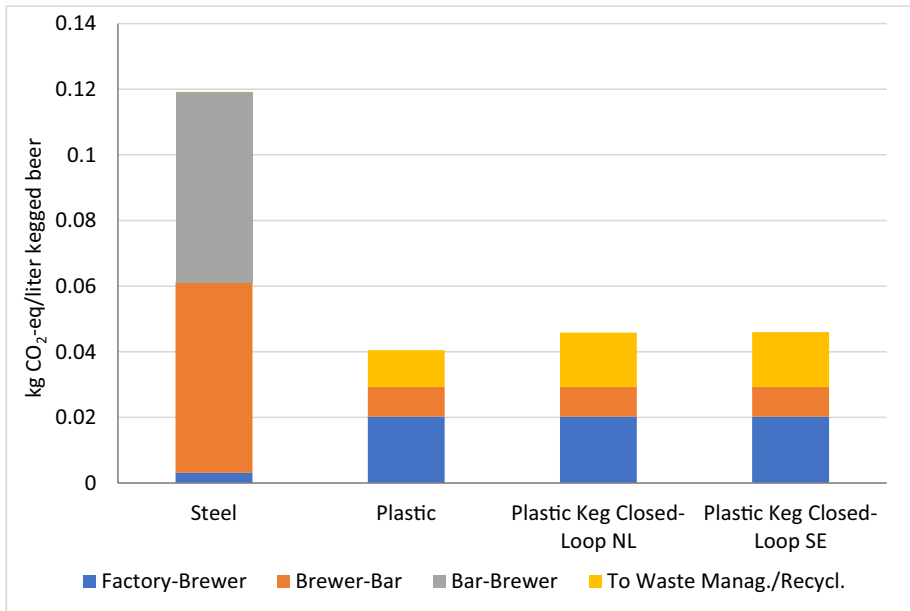


Fig. 3 GHG emissions for different transportation processes for the different kegs. This includes transportation from keg factory to brewery (Factory-Brewer), from the brewer to retail locations (Brewer-Bar), for return of the kegs from retail to brewer (Bar-Brewer), and for end-of-life activities for waste management and recycling (To Waste Manag./Recycl.). Results shown in kg CO₂-eq per liter kegged from transportation processes

compared to the original plastic keg scenario. There was no substantial difference in water depletion compared to the baseline plastic keg, despite the added cleaning of the shredded PET before being repurposed into new granulate. The PET granulate has a large influence on GHG emissions and fossil resource use, where the closed-loop recycling approach reduces the GHG emissions and fossil resource depletion.

Analysis of LCA Results

Transportation As outlined above, the extent of transportation of the kegs varies considerably between the keg scenarios and is shown to be an important contributor to nearly all impact categories. To illustrate the influence of the transportation phase, Fig. 3 provides an overview of the GHG emissions from all transportation processes during the life cycle of the plastic and steel kegs.

As illustrated, the GHG emissions for the transportation from the brewery to the bar and back are much larger for the steel kegs compared to their plastic counterparts due to the added distance and use of a light commercial vehicle for these shipments. However, the GHG emissions from transporting kegs from the factory to the brewery and to the waste management facility are larger for the plastic kegs compared to the steel kegs. This is primarily due to the single use of plastic kegs compared to the reuse of the steel kegs. Furthermore, in the closed-loop scenarios, the transportation to return the PET to the Netherlands does not expressively increase the overall GHG emissions for these scenarios.

