Packaging Technology and Science

WILEY

Packaging Technology and Science
An International Journal

RESEARCH ARTICLE OPEN ACCESS

Steps Towards a Template for Fair Comparisons Between Single-Use and Reusable Items

Mieke van den Berg[1] | Roland ten Klooster[2]

[1]The LCA Centre, Beuningen, the Netherlands | [2]University of Twente, Enschede, the Netherlands

Correspondence: Roland ten Klooster (r.tenklooster@utwente.nl)

Received: 14 December 2024 | **Revised:** 28 July 2025 | **Accepted:** 4 August 2025

Funding: The authors received no specific funding for this work.

Keywords: life cycle assessment | reusable packaging | reuse LCA | reuse system impact factors | reuse systems calculations

ABSTRACT

In this paper, the factors taken up in LCA studies comparing single-use to reuse are evaluated. Based on literature research, the insight was obtained that there are many single-use vs. reuse comparisons that do not take into account the full picture of a reuse system. These factors are defined and further explored using single-use/reuse system comparison case studies. A method to calculate the impact of reuse systems and to compare it to single-use systems is presented in terms of equations based on the case studies. The equations are used to show the relevance of taking up specific parameters using different input values. Significance is shown for the following factors:

- Single-use components in a reuse system
- Constant factors in a reuse system
- Pool size compared to system size in a reuse system
- Loss percentage

With this method, several factors are taken up outside of LCA software in order to determine a break-even point or to understand the trajectory of the system impact over rotations. Together with inventory reporting according to ISO 14040/14044 this can be the basis for transparent reuse system impact calculations and its fair comparison to single-use system impact.

1 | Introduction

In the goal for a circular and climate-neutral world economy, several plans and directions have been laid out in recent years. In Europe these include, for example, the European Green Deal [1] and the Circular Economy Action Plan (CEAP) [2]. To contribute to reaching these objectives, the European Commission proposed revising the Packaging and Packaging Waste Directive (PPWD) into a regulation, as published on 22 January 2025 [3]. The packaging and packaging waste regulation (PPWR) has the objective of ensuring that all packaging on the EU market is reusable or recyclable in an economically viable way by 2030. Individual countries are thereby also motivated to formulate and execute their own implementations of such directives. As an example, the Dutch circular economy (CE) policy targets a 50% reduction of plastics made from fossil fuels by 2030. Another goal in the PPWR is to significantly increase the use of reusable packaging. In the Netherlands this is seen as one of the pathways to achieve this goal [4]. Companies and organizations are considering the use of reusable packaging due to the upcoming legislation and because packaging that is reused or refilled gives the impression of being more sustainable than a single-use solution, whether true or not, due to there being less visible waste/litter. To get insight into the environmental impact of single-use packaging versus returnable packaging, Life Cycle Assessment (LCA) studies are often used [5].

Standards such as ISO 14040 and 14044 describe the guidelines for how an LCA study must be conducted, in order to make comparative assertions (ISO 14025). Those comparative assertions have been focused on single-use cases, which have led to guidelines for fair comparisons. The functional unit (FU), material composition and country of origin have been identified as important LCA input stages and should be known to a similar level for all products in the study [6]. This is the starting point for LCA. However, in the case of reuse systems and comparison to single-use systems, there are no additional guidelines. It is up to the operative to determine the factors to consider in the system.

Thoden van Velzen and Brouwer [7] found that certain factors are often not taken up in LCA (reuse) studies. These include, for example, breakage/damage rates in reusable packaging systems, weight ratio of reusable vs. single-use packages, required pool size to operate a reusable system and recycled content of single-use packaging [7]. WRAP published concerns about factors often not taken up in LCAs of reusable packaging [8]. In fact, these sources state that LCA comparisons of single-use versus reusable systems compare systems with different factors without standards or guidelines within the ISO Standard. This observation gives rise to the question of what is taken up in reuse/single-use LCA comparisons, what commonly overlooked factors are, what the differences are between comparisons, what the impact of commonly overlooked factors is, and therefore what factors and how they should be taken up in realistic and transparent single-use to reuse system comparisons.

In this paper, several aspects of the single-use to reuse system comparison are explored. Firstly, an overview is made of what is often taken up in comparison studies of single-use versus reuse and what is missing based on the mentioned sources. To understand comparisons, reuse cases are presented, including formulas that use the potentially relevant factors for calculating the environmental impact of the systems. Based on these studies, the effect of several potentially relevant factors is explored. In the end, an overview of the parameters that can influence an outcome of a comparison study is presented. The possible use of these insights and what this would mean for comparison studies of single-use versus reusable items is discussed.

2 | Literature Study

In this chapter, the factors that are currently included in the comparison between reuse and single-use LCA studies in published papers are explored. Studies by Thoden van Velzen and Brouwer [7], Bradley and Corsini [9] and Wrap [8] present various factors that are relevant to LCA studies and in comparing single-use systems to reuse systems.

The relevant factors found in WRAP [8] are raw materials, energy in manufacturing, return rate, transport distances, pool size, type of transport and recycled content as important impact factors [8]. Other secondary factors with varying impact according to the study are end of life in reuse packaging, recycling location, type of energy mix, secondary and tertiary packaging items, washing impact and repair of reusable packaging. In addition to these factors, the factors that are often not taken up in LCA studies found by Thoden van Velzen and Brouwer [7] are breakage/damage rates in the reusable packaging system, weight ratio of reusable vs. single-use packages, required pool size to operate a reusable system and recycled content of single-use packaging. Similarly, factors that influence the sustainability of reusable packaging systems are reportedly, among others, the recycled content, material type, weight, transport volume ratio, distance, return, loss and breakage rates [9].

To test how and if these factors are present in LCA studies, a literature review was carried out on 18 papers dealing with packaging LCA, for which the results are summarized in Table 1. This study does not look at how the ISO standards are taken up in the studies.

2.1 | Literature LCA Study Findings

The parameters that are compared are taken from the published papers: FU, use of single-use packaging items as additional packaging to the returnable packaging, packaging weight, country of origin with used energy grid, recycled content used, transport distance, vehicle load and end of life, followed by the factors that are mentioned by Wrap and Thoden van Velzen.

All studies present a FU, which is the foundation for how products are compared in a study. Additional single-use transport packaging items are included in three studies. This can be a box to transport reusable cups or bowls in or pallet straps and wraps. The packaging weight is always included, sometimes based on other literature studies, sometimes empirically obtained.

The country of production determines the energy sources for a large part and is only addressed in half of the investigated studies. The energy grid mixture of a specific country or sometimes specific factory greatly determines the global warming potential and other impact categories because electricity can be generated from fossil energy (oil, coal, natural gas), renewable energy sources (wind, solar, geothermal, hydro) or nuclear energy. Recycled content is not taken up in every study, partially because it is, in specific cases, not available for the purpose. These values are sometimes based on case studies, other literature studies or assumptions. It becomes clear from Table 1 that the transport distances are included in all studies but not always presented. The analysis of the studies shows that the vehicle load is only included in one of the 18 studies. End of life is always part of a study and can be taken up in different ways, such as cutoff or allocation (system expansion). The end-of-life scenario is, however, not always clear from a study. A large amount of products is covered, but the data quality of the inventory used in LCA studies is reportedly divergent [28], which is the same for the studies in Table 1.

Reuse LCA studies are often of high complexity, which was also reviewed in a study by Hann [29]. The study evaluates two LCA studies on reuse systems compared to single-use systems. One of the key points here was that the comparison is often made between an optimal single-use system and a novel, suboptimal reuse system [29].

As already mentioned by WRAP [8] and Thoden van Velzen and Brouwer [7], a reuse system has factors that a single-use system

TABLE 1 | Literature review on factors taken up in LCA studies comparing reuse and single-use packaging systems.

Study	Single-use transport packaging (1)	Weight (2)	Country of production (3)	Recycled content (4)	Transport distances (5)	Vehicle capacity (6)	End of Life (EOL) (7)
[10]	—	Included	Included	—	Included	—	Different scenarios, recycling rates included
[11]	—	Defined in terms of FU	—	Included	Included	—	Recycling and incineration for PP and PET; recycling for SS; composting for PLA
[12]	—	Various options included	Averages of Europe	—	Based on assumptions	—	Allocation method, included for PP, PET 85%, glass 89%
[13]	—	Included	Implicit	Included in single-use PET cup	Included	—	Cutoff and system expansion (allocation) using CFF
[14]	—	Included	Included for some	—	Included	—	Included, 93% recycling, 7% incineration (reusable plastic crate)
[15]	Grouping in 12 (PET) and 6 (glass). Tertiary packaging (boxes, stretch film)	PET 22.8 g/25.7 g, glass 450 g	—	Inherent in glass, included in tertiary packaging	Includes return transport	—	Included, also for other packaging components
[16]	Included	Included	—	—	From literature (Almeida and Bengtsson [10])	—	0.25% paper cup recycling, but 100% also included
[17]	—	Included	Included	Also accounted for EoL recycled amount	Included	—	Included
[18]	—	Included	Included	—	Also customer transport	—	Included
[19]	—	Included	Included	Inherent in glass	Incl. system transport	—	Recycling for single-use system, none for reuse system
[20]	—	Included	—	—	Same values for reuse and single-use options	—	Included

(Continues)

TABLE 1 | (Continued)

Study	Single-use transport packaging (1)	Weight (2)	Country of production (3)	Recycled content (4)	Transport distances (5)	Vehicle capacity (6)	End of Life (EOL) (7)
[21]	—	Included	—	—	Optimistic in single-use case. Washing centre 650 km	—	Included
[22]	Steel and plastic kegs are transported directly on pallets	Included	Included	Included in PET 80%, steel unclear	Included	—	Included
[23]	—	Included	—	—	Included	—	Included
[24]	—	Included	Included	—	Included	—	90% landfill, 10% recycled (South Africa)
[25]	—	PS 4.2 g, PLA 4.2 g, biopaper 5.6 g, reusable 370 g	—	—	—	—	Reusable cup incineration
[26]	—	Included	Included (in geographical scope)	Crates replacing losses	Only for washing and reconditioning	—	Included (recycling)
[27]	—	1700 g PP vs. 180 g cardboard; 118 g PP bag, 30 g LDPE bag vs. 180 g box	—	In sensitivity studies	Inefficient return transport distances	Included	Included
Study	Washing (8)	Return rate (9)	Lifespan (10)	Pool size (11)	Losses method (12)	Sensitivity study (13)	Equation (14)
[10]	Included	—	Included	—	—	Included	—
[11]	Included	—	Defined as at least 3 years for the Stainless steel reuse cup	—	—	—	—
[12]	Handwashed, dishwashed (from Martin [22]), industrial washed	Not mentioned	Included, defined as dispersion	-—	After lifespan, implicit	End of Life	Not for system impact
[13]	Included	Based on empirical data	Number of servings equation	Starting cups calculation	—	End of life methods as sensitivity	—

(Continues)

TABLE 1 | (Continued)

Study	Single-use transport packaging (1)	Weight (2)	Country of production (3)	Recycled content (4)	Transport distances (5)	Vehicle capacity (6)	End of Life (EOL) (7)
[14]	Included for 97.6% of the crates	1% + 0.4% breakage rate	Included (lifetime of 5 years, used 50 times)	—	—	Included, transport an EoL	—
[15]	Included	Included	Included based on bottling company information and other papers	—	—	—	—
[16]	Included, handwashed and dishwashed	—	Assumed at 500 uses	—	—	Worst and best case EoL scenarios	—
[17]	Dishwasher and handwashing	—	Only mentioned in breakeven calculations	—	—	—	—
[18]	Included	—	20 rotations	—	—	Travel distance, washing, energy source	—
[19]	Included	—	—	—	—	—	—
[20]	Included	—	200 rotations	—	—	Travel distance	—
[21]	Included	—	150 rotations	—	—	—	—
[22]	Included	—	Set at 80	Included to account for losses	Zero losses assumed	PET recycling location, Transport distances	Supplement
[23]	Primary and secondary data	—	30 cycles based on PEF	—	—	Recycled content	—
[24]	Included	—	10 servings	—	—	Included	—
[25]	Handwashed and dishwashed	—	1750 rotations	—	—	—	—
[26]	Scenarios	Break rate 0.55%	Evaluated until 125	—	Included every rotation	—	—
[27]	Indicated as reprocessing	Included	Technical lifespan	—	Set to 0	Virgin cardboard, recycled PP, recycled content (80%)	—

does not have, such as washing, system transport, return rates and losses, pool size and a product lifespan. Transport distances for transport in reuse systems are the same in every rotation, which makes the impact a relevant factor for the impact of a system [5]. These values are presented in only six studies. Washing is an additional source of impact in reuse systems, which is the same in every rotation, so not divided over the system size. Many studies focus on the method of washing and the impact of the methods, such as handwashing, dishwashing and industrial washing. The focus may also lie on the transport distance to a washing facility, which is in most cases either not local to the reuse system or a fictive location. The pool size is taken up in two studies, return rates are taken up in five studies, while lifespan is a factor included in 17 studies in different ways. If single-use versus reuse system comparison is taken up, it is included in different ways. Sometimes presented in a cumulative impact over a certain number of rotations of the reuse system, while other studies present the impact of one system relative to the impact of another system. In most of the studies, the formulas used for calculating the outcome are not presented; often they are a black box.

In Table 1, an analysis of LCA studies in which return systems are compared with one-way systems is taken up. Points that are mentioned are taken up, points that are clearly presented or discussed or that can be derived from the papers. If a '—' is taken up, this means no information about this topic is presented.

It can be concluded on the basis of the researched studies that there are differences concerning the factors that are taken up in published comparison LCA studies. The analysis of the LCA studies also shows that the way reuse systems are calculated is not explicitly presented in many of the studies. To get insight into the consequences on the outcome of comparison studies in which certain factors are not included, several cases are analysed and the used mathematical equations are presented. This is taken up in Chapter 3.

An enumeration of the parameters that are taken up in Table 1 in two parts as presented: (1) single-use transport packaging, (2) weight of the item(s), (3) country of production, (4) recycled content, (5) transport distances, (6) vehicle capacity and (7) end of life (EOL) in the first table, followed by (8) washing, (9) return rate, (10) lifespan, (11) pool size, (12) losses method, (13) sensitivity study and (14) equation.

3 | Case Studies on Reuse Systems

Generally, reuse systems differ from single-use systems in several aspects. A reuse system is circular, and after-use steps, such as washing and transport, are required. A single-use system, on the other hand, is linear, and the product is disposed of after use. The products in the system also differ because the design requirements are drawn up for different functions—reuse packaging may need to be sturdier, and other factors such as the materials used to fulfill the requirements can differ. A reuse system also needs different system requirements, for example, washing, additional transport or additional packaging.

Three case studies, in which single-use items are compared with reusable items, are studied in more detail in the following sections. This is done by presenting the case study and the equations used in calculating the impact of a single use and a reuse system. The focus is on the variables that influence environmental impact, not issues like traceability or how the system is organized. It is important to note that these equations are the backbone of an Excel model. An equation is formulated to calculate the impact of one rotation of one product.

3.1 | Case Study—Buckets

In the first case study, the FU is the packaging used to contain 10 L of water or one flower bouquet or plant. The intention of the assessment was to understand if and where a break-even point occurs, to use as a business case; therefore, the systems are assessed over multiple rotations. The single-use and reusable products both are a bucket, which is used to transport flower bouquets to a retailer, with return transport divided over different routes (via flower binder, growers or to storage). The impact of production (including the production up to the distribution centre of the brand owner) and transport in the system is calculated by LCA using cutoff for EoL, based on the inventory information presented in Table 2 and Table 3. The outcomes of this are used in the system calculations presented below and the results in Section 4. The scope of the single-use system is in Figure 1 and for the reuse system in Figure 2. This case study does not include replenishment. The losses that occur in the system are represented in the production of new products in each rotation. The case studies in Sections 3.2 and 3.3 do include replenishment.

The single-use and reusable buckets are both made from PP. The weight of the single-use bucket is 140 g and of the reuse bucket 250 g. In the single-use system, the buckets are sent from the distribution centre to the recycler. The reuse system is considered a partial open-loop system, because it takes place in a retail setting. However, these buckets are standardized and not meant for consumer use, which is why the lifespan is high (and losses are low). It is assumed that of the lost buckets (which is 2% of the total), 50% is recycled and 50% is incinerated in both the single-use and reuse cases. The section marked in the light-colored box in Figure 2 indicates where the product rotation takes place.

The results of the LCA calculations are used as input in a calculation tool, to include the pool size, number of packaging items in rotation and losses per rotation. Results of the system calculations are presented in Chapter 4. This case study does not include replenishment. The losses that occur in the system are represented in the production of new products in each rotation. The case studies in Sections 3.2 and 3.3 do include replenishment.

3.1.1 | Equation Used to Calculate the Impact of one Single-Use Bucket

The equation for one rotation of one product in the single-use system is presented in this section. The impact (***pack***) is comprised of: the production of virgin materials (***vm***), production of the packaging (***p***), transport up to the retailer (***t***) and end of life (***eol***). The percentage of recycled content (***rc***) is taken up to show the effect of this on the calculation. The impact of the production of recycled materials is indicated by ***rm***.

$$Pack\ impact = rc \times rm + (1 - rc) \times vm + p + t + eol \quad (1)$$

3.1.2 | Equations Used to Calculate the Impact of one Reusable Bucket

The equation below is based on the supply chain presented in Figure 2 and is used to calculate the impact of one specific rotation of one bucket in the reuse system with the parameters: pool size (***ps***), packaging items in rotation (***piir***), loss percentage (***l***), the impact of system transport (***st***), the impact of washing (***w***) and the number of rotations (***n***).

$$Reuse\ system\ impact = \frac{(vm + p + t) \times ps}{piir \times n} + packimpact \times l + (w + st) \quad (2)$$

This reuse system is an open loop system. The production, transport and EoL of the new buckets to replace those lost from the system is indicated by ***packimpact*l***. The effect of losses on return transport is not taken up in this equation. This is partly due to the different scenarios that can occur, such as transport directly to the retailer DC, to the brand owner or all the way back to the flower auction.

3.2 | Case Study—Flower box

In the second case study, the FU is the packaging required to hold fresh-cut flowers with a volume of approximately 130 L. The intention of the assessment is to understand if and where the existing reusable box system breaks even with the single-use box system; therefore, the systems are assessed over multiple rotations. The scope of the single-use system is in Figure 3 and that of the reuse system is in Figure 4. The impact of the production (including the transport to the distribution centre of the brand owner) and end-of-life scenario of the box and transport in the system is calculated by LCA using cutoff for EoL. This is based on the inventory information presented in Table 4 and Table 5. The outcomes of this are used in the system calculations presented below and the results in Section 4. Compared to the previous case

TABLE 2 | Inventory information used in the LCA calculation for the packaging used in the single-use system: the single-use bucket.

Component	Weight	Material	Production location	Transport	Transport distance (km)	EoL
Single-use bucket	140	25% rPP 75% PP	Recycled content—RER Injection moulding—NL	EURO6	Material transport: 351 System transport: 340	50% recycling 50% incineration

TABLE 3 | Inventory information used in the LCA calculation for the packaging used in the reuse system: the reusable bucket.

Component	Weight	Material	Production location	Transport	Transport distance (km)	EoL
Reusable bucket	250	25% rPP 75% PP	Recycled content—RER Injection moulding—NL	EURO6	Material transport: 432 System transport: 621	50% recycling 50% incineration

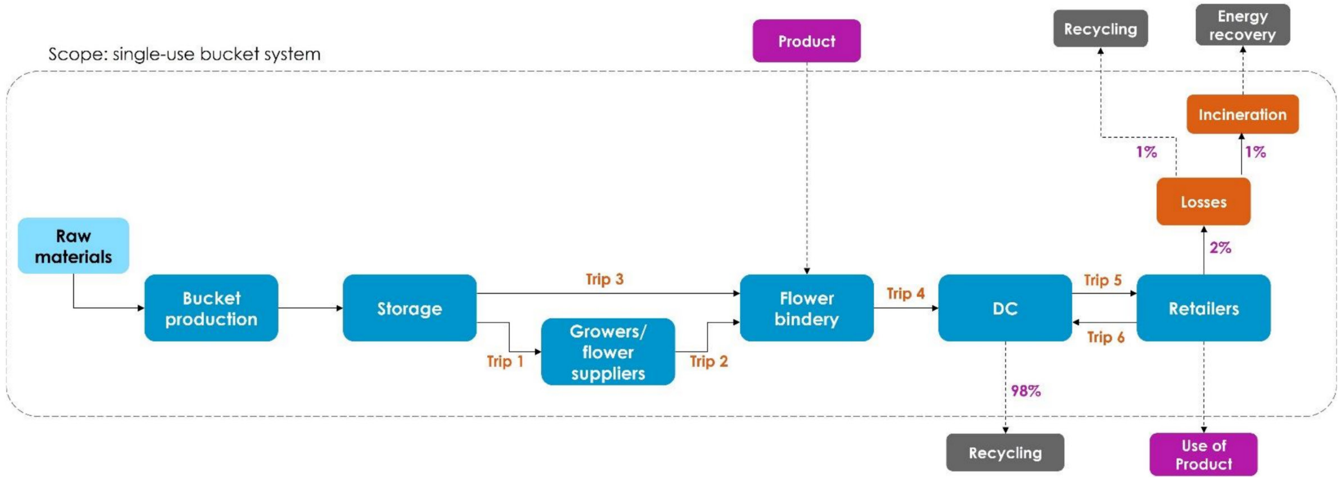

FIGURE 1 | Supply chain of the single-use system for the bucket.