Table 6 Break-even distances for plastic kegs relative to steel keg between brewer and bar

| Scenario | Break-even GHG emissions (km) | Break-even fossil depletion (km) |
|----------------------------|-------------------------------|----------------------------------|
| Plastic keg | 245 | 217 |
| Plastic keg closed-loop NL | 155 | 149 |
| Plastic keg closed-loop SE | 150 | 143 |

Furthermore, the market for keged beer can be extensive. In a country such as Sweden, with large distances between major urban areas, the sensitivity of the distance was tested using a break-even point. This was done to show where the plastic kegs may be beneficial compared to the steel keg. Table 6 presents an overview of the break-even distances for GHG emissions and fossil resource depletion. For GHG emissions, the results suggest that the plastic keg can become a better choice for packaging when transportation to the end-user is more than 245 km from the brewery. The fossil resource depletion is also equal at around 217 km, after which the plastic kegs can be a better choice. Further details on the calculation of the break-even point are provided in the Supplementary Material (Sect. 2).

Once again, the introduction of the closed-loop recycling system has the potential to improve the environmental performance. Here, the closed-loop system in Sweden shows the largest improvements with a break-even GHG emission point at roughly 150 km—only slightly above the assumed distance of 100 km—suggesting they are a comparable choice to steel kegs.

Steel Keg Lifetime/Uses The previous section addressed the transportation distance, showing the break-even point where the plastic kegs may become a better option. Another important assumption is the number of reuses of the steel kegs. As the number of reuses of the steel kegs may be much higher than the assumed average of 80 uses assumed in the previous section, the sensitivity to this choice was also analyzed.

As shown in Fig. 4, the impact of the steel keg decreases exponentially as the number of uses increases. The break-even point for using a steel keg is at 38 uses. Therefore, even halving the number of assumed uses illustrates that the steel keg still has lower GHG emissions than the plastic keg, given that other variables remain constant (e.g., transportation distance). Furthermore, the break-even point for GHG emissions where the steel keg is a better choice than both the closed-loop scenarios is roughly 60 uses, again lower than the assumed 80 uses. The sensitivity to the number of uses is further exemplified in Fig. 5, where the sensitivity to the number of uses is compared to the plastic keg scenario. The results illustrate that increasing the assumed number of uses largely reduces the overall impacts of the steel kegs compared to the plastic keg.

Life Cycle Costs

The results suggest that the life cycle costs associated with the steel keg are lower than those of the plastic keg (see Fig. 6). This is primarily due to the lower number of kegs employed and their extended lifetime, despite higher initial costs. Furthermore, as illustrated, a large share of the life cycle costs for the different keging solutions is due to the transportation and distribution of the kegs to retail locations. This is higher for the steel