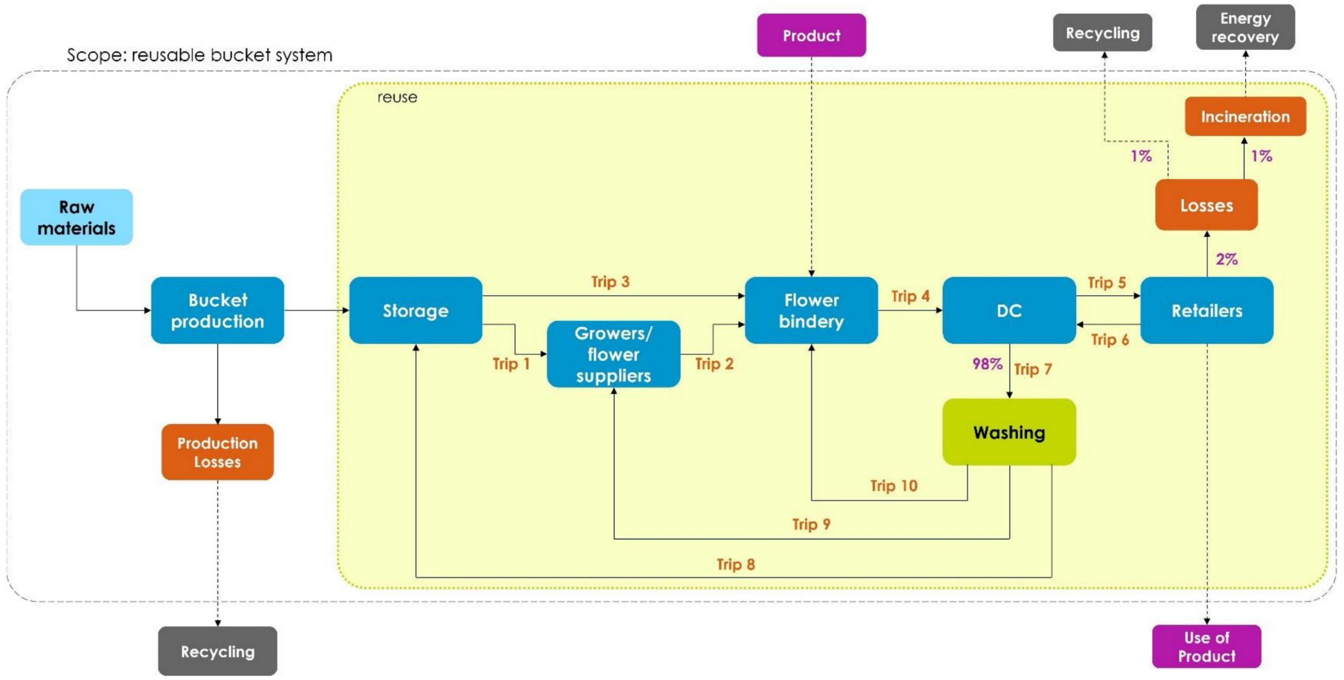

FIGURE 2 | Supply chain of the reuse system for the bucket.

study, this study introduces tertiary packaging used in transport for rotating the reusable products. Another difference compared to the previous case study is the closed-loop system.

The single-use product is a corrugated board box and the reusable product is a corrugated polypropylene box. The corrugated board box weighs 1.793 kg, and the corrugated polypropylene box weighs 1.875 kg. The reuse system is a closed loop system, in which all damaged boxes return to the box manufacturer in France to be recycled and use the recycled material in the new boxes produced to replenish the system. The reuse system takes place between the brand owner location A and B and the final retailer (trip 2 to trip 5). The section marked in the light coloured box in Figure 4 indicates where the product rotation takes place. For the single-use system, recycling is assumed to be the EoL scenario. It is assumed that no washing of the boxes is necessary. In both systems, tertiary packaging items (TPI) are required for the transportation of the boxes, so extra material is used for the transport and therefore must be taken into consideration in the comparison. Tertiary packaging is also required for return transport.

The results of the LCA calculations are used as input in a calculation tool, to include the pool size, number of packaging items in rotation, losses and replenishment in a specific rotation.

3.2.1 | Equations Used to Calculate the Impact of a Single-Use box

The equation for one rotation of one product in the single-use system is presented in this section. The impact is comprised of the production of virgin materials (***vm***), production of the packaging (***p***), transport up to the retailer (***t***) and end of life (***eol***). The percentage of recycled content (***rc***) is taken up to show the effect of this on the calculation. The impact of the production of recycled materials is indicated by ***rm***.

$$pack = rc \times rm + (1 - rc) \times vm + p + t + eol \quad (3)$$

3.2.2 | Equations Used to Calculate the Impact of the Reusable box

The equations below are used to calculate the impact of a box in a reuse system based on the case study in Section 3.2. The included parameters are: pool size (***ps***), packaging items in rotation (***piir***), loss percentage (***l***), the impact of transport in the system ***t1*** and ***t2345*** and the number of rotations ***n***. The impact of production, transport and EoL of tertiary packaging is included as well, for which there are three tertiary packaging items (***tp***). The number at which boxes need to be produced to replenish the pool due to losses is the replenishment number (***rn***). The initial pool size minus losses is the *boxes remaining in the pool*.

Where *initial pool size > boxes remaining in the pool*, the following equation is used for impact calculations per box per rotation after n rotations.

$$impact1 = \frac{ps \times (rc \times rm + (1 - rc) \times vm + p + t)}{piir \times n} + eol \times l + (1 + l) \times t1 + tp + t2345 \quad (4)$$

In the case where *initial pool size =< boxes remaining in the pool*, the following equation is used to calculate the impact per box per rotation after n rotations.

$$impact2 = \frac{(rc \times rm + (1 - rc) \times vm + p + t) \times (ps + (ps - rn))}{piir \times n} + eol \times l + (1 + l) \times t1 + tp + t2345 \quad (5)$$

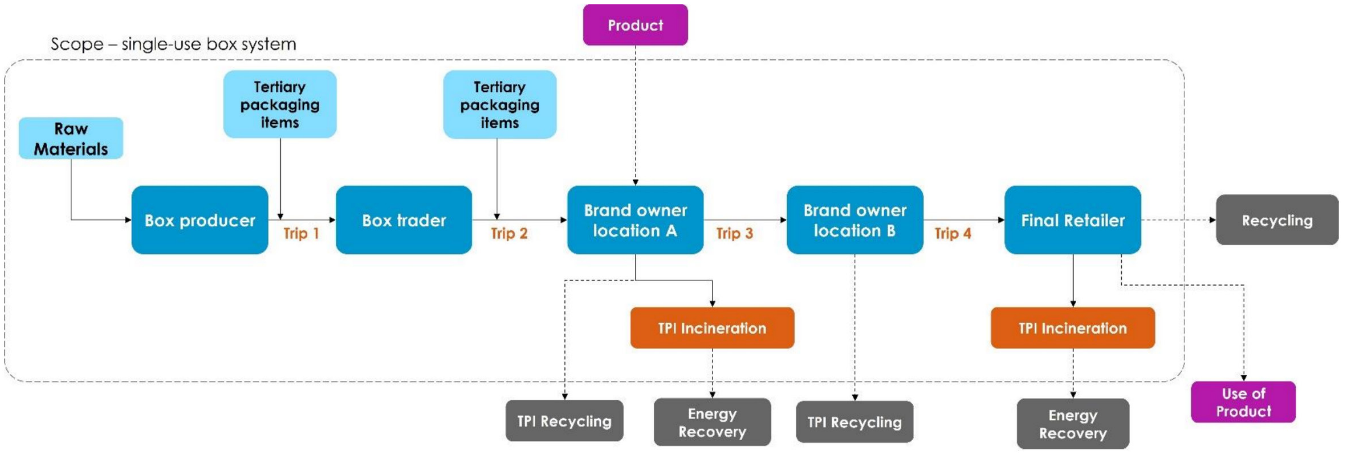

FIGURE 3 | Supply chain of the single-use system for the corrugated cardboard box.

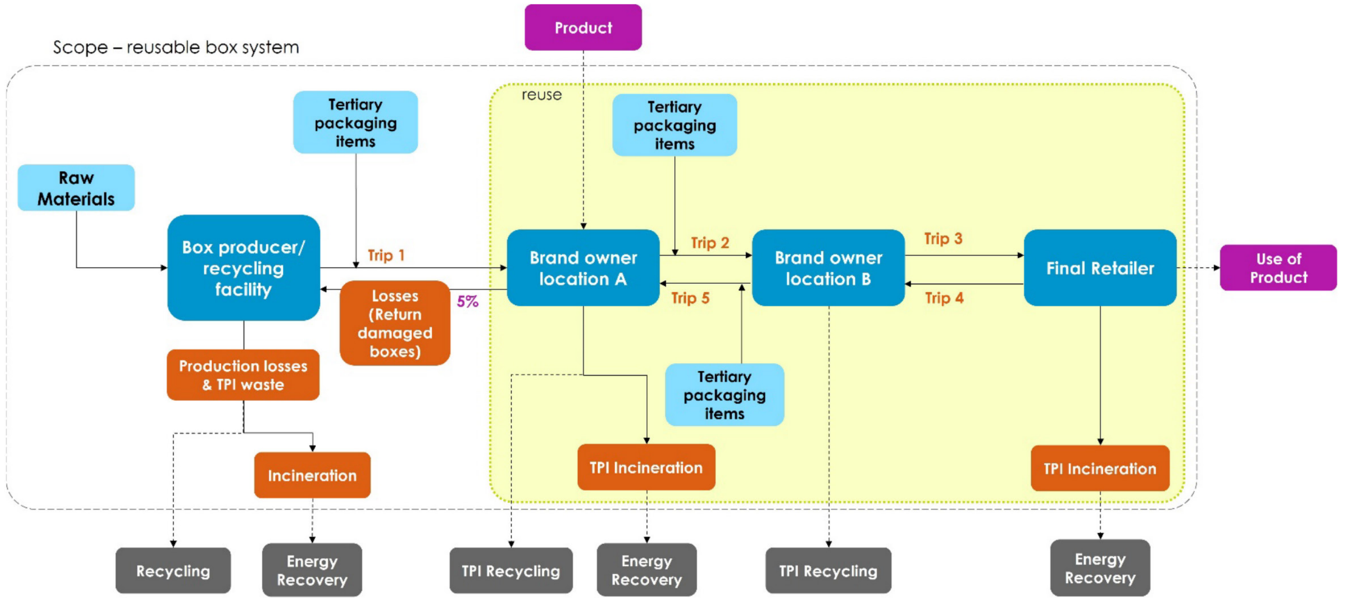

FIGURE 4 | Supply chain of the reuse system for the foldable corrugated plastic box.

This reuse system is a closed loop system. The transport of boxes from the brand owner to the manufacturer is the transport related to the damaged boxes that need to be recycled, which is indicated in the equations above by ***l*t1***. This is additional transport to the transport included in the impact of the packaging (***pack***) parameter.

3.3 | Case Study—Reusable Bottle

The reuse system in the third case study focuses on single-use and reusable beverage bottles. The FU in this case study is the packaging required to contain 1 L of beverage. The intention of the assessment was to understand if the reusable system should be implemented based on a break-even point; therefore, the systems are assessed over multiple rotations. For this case, only pilots have been done. The impact of both systems (including production, EoL and transport to the DC of the brand owner) and transport in the system is calculated by LCA using cutoff for EoL. This is based on the inventory information presented in Tables 6 and 7. The outcomes of this are used in the system calculations presented below and the results in Section 4. The scope of the single-use system is in Figure 5 and of the reuse system in Figure 6. The products in this case study are slightly more complex, with additional single-use components in a reuse system. Furthermore, the difference with the previous case study is the high loss percentages and the very large weight difference between the single-use and reusable products. Additionally, the single-use system has an existing deposit return system (DRS).

The packaging used in the single-use system is a single-use PET bottle and a single-use label and cap. The packaging used in the reuse system is a reusable glass bottle (RGB) and a single-use label and cap. The weight of the single-use PET bottle is 32 g, and the weight of the RGB is 933 g. Secondary

TABLE 4 | Inventory information used in the LCA calculations for the packaging components used in the single-use system: the cardboard box and tertiary packaging used in transport.