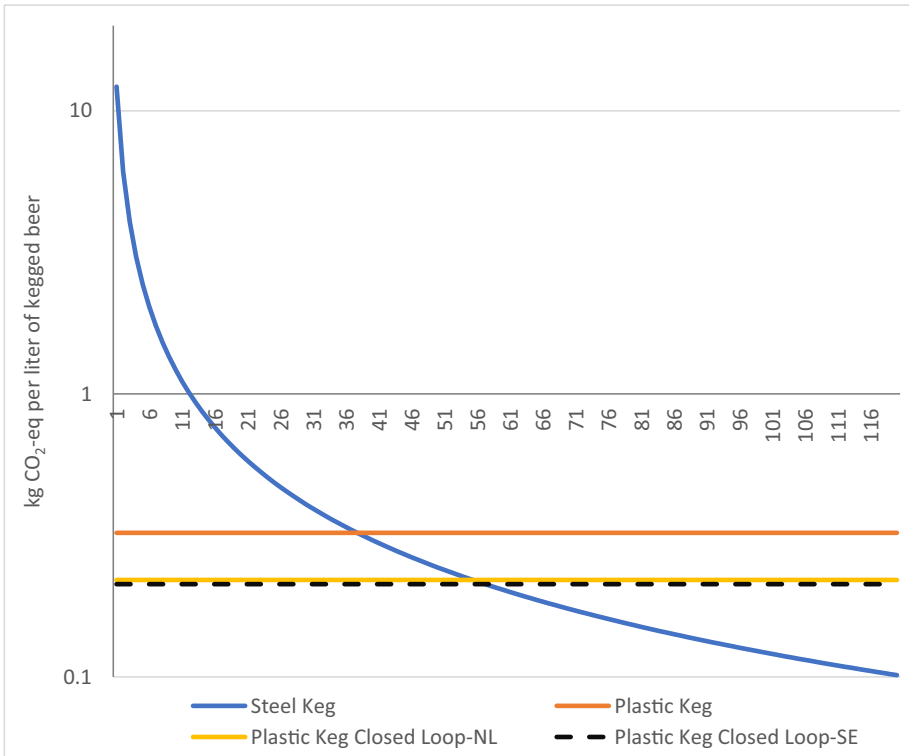


Fig. 4 Overview of changes in GHG emissions as the number of uses increases. The results are shown in kg CO₂-eq per liter of kegged beer, plotted on the y-axis on a logarithmic scale

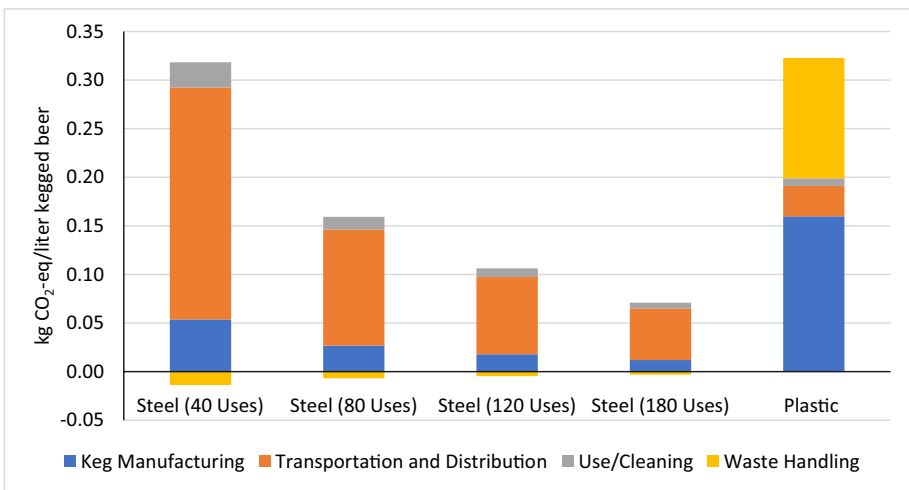


Fig. 5 Sensitivity to the number of reuses for the steel kegs, compared to the plastic keg scenario. All results are illustrated in kg CO₂-eq per liter kegged beer

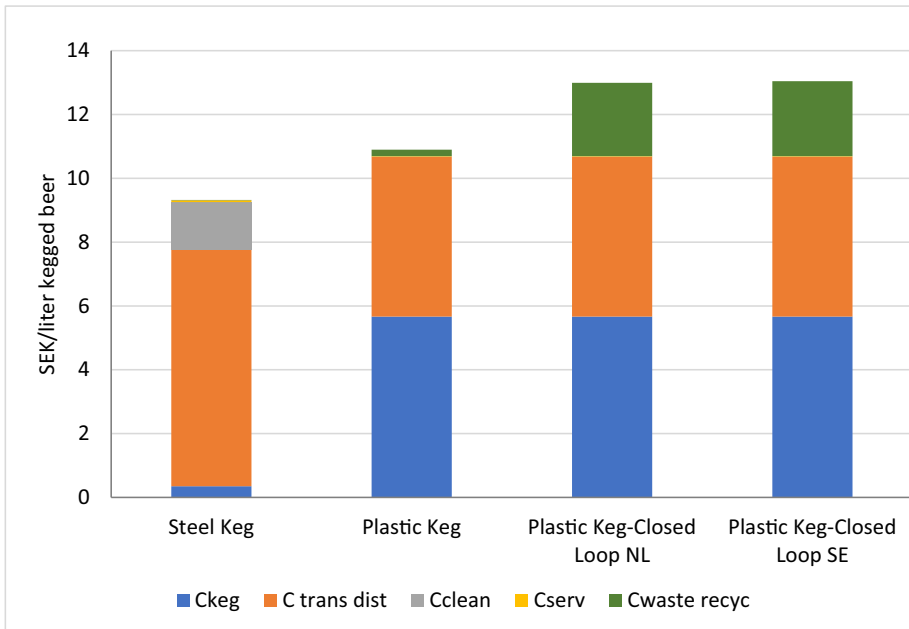


Fig. 6 Life cycle costs per liter kegged for different keggling solutions. All costs are in Swedish kronor (SEK) per liter kegged beer. Ckeg costs for kegs, Ctrans distr costs for distribution and transportation, Cserv costs for serving, Cclean cleaning costs including all machinery, materials, and labor for cleaning kegs, Cwaste recyc costs for waste disposal and recycling

kegs than the plastic kegs due to the weight of the steel kegs and the added transportation back to the breweries after use. The costs of the kegs themselves contribute largely to the costs, primarily for the plastic kegg solutions reviewed. For the steel kegs, the cleaning and serving also contributed to roughly 16% of the costs. The costs for waste handling are low in the steel and plastic kegg scenarios, while they contribute to roughly 18% of the overall costs for the plastic kegs with closed-loop processes for recycling the PET. Overall, the costs for the plastic kegs are roughly 2 SEK more per liter of beer kegged and 4 SEK more per liter of beer kegged for the closed-loop plastic kegg scenarios.

The results suggest that, despite claims of their lower costs, it was found that the overall life cycle costs of steel kegs are lower than the plastic kegs. For the steel kegs, this amounted to a cost of roughly 932 000 SEK per year for the brewery, dominated by the costs for transportation and distribution in addition to cleaning costs. The plastic kegs have an annual cost for the brewery of around 1 090 000 SEK, which stems primarily from the costs of the kegs. For the brewery, similar costs are seen for the closed-loop plastic kegs, while there are additional life cycle costs for the waste management and recycling processes (see Fig. 7).

Analysis of LCC Results

The results may be sensitive to the assumptions made. One major assumption is the lifetime of the steel kegg, i.e., the number of uses of each kegg. Table 7 shows the sensitivity to the assumption on the steel kegg lifetime, with 40 uses (7 years), 80 uses

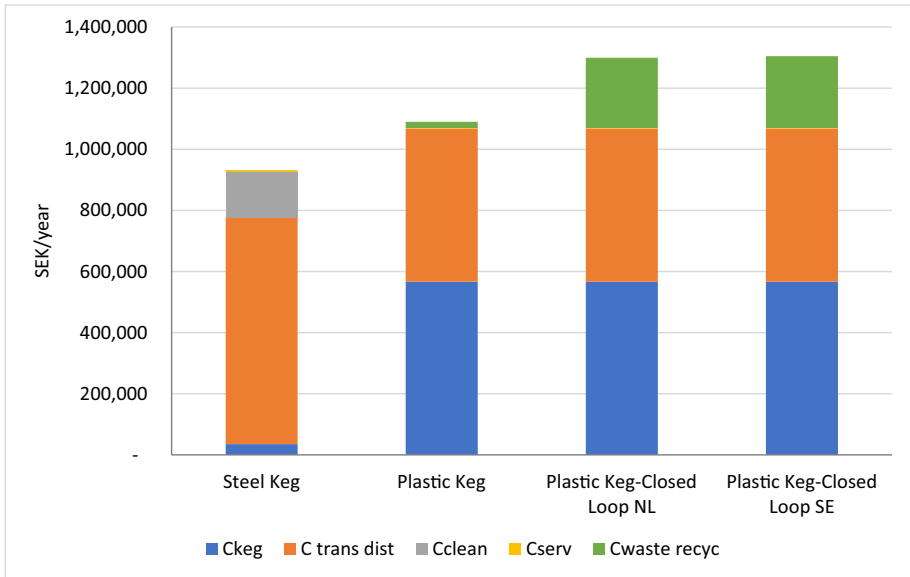


Fig. 7 Annual life cycle costs for kegs, shown in annual costs in Swedish kronor (SEK). *C_{keg}* costs for kegs, *C_{trans distr}* costs for distribution and transportation, *C_{serv}* costs for serving, *C_{clean}* cleaning costs including all machinery, materials, and labor for cleaning kegs, *C_{waste recyc}* costs for waste disposal and recycling