Component	Weight	Material	Production location	Transport	Transport distance (km)	EoL
Cardboard box	1793 g	Cardboard	Testliner, flute—NL Kraftliner—SE	EURO5 truck Train Sea freight	Material transport: 100 + 1320 (train) + 1124 (sea) System transport: 1097	100% recycling
Trip 1 tertiary packaging						
Tertiary packaging—cardboard sheet *(1 per 9 boxes)*	4790 g	Cardboard	Corrugated board box production—RER	EURO5 Truck	Material transport: 250 System transport: 80	100% recycling
Tertiary packaging—wrap film *(1 per 100 boxes)*	114 g	LDPE	Packaging film production—GLO	EURO5 Truck		100% recycling
Tertiary packaging—bundle strap *(1 per 2.5 boxes)*	1.96 g	PP	Extrusion—RER	EURO5 Truck		100% incineration
Tertiary packaging—pallet strap *(1 per 50 boxes)*	42 g	PP	Extrusion—RER	EURO5 Truck		100% incineration
Tertiary packaging—wooden plate *(1 per 100 boxes)*	4910 g	Hard fibreboard	Fibreboard production—RER	EURO5 Truck		100% recycling
Trip 2 tertiary packaging						
Tertiary packaging—pallet corner *(1 per 5 boxes)*	365.4 g	Linerboard	Linerboard production—RER	EURO5 Truck	Material transport: 250 System transport: 37	100% recycling
Tertiary packaging—nylon strap *(1 per 0.55 boxes)*	13.99 g	Nylon	Extrusion—RER	EURO5 Truck		100% incineration
Tertiary packaging—wrap film *(1 per 20 boxes)*	114 g	LDPE	Packaging film production—GLO	EURO5 Truck		100% recycling
Tertiary packaging—cardboard sheet *(1 per 9 boxes)*	4790 g	Cardboard	Corrugated board box production—RER	EURO5 Truck		100% recycling

TABLE 5 | Inventory information used in the LCA calculations for the packaging components used in the reuse system: the reusable corrugated plastic box and tertiary packaging used in transport.

Component	Weight	Material	Production location	Transport	Transport distance (km)	EoL
Reusable corrugated plastic box	1875 g	68% virgin PP 20% rPP 10% filler 2% masterbatch	Recycling—FR Extrusion—FR	EURO5 truck	Material transport: 567 System transport: 2623	100% recycling
Trip 1 tertiary packaging						
Tertiary packaging - pallet straps *(1 per 52.5 boxes)*	100 g	PET	Extrusion—RER	EURO5 Truck	Material transport: 250 System transport: 663	100% incineration
Tertiary packaging—wrap film *(1 per 105 boxes)*	250 g	LDPE	Packaging film production—GLO	EURO5 Truck		100% recycling
Tertiary packaging—pallet corner *(1 per 26.25 boxes)*	161.7 g	PP	Extrusion—FR	EURO5 Truck		100% recycling
Trip 2 tertiary packaging						
Tertiary packaging—nylon strap *(1 per 0.5 boxes)*	13.99 g	Nylon	Extrusion—RER	EURO5 Truck	Material transport: 250 System transport: 680	100% incineration
Tertiary packaging—pallet corner *(1 per 5 boxes)*	365.4 g	Linerboard	Linerboard production—RER	EURO5 Truck		100% recycling
Tertiary packaging—wrap film *(1 per 20 boxes)*	114 g	LDPE	Packaging film production—GLO	EURO5 Truck		100% recycling
Tertiary packaging—cardboard sheet *(1 per 9 boxes)*	4790 g	Cardboard	Corrugated board box production—RER	EURO5 Truck		100% recycling
Trip 4 tertiary packaging						
Tertiary packaging - pallet straps *(1 per 52.5 boxes)*	100 g	PET	Extrusion—RER	EURO5 Truck	Material transport: 250 System transport: 300	100% incineration
Tertiary packaging—wrap film *(1 per 105 boxes)*	250 g	LDPE	Packaging film production—GLO	EURO5 Truck		100% recycling

packaging is included for both systems. Six single-use PET bottles are grouped by shrink film that weighs 13 g. Six RGB are grouped by an HDPE crate that weighs 1.3 kg. The packaging for one FU is comprised of the bottle, a cap, a label and 1/6th of the secondary packaging and a share of tertiary packaging. Tertiary packaging is only included in the single-use system, namely pallet wrap and a single-use big-bag for return transport of the bottles.

The study assumes an open loop system, where damaged or lost RGBs are assumed to be recycled and incineration is assumed for the cap and label at end of life. Losses occur at the consumer; additionally, damages occurring or detected at the filler are seen as losses. Due to the losses, replenishment of the bottles rotating in the system is required. The pallet load is relevant in this case study as well. The weight of the bottle plays a role in the number of bottles that can be transported per pallet. In this case, double the single-use bottles can be transported on a pallet compared to the RGB, resulting in double the transport for the RGB. The section marked in the light-coloured box in Figure 6 indicates where the product rotation takes place. The washing energy, water and cleaning detergent consumption are presented in Table 8.

The results of the LCA calculations are used as the input in a calculation tool to include the pool size, the number of packaging items in rotation, losses and replenishment per rotation.

3.3.1 | Equation Used to Calculate the Impact of a Single-Use Bottle

The equation for one rotation of one product in the single-use system is presented in this section. The impact is comprised of the production of virgin materials (***vm***), production of the packaging (***p***), transport up to the retailer (***t***) and end of life (***eol***). The percentage of recycled content (***rc***) is taken up to show the effect of this on the calculation. The impact of the production of recycled materials is indicated by ***rm***.

$$pack = rc \times rm + (1 - rc) \times vm + p + t + eol \quad (6)$$

TABLE 6 | Inventory information used in the LCA calculations for packaging components used in the single-use system: the bottle, cap, label and shrink film and the tertiary packaging used in transport trips.

Component	Weight	Material	Production location	Transport	Transport distance (km)	EoL
Bottle	32.5 g	90% rPET, 10% PET	PET drying and preform injection moulding—BE Blow moulding—NL	EURO6 truck	Material transport: 405 System transport: 275	90% recycling 10% incineration
Cap	1.95 g	HDPE	Injection moulding—DE	EURO6 truck	Material transport: 1319 System transport: 275	100% incineration
Label	0.377 g	Foamed PP	Extrusion and Printing - DE	EURO6 truck	Material transport: 1390 System transport: 275	100% incineration
Shrink film *(per 6 bottles)*	13.52 g	LDPE	Extrusion—BE	EURO6 truck	Material transport: 178 System transport: 275	100% recycling
Trip 1 tertiary packaging						
Tertiary packaging - pallet wrap *(per 840 bottles)*	100 g	LDPE	Extrusion—RER	EURO6 truck	Material transport: 250 System transport: 275	100% recycling
Trip 3 tertiary packaging						
Tertiary packaging—bag *(per 380 bottles)*	455.83 g	LDPE	Extrusion—RER	EURO6 truck	Material transport: 250 System transport: 275	100% recycling

TABLE 7 | Inventory information used in the LCA calculations for packaging components used in the reuse system: the bottle, label, cap and crate.

Component	Weight	Material	Production location	Transport	Transport distance (km)	EoL
Bottle	933 g	White container glass (62.5% glass cullet)	Blow moulding—NL	EURO6 truck	Material transport: 390 System transport: 512	100% recycling
Cap	2.701 g	PP	Injection moulding—DE	EURO6 truck	Material transport: 705 System transport: 512	20% incineration 80% recycling
Label	0.890 g	Paper	Paper production—DE, printing/conversion—FR	EURO6 truck	Material transport: 2027 System transport: 512	100% incineration
Crate *(per 6 bottles)*	1321 g	HDPE	Injection moulding—BE	EURO6 truck	Material transport: 362 System transport: 512	Assumed 60x reusable, 100% recycling

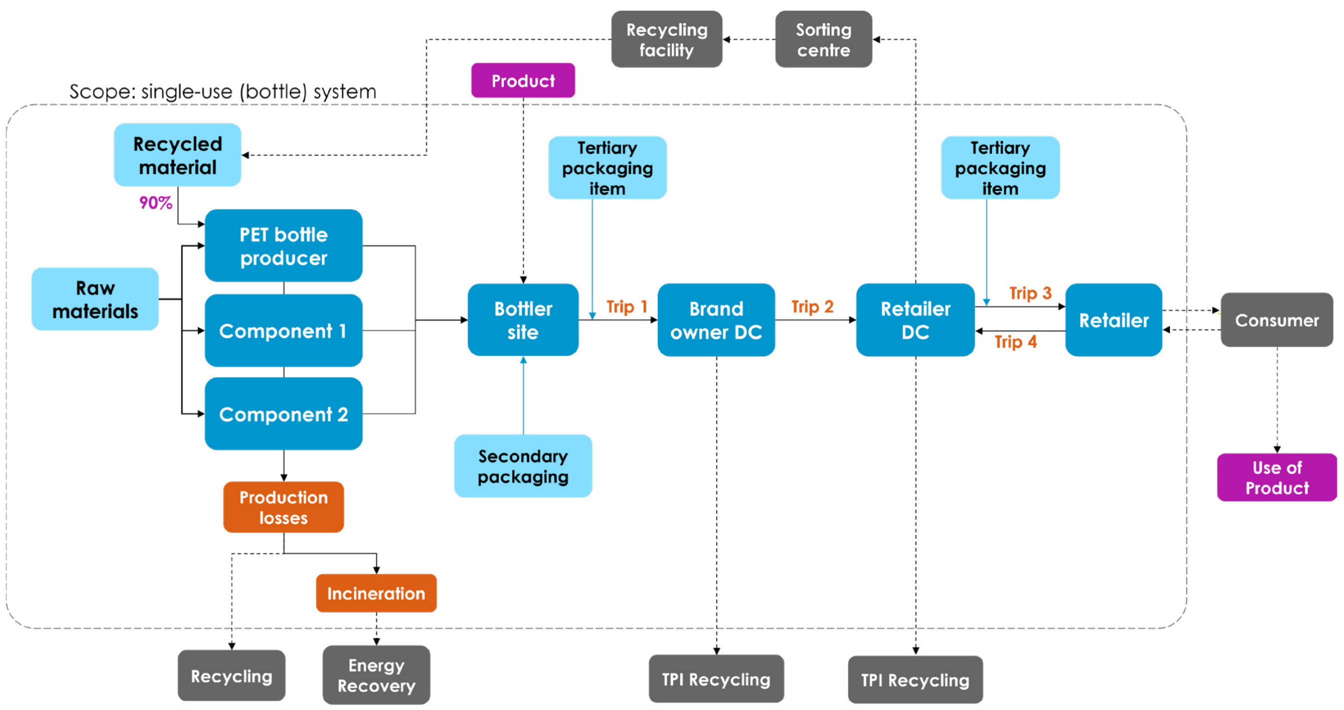

FIGURE 5 | Supply chain of the single-use system for the PET bottle.

3.3.2 | Equations Used to Calculate the Impact of the Reusable Glass Bottle

For the reusable bottle case study described in Section 3.3, the equations described below are based on the supply chain as introduced in Figure 6.

The equations below are used to calculate the impact of a bottle in the reuse system with the parameters pool size *(**ps**)*, packaging items in rotation *(**piir**)*, loss percentage at the consumer level *(**cl**)*, loss percentage due to damage detected at the bottler facility *(**dl**)*, the impact of washing (***w***) and the impact of the system transport *(**t123**, **t45**, **t6**)*. The impact of the production and transport up to the bottler facility and end of life of the two single-use components ***c1*** and ***c2*** is added separately. If there are additional single-use components to the packaging system, they can be added similarly. The number of rotations (***n***) is a variable parameter. The number at which new bottles need to be produced to replenish the pool due to losses is the replenishment number (***rn***).