Table 7 Sensitivity to the lifetime of steel kegs. All costs are shown in Swedish kronor (SEK). *C_{keg}* costs for kegs, *C_{trans distr}* costs for distribution and transportation, *C_{serv}* costs for serving, *C_{clean}* cleaning costs including all machinery, materials, and labor for cleaning kegs, *C_{waste recyc}* costs for waste disposal and recycling

| Cost | Steel keg (100 uses) | Steel keg (80 uses) | Steel yeg (40 uses) |
|--------------------------------|----------------------|---------------------|---------------------|
| <i>C_{keg}</i> | 24 580 | 35 120 | 70 240 |
| <i>C_{trans distr}</i> | 742 730 | 742 730 | 742 730 |
| <i>C_{clean}</i> | 147 530 | 147 530 | 147 530 |
| <i>C_{serv}</i> | 5 820 | 5 820 | 5 820 |
| <i>C_{waste recyc}</i> | 750 | 930 | 1 860 |
| <i>Total</i> | 921 410 | 932 130 | 968 180 |

(14 years), and 100 uses (20 years). As illustrated, while the other costs for the kegs are not changed annually, the allocated costs for the kegs are largely influenced. This suggests that extending the lifetime of their keg fleets should take priority to lower costs for the breweries.

Similar to the LCA, in the LCC, the transportation of the kegs was shown to have a large influence on the overall life cycle costs. Figure 8 provides an analysis of the sensitivity to the distribution distance for the kegged beer, assessing the sensitivity to distribution of over 200 km. As illustrated, the annual life cycle costs may increase, with a 16% increase illustrated for the steel kegs and resulting in a 4% increase for the

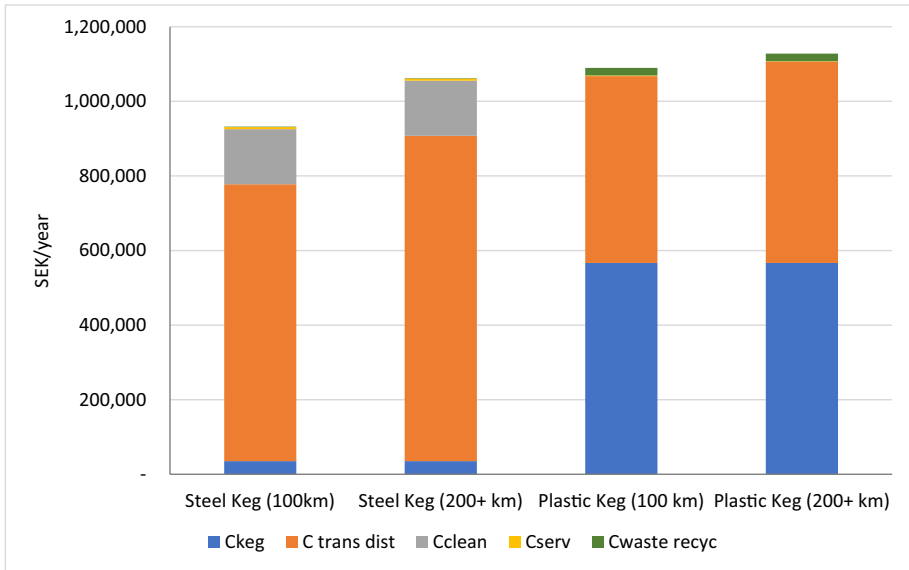


Fig. 8 Reviewing the sensitivity of the annual life cycle costs to the transportation distance. All costs are shown in Swedish kronor (SEK). Ckeg costs for kegs, Ctrans distr costs for distribution and transportation, Cserv costs for serving, Cclean cleaning costs including all machinery, materials, and labor for cleaning kegs, Cwaste recyc costs for waste disposal and recycling

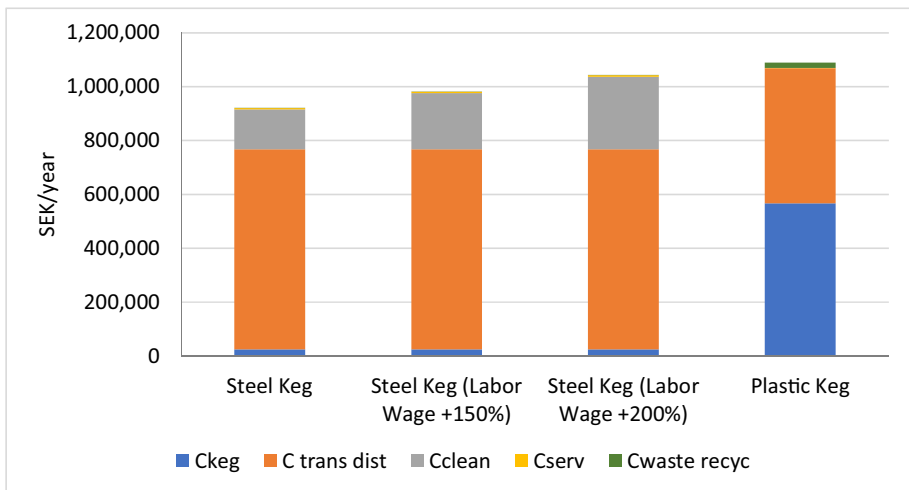


Fig. 9 Reviewing the sensitivity of the annual life cycle costs to the labor wage costs for the steel keg and compared to the plastic keg. All costs are shown in Swedish kronor (SEK). Ckeg costs for kegs, Ctrans distr costs for distribution and transportation, Cserv costs for serving, Cclean cleaning costs including all machinery, materials, and labor for cleaning kegs, Cwaste recyc costs for waste disposal and recycling

plastic kegs. This again underscores the sensitivity of the analysis for the transportation distance, especially for the steel kegs.

Sensitivity to labor costs.

As outlined above, labor costs for cleaning steel kegs may also be sensitive to assumptions made. In order to outline this, the costs of labor for the brewery were increased to show its influence on the cleaning costs for the steel kegs. As shown in Fig. 9, this would increase the cleaning costs of the steel kegs. However, despite its influence, even with a doubling of the cleaning costs, the overall costs of the steel keg would still remain slightly less than the plastic kegs.

Discussion

LCA and LCC Results

The results suggest that steel kegs have many environmental and economic performance advantages over their single-use plastic counterparts. The advantages stem primarily from a large number of reuses and lifetime of steel kegs. Similar findings have been outlined in [34], who found that steel kegs, among other packaging choices, had the least impact per liter of packaged beer. However, it is important to note that the results are sensitive to a number of assumptions, including the lifetime of the keg, number of uses, and distribution distance to the market, which can affect the results of the LCA and LCC for the steel kegs.

The GHG emissions associated with the steel keg production outlined in this study are similar to those in previous studies [5, 34]. However, previous studies have focused only on GHG emissions, and thus no comparisons with other environmental impact categories are possible. Although no previous assessments have reviewed the sustainability of different keging options, the results concur with earlier findings on the influence of packaging for the brewing industry (see, e.g. [5, 8, 33, 34]).