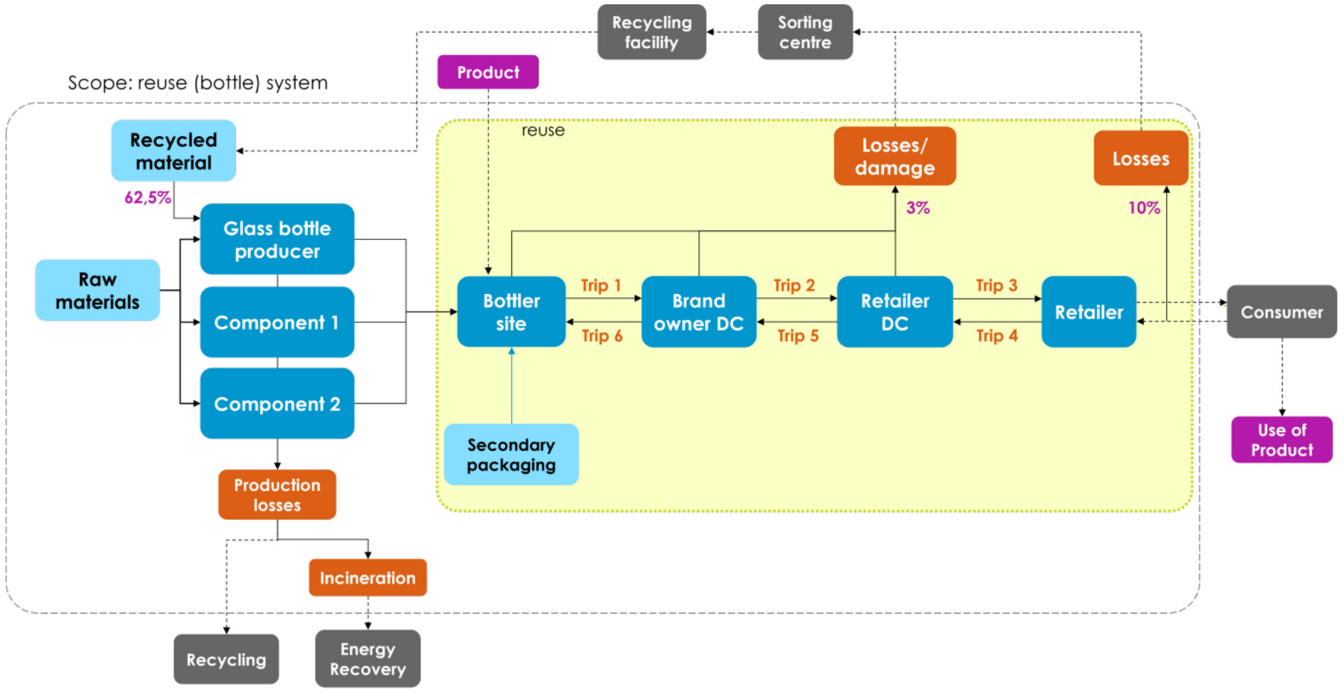

FIGURE 6 | Supply chain of the reuse system for the reusable bottle.

TABLE 8 | Inventory information used in the LCA calculations for the washing process of the RGB.

Process	Amount per bottle
Electricity	0.00878 kWh
Water	0.3 L
Detergent (caustic soda)	0.006 g

Where *pool size* > *bottles remaining in the pool*, the following equation is used for impact calculations per bottle per rotation after *n* rotations:

$$rs1 = \frac{(rc \times rm + (1-rc) \times vm + p + t) \times ps}{piir \times n} + eol \times l_{c1,c2} + c1 + c2 + w + t123 + (1-cl) \times t45 + (1-(cl+dl)) \times t6 \quad (7)$$

In the case where *pool size* =< *bottles remaining in the pool*, the following equation is used to calculate the impact per bottle per rotation after n rotations is calculated using the following equation:

$$rs2 = \frac{(rc \times rm + (1-rc) \times vm + p + t) \times (ps + (ps - rn))}{piir \times n} + eol \times l_{c1,c2} + c1, c2 + w + t123 + (1-cl) \times t45 + (1-(cl+dl)) \times t6 \quad (8)$$

The HDPE crate for the RGB is a reusable crate and is assumed to last 60 rotations. It is only taken up in transport and for the production of a pool size in the first rotation.

This reuse system is an open loop system. The transport of the bottles back to the filling plant is ***t4***, ***t5*** and ***t6***, which is decreased by the damaged or lost bottles with ***t45*(1-cl)*** and ***(1-(cl+dl))*t6***. These sections of the equation ensure that the impact of the return transport does not include the transport of lost or damaged bottles. It is assumed that the lost or damaged bottles are recycled; this is excluded due to the cutoff approach. If they were incinerated, the impact of the incineration of the lost bottles should be included in the equations.

3.4 | Trends in Equations—Is one Master Equation Possible?

From the supply chains presented in Section 3 and the equations previously presented, it becomes clear that every reuse system requires its own formulation of equations. There are multiple similarities. Factors such as pool size and the production of the product are divided over the number of packaging items in rotation and the number of rotations. Factors such as single-use components in a reuse system, transport in the system, end of life due to loss, and washing are not divided over the number of packaging items in rotation and the number of rotations. It is important to consider the meaning of the parameters, such as what is included in the transport in the system or in the impact number of a product. There are occasionally other factors that need to be considered, such as additional (tertiary packaging) components or the location where certain losses occur in the supply chain, and therefore their related transport. This is, however, case-specific. Some of the example cases do take those types of situations up to show how it can be done.

4 | Effect of Parameters

This section explores how the environmental impact of a reuse system is affected by certain parameters, based on the case studies and its equations introduced in Chapter 3 and findings from literature research as in Table 1. The difference between the types of parameters introduced in Section 4.1 is shown. Previously mentioned factors that are evaluated are parameters pool size, replenishment and losses included in this. An impact difference or contribution of a component (of a packaging item or system) to the total of > 10% is seen as significant. If in this paper an effect is called 'significant', this means with an effect of more than 10%.

4.1 | Parameter Types

The type of parameters can be categorized as constant or variable. The constant parameters are those that are based on numbers calculated in life cycle assessment and are independent from the number of packaging items in rotation and are constant in each rotation. These are parameters such as washing, single-use components, transport in the system, etc. The variable parameters are those that are divided over the number of rotations. These are parameters such as pool size, number of packaging items in rotation or loss percentages.

In certain cases, it may be relevant to take up more parameters in a tool or calculation, such as the weight of a product. The impact parameters should be made available for this change as well. Examples of parameters related to weight are system transport, packaging impact and perhaps other factors such as washing.

4.1.1 | Factors Distributed Over System

The impact of one product can be calculated by normal LCA, taking up transport up to the first step in the system, raw material production, conversion and end of life. System variables such as pool size, number of packaging items in rotation, number of rotations and losses eventually determine the actual impact of the production and EoL of the packaging.

The pool size is the number of packaging items in a system that are initially produced to keep the system running for a certain timespan, taking effects such as losses and peak moments into account. In the conference report Environment and Packaging in 1992, a case of reusable packaging is shown from German Mineral Springs. A standardized bottle from white glass of 0.7 L with a classic shape is used for packing water. Because of the high level of standardization in the sector, 1.4 billion bottles are in circulation. To sustain the returnable system, a total of 14 billion bottles is necessary [30]. Bottles must be present at every station in the system: at the filler, the supermarket and the consumer. To avoid shortages or overcapacities, bottles are occasionally interchanged in considerable quantities to other participating businesses. This case description shows what quantities are sometimes needed for a reuse system. The pool size is determined by factors such as demand, loss rate and scale of the system, but also the size, weight and storage time of the items. The pool size can sometimes be difficult to determine if a system is not yet in place. Calculations can be based on the cycle time and peak volume [31]. However, this paper does not focus on how pool size must be calculated. When a system is already in place, such as for beer bottles [32], the reuse number can be calculated more accurately.

The replenishment number is the point at which the remainder of the pool is replenished. It is the number of products that is

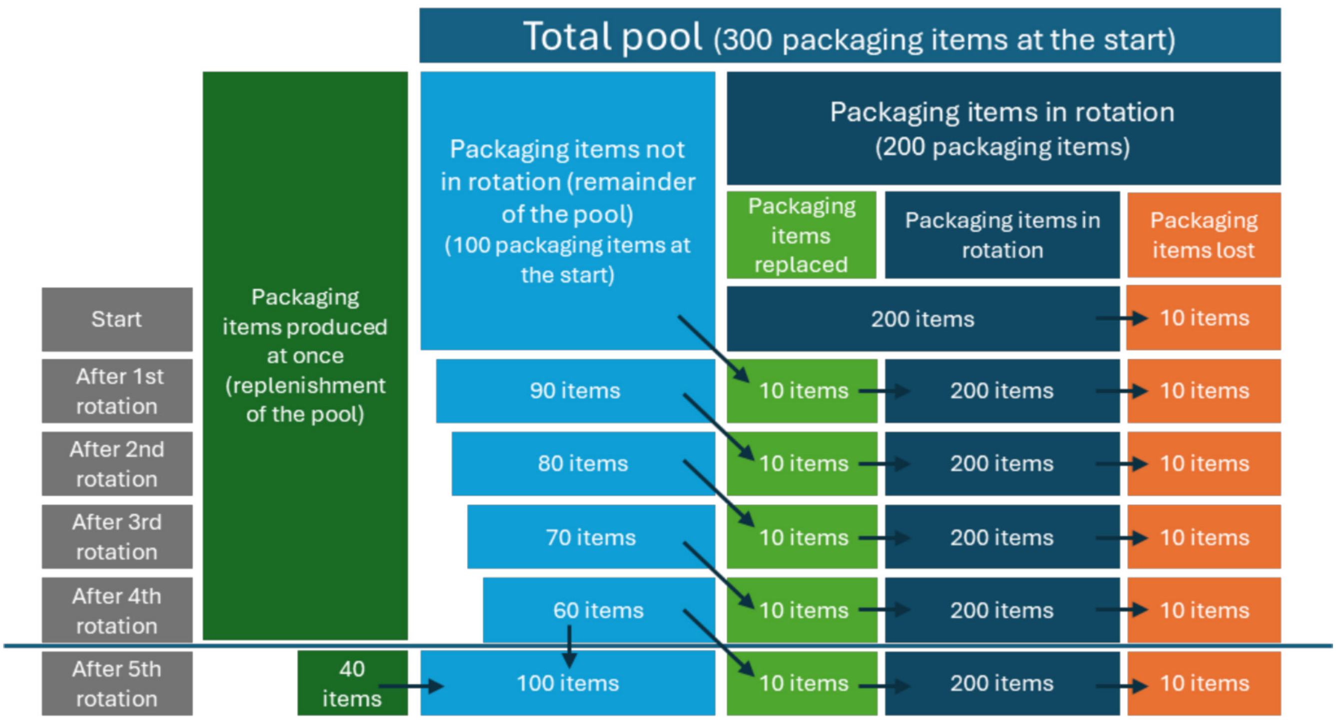

FIGURE 7 | Schematic overview of replenishment.

required to increase the pool size, for example, back to its starting level; see Figure 7. The pool decreases over time as the losses in the system are replenished. The replenishment number can be influenced by the minimum order quantity or a certain number of products required to increase system size for peak moments. In calculating the impact, this means that a number of products

TABLE 9 | Values used to illustrate the effect of RGB weight in four scenarios of the reusable bottle system.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Initial pool size	200	200	200	200
System size	100	100	100	100
Replenishment	150	150	150	150
Losses	4%	4%	4%	4%
Bottle weight (g)	933[a]	750	600	450

[a]Original weight as presented in the inventory table.