The life cycle costs for the steel kegs were also found to be the lowest of the keging options, despite the perceived added costs of cleaning and initial investment costs for a steel keg fleet, which were found to be only a small share of the overall life cycle costs. It was found that the life cycle costs for the steel kegs are dominated by transportation and distribution costs, while for the plastic kegs, the costs associated with purchasing the kegs were equally as important. No previous assessments of the life cycle costs for kegs are available. However, Amienyo and Azapagic [33] assessed the life cycle costs of beer in different packaging systems, i.e., glass bottles and aluminum cans. The life cycle costs for packaging in the aforementioned study are lower compared to the results in this study but also point to the packaging as a primary contributor to the total life cycle costs of the beer.

Results outlined in this study also highlight the potential for improving the environmental performance of plastic kegs by implementing local recycling strategies through a closed-loop process to recycle the PET, similar to those available in other countries. Similar assertions have been made for recycling and collection schemes for applying LCA of materials and packaging [50]. This was primarily due to the reduced requirements for virgin material and reduced incineration of the plastic components. Similar findings have been highlighted in Eriksen et al. [51] and Chilton et al. [52] for recycling PET bottles. Nonetheless, the closed-loop scenarios illustrate an increase in water depletion compared to the baseline plastic keg due to cleaning the shredded PET before being repurposed into new granulate, an often disregarded detail for the recycling of

PET [52]. Furthermore, it was found that the added transportation to the plastic keg recycling plant and thereafter to the Netherlands had little influence on the results, similar to the results of Niero and Olsen [31].

Sensitivity and Limitations

One key sensitivity outlined in this study is the distribution distance assumed. This study assumes that this distance is within 100 km, i.e., within the Stockholm region in this case. In reality, for a country such as Sweden, this may be an underestimate; many of the largely populated urban areas are more than double this distance apart. As the sensitivity shows, this can greatly affect the outcome for the kegs. The break-even analyses determine that for distribution distances over 245 km, the plastic kegs have GHG emissions on par with those of the steel kegs, suggesting they could be the more sustainable option for the breweries. This break-even distance is higher than the results in a previous study [24], which suggests the break-even point to be roughly 150 km. Nevertheless, the results indicate the steel kegs are better for the local market, while plastic performed better outside the local market, which is especially important in a country with large transport distances such as Sweden. The closed-loop scenarios for the plastic kegs narrow this gap, bringing the break-even distance to around 150 km or below, similar to the results in [24]. In the study by Cimini and Moresi [34], the steel kegs had an average distribution distance of 150 km and had the lowest impacts of all the different packaging systems. This suggests that steel kegs are a viable option for local markets. These results provide the brewing industry with insights into the environmental impacts of keggings solutions to promote better decisions and more sustainable production methods for local and extended markets.

The study was also limited to a number of assumptions specific to the kegs that may have affected the results of the study. This study assumed that the kegs would be used an average of 80 times. However, the analysis identified that the results were sensitive to this assumption, and with increased lifetime, the environmental and economic performance of the steel kegs improved greatly. Furthermore, despite the lack of previous studies outlining the lifetime of steel kegs, manufacturers have highlighted that the lifetime can greatly exceed 100 uses, depending on the number of reuses reported, with a lifetime of roughly 30 years mentioned by several producers [34, 36]. The results point to the potential of increased care and maintenance to increase the lifetime, which may improve the performance, ultimately lowering the impacts for the distributed beer. Similar findings on the sensitivity to the number of uses of beverage containers have been outlined in [53–55] when assessing the potential use and reuse of other beverage containers. The assumptions on recycling rates for plastics may also be an important factor in the performance of the plastic kegs. For the recovery and recycling rate of the single-use plastic kegs, empirical evidence and other scientific studies outlining these factors are lacking in the literature. As such, we have relied on media reports and discussions with craft brewers. Therefore, this choice, along with the lifetime of the steel kegs, may have a large influence on the results, and similar limitations could be alleviated in more specific case studies with breweries to study the lifetime, and recycling, of their keg fleet. Finally, in light of the pressing need to close material loops [21, 56], and despite not reviewing these systems in this study, the comparison of reusable plastic keggings solutions should also be assessed, as reusable plastic kegs may also be competitive with steel kegs.

Implications for the Craft Brewing Industry

The results in this study have provided insights on the benefits and drawbacks of different keggling solutions. Important considerations beyond the initial cost are important to consider when choosing sustainable keggling solutions. However, many producers in the food and beverage industry have tended to focus on the minimization of packaging material and weight to address sustainability [14, 57, 58]. Nonetheless, in this study, it was found that conventional steel kegs have advantages over their plastic counterparts, despite their weight and potential for reuse. Previous studies of the sustainability of Swedish craft breweries have also failed to highlight the sustainability of packaging choices, focusing primarily on the perceived implications of lighter weight packaging and neglecting kegs [14], especially single-use varieties. As highlighted in Svanes et al. [59], material minimization alone should not be the most sustainable strategy for packaging, suggesting that costs, acceptance, and user-friendliness are important aspects to consider, which may allow brewers to focus on their core business. As such, environmental and economic sustainability does not constitute the most critical drivers for the craft brewing industry. Yet, as Halst-Pullen et al. [57] suggest, while a large share of breweries believe that incorporating sustainability can lead to higher profits, few follow suit.

Furthermore, considering the growing policy focus on the reduction of single-use plastics in Europe [21], the development of new single-use plastic systems should be critically questioned [18, 60]. Once again, the growing use of single-use kegs marks a peculiar change in packaging for the brewing industry at a time when single-use plastics have attracted extensive policy attention [18, 19, 21], and EU targets for waste reduction and recycling of packaging waste are becoming increasingly important [20, 61]. As single-use plastic kegs continue to expand their market share, developing closed-loop systems and recycling channels for these can improve their environmental performance and the societal value of the materials [42]. Progress towards closed-loop systems for these kegs exist in other countries, where the producer has made efforts to improve their recyclability and sustainability [27], although their efficiency and effectiveness to recover kegs are not known. In Sweden and other places, this may be due to limited knowledge and incentives on the benefits of recycling and recovery of the kegs. Previous research has also shown that improving the design for easier recycling and providing knowledge to the end-users on correct handling can greatly improve the potential for their recycling and contribution to a more circular economy [51, 62, 63].

Conclusions

This study has provided a novel contribution to the brewing literature on keg choices, filling the research gap by providing an empirical assessment of both the environmental and economic sustainability of single-use plastic and steel keggling solutions. Steel and single-use plastic keggling scenarios were compared, illustrating the importance of keg material choices, transportation distance, lifetime, and the number of reuses, providing craft brewing operations with the knowledge to improve the sustainability and economic viability of their operations. It was found that steel kegs had lower environmental impacts and reduced life cycle costs compared to plastic counterparts. The results suggest that steel kegs are more suitable for a local market, while plastic performed better outside of the local market, which is

especially important in countries with large distances between urban centers such as Sweden. Furthermore, the results also highlight the potential for improving the performance of plastic kegs by implementing local recycling strategies through a closed-loop process to recycle PET similar to those available in other countries. The keggings solutions were also found to be sensitive to transportation distance, with plastic kegs having lower GHG emissions if the distance from the brewery to a bar is greater than roughly 250 km, in addition to the performance of the steel kegs being sensitive to the assumed lifetime and reuse rate.

With the transition to a more circular economy attracting attention in policy, industry, and academia, the adoption and growth of single-use plastic packaging systems must be critically questioned. These results provide the brewing industry with insights into the environmental impacts of keggings solutions in order to progress towards more sustainable beer production. Lastly, they also provide an information base to policy-makers that may seek to introduce policy instruments to improve plastics recycling systems and reverse trends moving from circular to linear systems.

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Availability of Data and Material N/A.

Code Availability N/A.

Declarations

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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