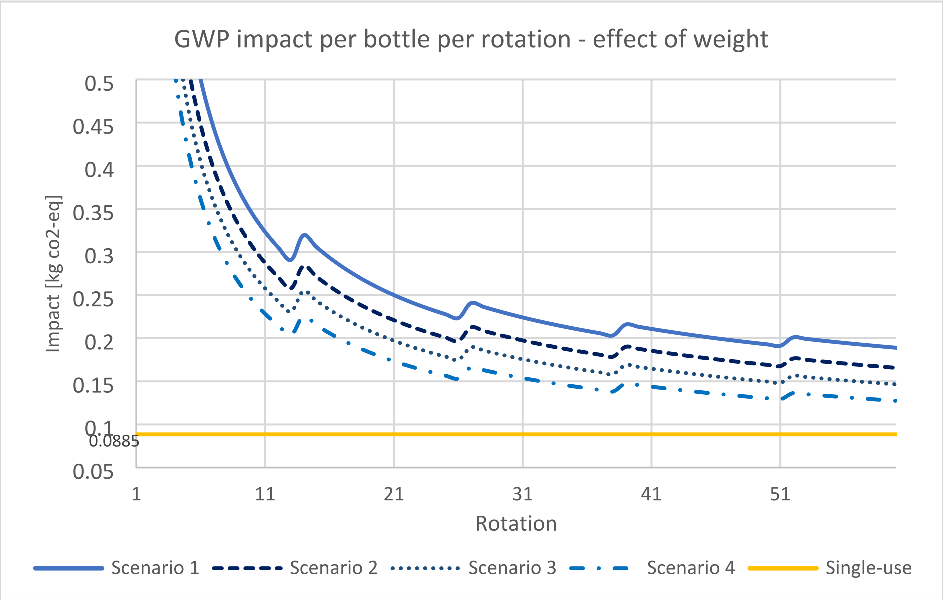

FIGURE 8 | The effect of bottle weight on the impact of the reusable bottle system.

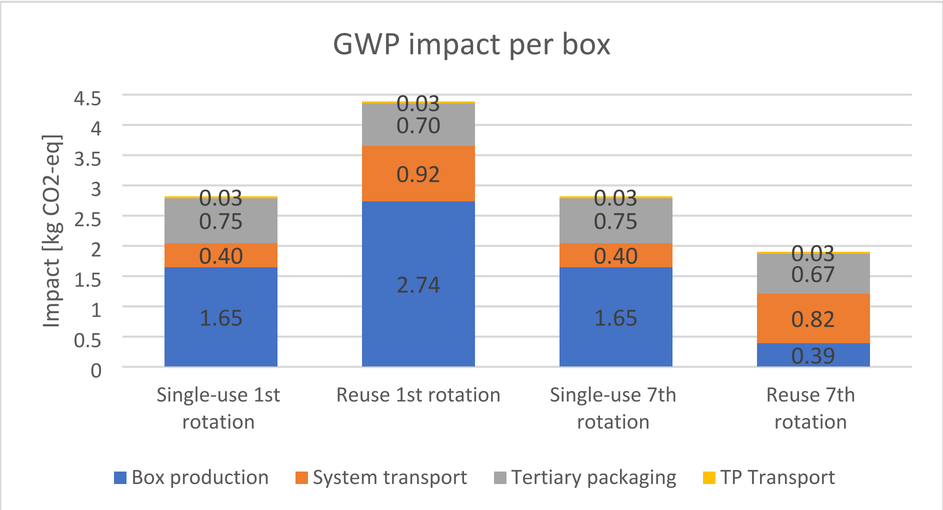

FIGURE 9 | GWP impact per single-use and reusable box in the 1st and 7th rotations.

are produced again after a number of rotations. The impact of replenishment is taken up in the impact of the specific rotation and divided over all previous rotations.

The return rate is another parameter that is distributed over the system, and it directly influences the rotation at which replenishment occurs (and therefore the number of times it occurs within the lifespan of a product). If the losses from a system are large, then replenishment takes place more often and/or is larger in size. Losses are also directly correlated to the impact of the end of life.

4.1.2 | Constant Factors per Rotation

There are certain parameters in a reuse system of which the impact is constant over each rotation, and so do not depend on the number of packaging items in rotation, pool size, number of rotations or losses. These are impacts such as washing, system transport and single-use components for a reusable packaging item. Single-use components can be caps or labels used on bottles and single-use secondary or tertiary packaging items used in system transport.

An LCA study is one of the first steps in calculating the impact of a reuse system. The factors mentioned above can already be an indication in a system comparison between reuse and single-use. For example, there will never be a breakeven point if the impact of the single-use product is equal to or lower than the impact of the constant factors in the reuse system. This can be seen as a screening step.

4.2 | Effect of Weight of the Reusable Product

For the case study of the reusable bottle system (see Section 3.3), the impact of the weight of the RGB on the possible breakeven point is evaluated. Therefore, the four reuse system scenarios are compared to the constant impact of the single-use system, which is calculated as presented in Equation 6, with the input presented in the inventory tables. Four scenarios are laid out, for which the RGB weight is varied, but all other parameters remain constant. The scenarios are depicted in Table 9 below, and the corresponding effect is shown in Figure 8. The impact of

TABLE 10 | Values used to illustrate the effect of pool size in two scenarios.

	Scenario 1	Scenario 2	Scenario 3
Initial pool size	200	400	100
Packaging items in rotation	100	100	100
Replenishment	N/A	N/A	N/A
Losses	13%	13%	13%

TABLE 11 | Values used to illustrate the effect of pool size in three scenarios for the reusable box system.

	Scenario 1	Scenario 2	Scenario 3
Initial pool size	200	400	100
Packaging items in rotation	100	100	100
Replenishment	N/A	N/A	N/A
Losses	5%	5%	5%

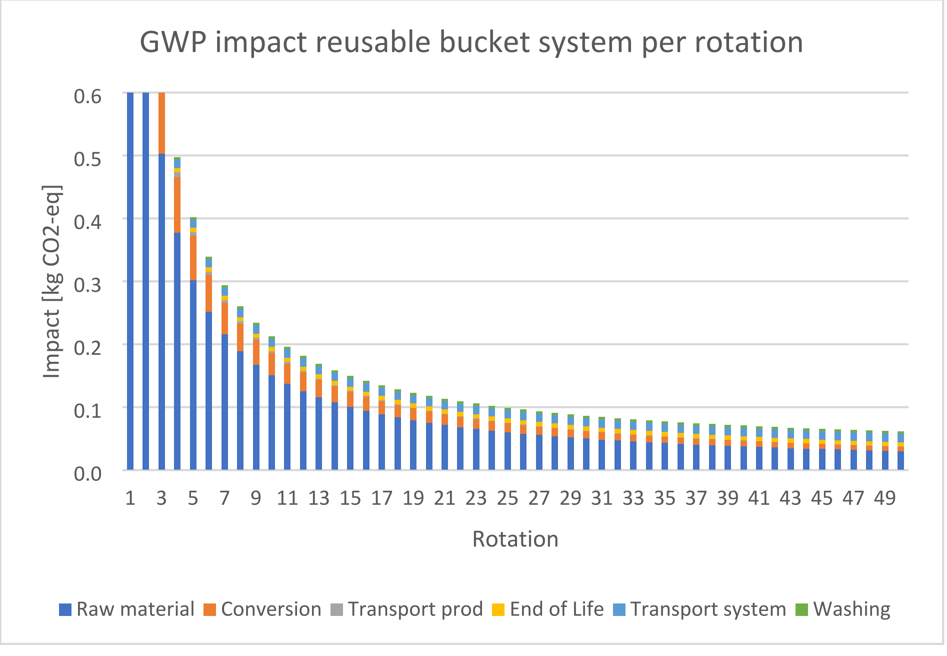

FIGURE 10 | GWP impact per bucket split in life cycle stages of a PP bucket for a lifespan of 50 rotations, pool size of 500 000 buckets (in the reuse system), packaging items in rotation 160 000, losses 2%—includes washing and system transport.

scenario 2 compared to scenario 1 is a decrease of about 12%, while the RGB weight decreases by 20%. The impact of scenario 3 compared to scenario 1 is a decrease of about 22%, while the RGB weight decreases by 36%. The impact of scenario 4 compared to scenario 1 is a decrease of about 30% while the RGB weight decreases by 52%.

The RGB weight determines the impact in all transport stages, the production of the packaging items in the pool and, to some extent (but not taken up in the variables in Table 9) the lifespan. The effects of lower RGB weight will, for example, positively affect the impacts of production and transport. However, decreasing the RGB weight might also affect the quality of the bottles in a negative way (e.g., by breaking more easily), leading to a higher loss percentage in the supply chain and reuse system. The possible change in pallet load due to changes in RGB weight is not taken up in the results in Table 9 and Figure 8 below.

The RGB weight has a significant impact on the impact of a system, but in this case study it does not influence the breakeven point because no breakeven point is found. However, in other cases it may have a big impact on the breakeven and in which rotation it occurs.

Product design and its related use are not taken up in this study, apart from the evaluation of weight. Product and system design

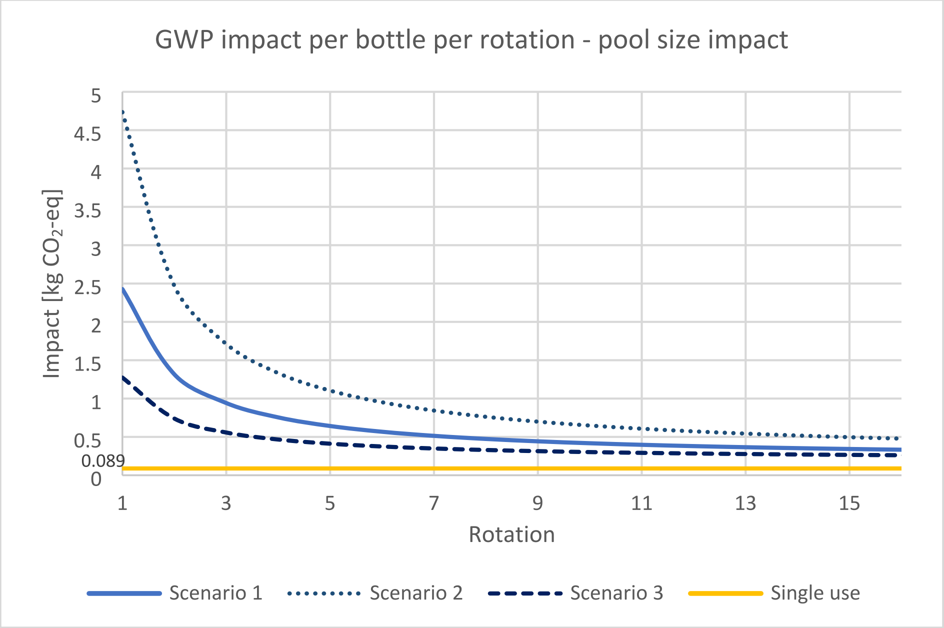

FIGURE 11 | The effect of pool size on the impact of the reusable bottle system.

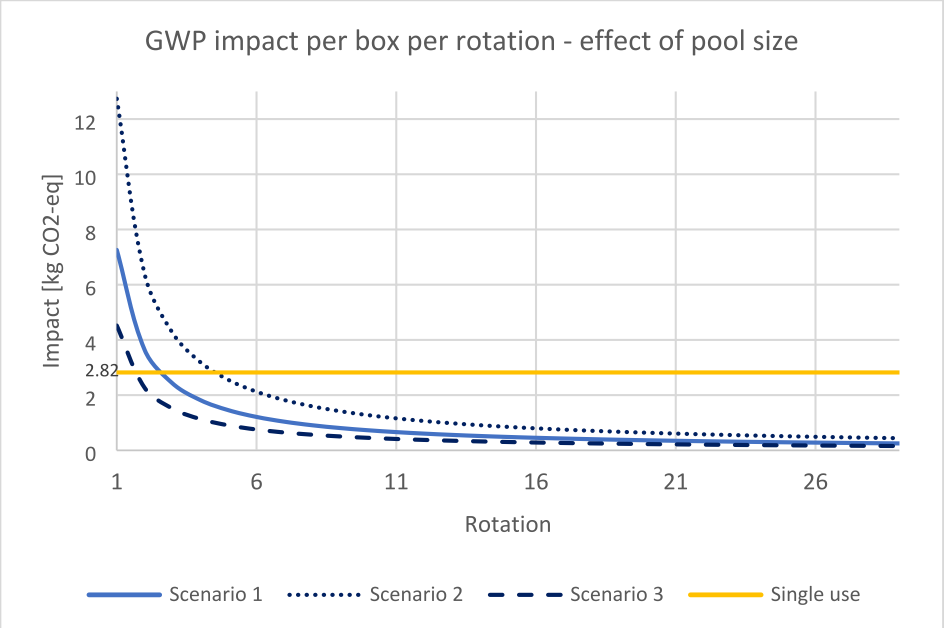

FIGURE 12 | The effect of pool size on the impact of the reusable box system.

may, however, be important factors in the determination of the loss and breakage rates or general lifetime of a (reusable) product [33].

4.3 | Effect of Constant Parameters Versus Variable Parameters

The constant parameters are not rotation dependent. The relative contribution of the constants to the total impact of a rotation is different per rotation, but the relative contribution does not change much after a certain rotation because the reuse system impact has asymptotic behaviour. This is illustrated in Figures 9 and 10 below. This effect is explained by the first part of the Equation 2 in Section 3.1.2: $\frac{(vm+p+t)\times ps}{piir\times n.}$

The top of the equation is the effect of raw materials, production and transport for the pool size of the reuse system. The bottom is the packaging items in rotation and the number of rotations. It illustrates not only the pool size but also the distribution over the number of rotations and the number of products in rotation. Consequently, as the number of rotations increases, the impact of the production, etc. decreases.

The impact of the single-use and reuse systems in the 1st and 7th rotation of the case study regarding flower boxes (see Section 3.2) is presented in Figure 9. The impact of the tertiary packaging in the reusable box system (includes raw materials, production, EoL) is 16% in the first rotation, but 35% in the 7th rotation. The differences in reuse system 'constant' impact relate to the losses, because transport or tertiary packaging for lost products is not taken up. Overall, the impact of the reusable box in the 1st rotation is 57% higher than the impact of the reusable box in the 7th rotation, and the impact of the tertiary packaging is constant. However, the relative impact of tertiary packaging is higher in the 7th rotation, because the impact of the production of the reusable box is divided over the number of rotations and the system. In this specific case, the GWP impact of tertiary packaging on the total reuse system impact has a significant impact.

TABLE 12 | Values used to illustrate the effect of replenishment in three scenarios for the reuse system.

	Scenario 1	Scenario 2	Scenario 3
Initial pool size	200	200	200
Packaging items in rotation	100	100	100
Replenishment	150	Direct	N/A
Losses	13%	13%	13%

The GWP impact of a virgin PP bucket per rotation in a reuse system (see the case study in Section 3.1) is shown in Figure 10 below. It shows that the EoL, washing and transport are equal for each rotation. Furthermore, the impact of the production, conversion and related transport is divided over the system and number of rotations. The differences between impact per rotation become smaller as the number of rotations increases, so if the washing and system transport impacts combined are already higher than a single-use impact, the systems will never break even. In this specific case, the rotation determines if the impact of the constant factors is significant.

4.4 | Effect of Pool Size

The case studies for boxes (see Section 3.2) and bottles (see Section 3.3) were evaluated to clarify the impact of the pool size. For both systems, three scenarios are analyzed with pool sizes of 100, 200 and 400 reusable items and 100 packaging items in rotation. For the RGBs, the loss rate is set at 13%, whereas for the boxes, the loss rate is 5%. An overview of the relevant parameters is given in Tables 10 and 11. The reuse system scenarios are compared to the constant impact of the single-use system, which

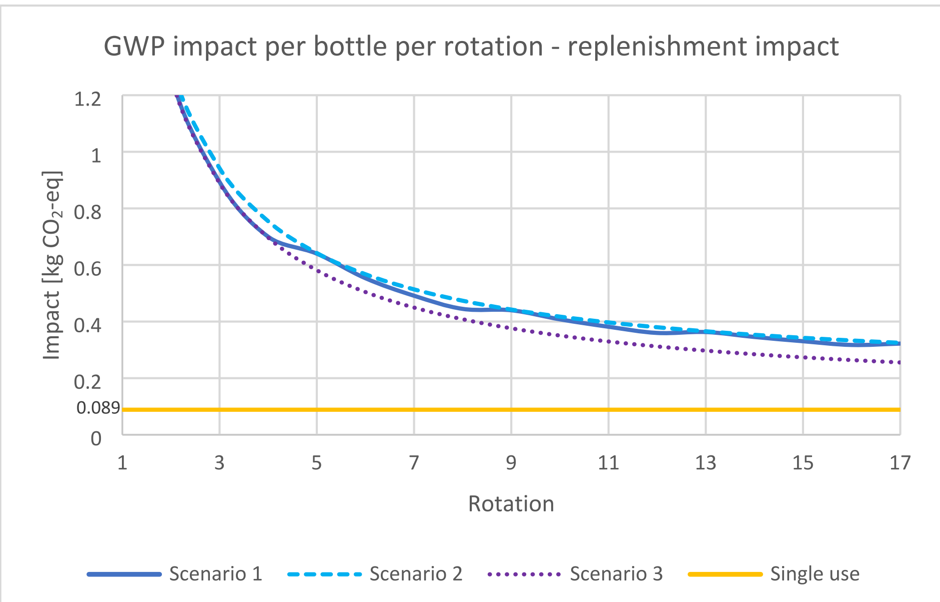

FIGURE 13 | The effect of replenishment on the impact of the reusable bottle system.

is calculated as presented in Equation 3 (boxes) and Equation 6 (bottles), with the input presented in the inventory tables. The corresponding results from the modeling are presented in Figures 11 and 12, which show a sizeable influence of the pool size in the initial stages.

The difference in losses between scenario 2 and scenario 1 (so a pool size four times larger) decreases from approximately 95%–42% over 16 rotations. The difference in losses between scenario 3 and scenario 1 (pool size two times larger) decreases from approximately 48%–21%. The breakeven point shifts from rotation 2 to rotation 4 depending on the pool size. In short, the size of the pool has a significant difference on the impact of a reuse system, and from Figure 12, it becomes clear that it can mean the difference in the rotation at which breakeven with the single-use system occurs. The total pool size has to be balanced to promote the chances of breakeven.

4.5 | Effect of Replenishment

The approach for the calculations in case studies 3.1 (buckets) and 3.3 (bottles) differs. They are both open-loop systems, have a pool size, packaging items in rotation, losses, washing, production and transport in the system. However, the replenishment is taken up differently. Replenishment is taken up in each rotation in the reusable bucket case study, where losses from the system are produced in each rotation. In the RGB case study, losses do occur every rotation, but the replenishment of the pool is only taken up at the rotation where the bottles remaining in the pool are below a certain number. This essentially means that a larger number of products will be produced at the same time than if the pool were to be replenished each rotation. This difference was also explained in Section 4.1.1.

The effect of the in- or exclusion of RGB replenishment scenarios in Table 12 on the GWP impact in the reusable bottle case is shown in Figure 13. Including it ensures that the system is replenished at a certain rotation, depending on the loss percentage. The zig-zag behavior of the impact with replenishment comes from the production of the lost bottles at the specific rotation at which they are replenished. Excluding it ensures that the pool is replenished at every rotation, which depends on the loss percentage. The RGB scenarios are compared to the constant impact of the single-use system, which is calculated as presented in Equation 6, with the input presented in the inventory tables.

The equations used for scenario 2 that do not include replenishment in an iterative manner are presented in equations 7 and 8 in Section 3.3.2. Compensation for losses is not included in the first rotation, because the system does not require replenishment before losses occur.

Scenario 3 has no replenishment, in the sense that the losses are not compensated by the production, transport and end of life of new packaging to replace those lost. As such, the equation used for the first rotation (Equation 7) is used for the following rotations as well.

It can be seen in Figure 13 that the impact of how replenishment is taken up does not result in large differences for the first eight

TABLE 13 | Values used to illustrate the effect of losses in three scenarios of the reusable box system.

	Scenario 1	Scenario 2	Scenario 3
Initial pool size	300	300	300
Packaging items in rotation	100	100	100
Replenishment	200	200	200
Losses	5%	2%	10%

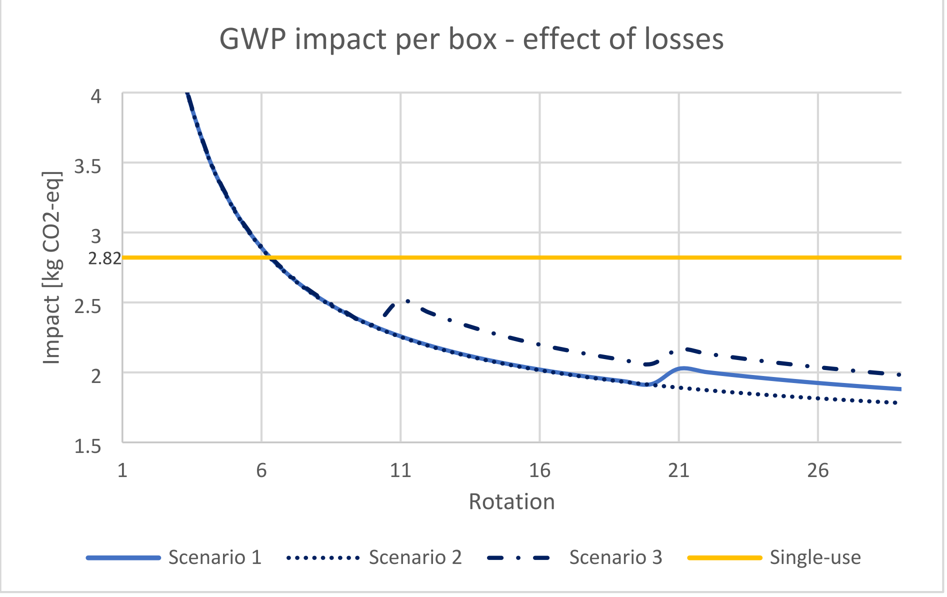

FIGURE 14 | The effect of loss percentage on the impact of the reusable box system.

rotations (< 10%). However, it does become significant from the 9th rotation onward, as it goes from 14% to 21% difference until the 21st rotation. There is no significant difference between the direct uptake of losses or replenishment.

4.6 | Effect of Losses

The effect of loss percentage is evaluated for the reusable boxes case study. The impact of losses on the total impact of one box based on the scenarios in Table 13 is shown in Figure 14. The zig-zag behaviour of the impact is due to the rotation at which replenishment occurs, which is related to the losses. The reuse system scenarios are compared to the constant impact of the single-use system, which is calculated as presented in Equation 3, with the input presented in the inventory tables.

The difference in losses in scenario 3 from scenario 1 is below 1% for the first four rotations; it increases from approximately 8%–12% from the 5th to the 12th rotation and becomes significant after the 12th rotation, where scenario 3 is 15–25% higher than scenario 1. It could mean that suddenly the single-use system has a lower impact for a certain rotation after breakeven. Still, the downward trend of the reuse system impact over rotations remains. It is clear from Figure 14 that the higher the losses, the bigger the impact of replenishment and of the total reuse system. Furthermore, the rotation at which replenishment occurs can change the breakeven point. The losses have a significant impact on the impact of a reuse system and its breakeven to the single-use system.

5 | Conclusions

It can be concluded that the factors pool size and losses are very relevant for the outcome of reuse/single-use system comparisons. Furthermore, various established parameters and influences on these systems are shown to be significant, such as the single-use components in a reuse system or the weight of a reusable product compared to that of the single-use product. In many studies, these parameters are overlooked.

There is a section of the system (equation) that has an impact divided over the number of packaging items in rotation and the number of rotations, and a section of reoccurring impact in each rotation. These need to be drawn up according to the specific supply chain with details on open vs. closed loop and where the losses occur. It is not possible to establish an equation that is suitable in every case; it always depends on the factors taken up and the supply chain.

The effect of fixed parameters such as weight can make the difference in breakeven point depending on the single-use system. The differences shown in the example provided in Section 4.2 underline the importance of the weight of a reuse product. The impact split presented in Section 4.3 shows that the impact of system transport, washing and, if relevant, single-use packaging items return every rotation to the same extent depending on the system. The starting point of the impact of the reuse system depends on the size of the pool. Section 4.4 shows that pool size can make the difference in breakeven point. The larger the pool, the higher the rotation where the breakeven point will be reached. The impact can vary greatly, but this depends on how the system is arranged and the number of packaging items in the system. Replenishment is not found in other studies. A difference of around 5% in the environmental impact of a specific rotation in a reuse system can be caused depending on how losses are taken up, by replenishment or by every rotation. Losses can influence the rotation at which breakeven occurs, as well as the environmental impact of one specific rotation.

In summary, significance is shown for the following factors:

- Single-use components in a reuse system
- Constant factors in a reuse system
  - For a reuse system to breakeven these two factors must be lower than the impact of the single-use system (screening step)
- Pool size compared to packaging items in rotation in a reuse system –must be in balance with demand.
- Losses

A proposal is made for how the relevant factors should be taken into account in reuse/single-use comparisons. Several factors need to be taken up outside of LCA Software in order to determine a break-even point or to understand the trajectory of the system impact over rotations. The equations presented in the case study chapters are the basis of adjustments that need to be made for system parameters. Together with inventory reporting according to ISO 14040/14044 this can be the basis for transparent reuse system impact calculations and its fair comparison to single-use system impact.

6 | Discussion

The literature review shows that reuse systems are often assessed virtually, not based on research of a running system from real life; the factors that play a role are not always overseen or predicted beforehand, as Palson shows. Moreover, several factors are dynamic. Success in the market can determine the throughput in the system, the efficiency and the efficient use of transport means. When a system is set up, it is hard to predict the throughput that is of importance for the calculations beforehand. The number of trips of reusable packaging cannot be forecast due to both the aforementioned aspects and the fact that the durability is engineered and will have uncertainties. If the choice is made to replenish broken packaging, the replenishment rate cannot be predicted beforehand. The single-use system can be used as a baseline to understand how the reuse system needs to perform (regarding losses and pool size compared to the number of packaging items in rotation); even though the equations can be used for this, it is not part of the study. Nevertheless, if comparisons between a single-use and reuse system are made more often with a certain format, the insight in practice will grow and assumptions can be based on the specific figures, resulting in a better correlation to practice.

A tool in which the uncertain parameters can be adjusted with LCA background data can help to provide insight and can be used as sensitivity analysis in LCA studies. It is important that this tool is still transparent. It can be taken up in the LCA report by describing the underlying equations.

For now, the system parameters are static. The calculations would work best for systems that are already established, whereas novel systems where, for example, a decrease of losses throughout the life of the system (i.e., a loss percentage of 10% at rotation 1 but only 5% at rotation 7 due to consumer acceptance and other improvements) would require dynamic parameters in the calculation tool. Future research could be on calculation methods for reuse systems with dynamic parameters.

Not included in the equations is the environmental impact of the age of the replaced products. This would show the environmental impact from replacing new products, i.e., first-in first-out, compared to products that have endured several rotations already.

Acknowledgements

The authors would like to acknowledge the contributions of several colleagues to this paper: Alan Campbell for providing insights in LCA and for the support to work on this paper; Rianne Hagen, Myrthe Berg and Diana Schiffer for their contribution to selecting reuse versus single-use case studies; Kim Whittenham for the 1st round of reviewing the paper and equations; Sybren Schoustra for the 2nd round of reviewing the paper.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Research data are not shared.

References

1. European Commission, *European Green Deal - Delivering on Our Targets* (European Commission, 2019), https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en.

2. European Commission, *A New Circular Economy Action Plan* (European Commission, 2020). Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN.

3. European Commission, *European Parliament Legislative Resolution of 24 April 2024 on the Proposal for a Regulation of the European Parliament and of the Council on Packaging and Packaging Waste* (Strasbourg European Parliament, 2025).

4. NPCE, *Nationaal Programma Circulaire Economie* (Rijksoverheid (Dutch Government), 2023).

5. H. Palson and J. Olsson, "Current State and Research Directions for Disposable Versus Reusable Packaging: A Systematic Literature Review of Comparative Studies," *Packaging Technology and Science* (2022): 391–409, https://doi.org/10.1002/pts.2722.

6. A. S. Campbell, *A Forensic Approach to Life Cycle Assessment* (University of Twente, 2019).

7. E. Thoden van Velzen and M. Brouwer, *Between Facts and Fiction - An Informed Opinion for Metal Packaging Europe* (Wageningen Food & Biobased Research: Wageningen, 2022), https://doi.org/10.18174/568438.

8. WRAP 2010 Single Trip or Reusable Packaging - Considering the Right Choice for the Environment WRAP.

9. C. Bradley and L. Corsini, "A Literature Review and Analytical Framework of the Sustainability of Reusable Packaging," *Sustainable Production and Consumption* 37 (2023): 126–141, https://doi.org/10.1016/j.spc.2023.02.009.

10. J. Almeida and J. Bengtsson, *Reusable Coffee Cups Life Cycle Assessment and Benchmark* (KeepCup, 2018), https://doi.org/10.13140/RG.2.2.35083.13607.

11. K. Changwichan and S. Gheewala, "Choice of Materials for Takeaway Beverage Cups Towards a Circular Economy," *Sustainable Production and Consumption* 22 (2020): 34–44, https://doi.org/10.1016/j.spc.2020.02.004.

12. D. Cottafava, M. Costamagna, M. Baricco, L. Corazza, D. Miceli, and L. Riccardo, "Assessment of the Environmental Break-Even Point for Deposit Return Systems Through an LCA Analysis of Single-Use and Reusable Cups," *Sustainable Production and Consumption* (2020): 228–241, https://doi.org/10.1016/j.spc.2020.11.002.

13. I. de Sadeleer and K. A. Lyng, "A Life Cycle Assessment on Single-Use and Reuse Beer Cups," *Circular Economy and Sustainability* 2 (2022): 1517–1539, https://doi.org/10.1007/s43615-022-00164-y.

14. A. Del Borghi, S. Parodi, L. Moreschi, and M. Gallo, "Sustainable Packaging: An Evaluation of Crates for Food Through a Life Cycle Approach," *International Journal of Life Cycle Assessment* 26 (2021): 753–766, https://doi.org/10.1007/s11367-020-01813-w.

15. C. Ferrara, G. De Feo, and V. Picone, "LCA of Glass Versus PET Mineral Water Bottles: An Italian Case Study," *Recycling* 6, no. 3 (2021): 50, https://doi.org/10.3390/recycling6030050.

16. S. Foteinis, "How Small Daily Choices Play a Huge Role in Climate Change: The Disposable Paper cup Environmental Bane," *Journal of Cleaner Production* 255 (2020): 120294, https://doi.org/10.1016/j.jclepro.2020.120294.

17. A. Gallego-Schmid, J. M. Mendoza, and A. Azapagic, "Environmental Impacts of Takeaway Food Containers," *Journal of Cleaner Production* 211 (2019): 417–427, https://doi.org/10.1016/j.jclepro.2018.11.220.

18. C. Hitt, J. Douglas, and G. Keoleian, "Parametric Life Cycle Assessment Modeling of Reusable and Single-Use," *Resources, Conservation and Recycling* 190 (2023): 106862, https://doi.org/10.1016/j.resconrec.2022.106862.

19. D. Landi, M. Germani, and M. Marconi, "Analyzing the Environmental Sustainability of Glass Bottles Reuse in an," in *26th CIRP Life Cycle Engineering (LCE) Conference* (MDPI, 2019), https://doi.org/10.1016/j.procir.2019.01.054.

20. M. Levi, S. Cortesi, C. Vezzoli, and G. Salvia, "A Comparative Life Cycle Assessment of Disposable and Reusable Packaging for the Distribution of Italian Fruit and Vegetables," *Packaging Technology and Science* 24 (2011): 387–400, https://doi.org/10.1002/pts.946.

21. F. López-Gálvez, L. Rasines, E. Conesa, P. Gómez, F. Artés-Hernández, and E. Aguayo, "Reusable Plastic Crates (RPCs) for Fresh Produce (Case Study Cauliflowers): Sustainable Packaging but Potential Survival and Risk of Cross-Contamination," *Food* 10, no. 6 (2021): 1254, https://doi.org/10.3390/foods10061254.

22. M. Martin, S. Herlaar, A. Jönsson, and D. Lazarevic, "From Circular to Linear? Assessing the Life Cycle Environmental and Economic Sustainability of Steel and Plastic Beer Kegs," *Circular Economy and Sustainability* 2 (2022): 937–960, https://doi.org/10.1007/s43615-021-00142-w.

23. D. R. Morgan, D. Styles, and E. T. Lane, "Packaging Choice and Coordinated Distribution Logistics to Reduce the Environmental Footprint of Small-Scale Beer Value Chains," *Journal of Environmental Management* 307 (2022): 114591, https://doi.org/10.1016/j.jenvman.2022.114591.

24. K. I. Olatayo, P. T. Mativenga, and A. L. Marnewick, "Life Cycle Assessment of Single-Use and Reusable Plastic Bottles in the City of

Johannesburg," *South African Journal of Science* 117, no. 11/12 (2021), https://doi.org/10.17159/sajs.2021/8908.

25. J. Potting and E. van der Harst, "Facility Arrangements and the Environmental Performance of Disposable and Reusable Cups," *International Journal of Life Cycle Assessment* 20 (2015): 1143–1154, https://doi.org/10.1007/s11367-015-0914-7.

26. C. Tua, L. Biganzoli, M. Grosso, and L. Rigamonti, "Life Cycle Assessment of Reusable Plastic Crates (RPCs)," *Resources* 8, no. 2 (2019): 110, https://doi.org/10.3390/resources8020110.

27. T. Zimmermann and R. Bliklen, "Single-Use vs. Reusable Packaging in e-Commerce: Comparing Carbon Footprints and Identifying Break-Even Points," *Gaia* 29 (2020): 176–183, https://doi.org/10.14512/gaia.29.3.8.

28. A. Bher and R. Auras, "Life Cycle Assessment of Packaging Systems: A meta-Analysis to Evaluate the Root of Consistencies and Discrepancies," *Journal of Cleaner Production* 476 (2024): 143785, https://doi.org/10.1016/j.jclepro.2024.143785.

29. S. Hann, *Unveiling the Complexities: Exploring LCAs of Reusable Packaging in the Take-Away Sector* (Eunomia Research & Consulting, 2023).

30. A Case of Reusable Packaging for German Mineral Spring Water, *European Congress Environment and Packaging, Prevention, Refill and Reuse in Europe in the 90's and Beyond* (Friends of the Earth International, MilieuDefensie, 1992).

31. D. Mollenkopf, D. Closs, D. Twede, S. Lee, and G. Burgess, "Assessing the Viability of Reusable Packaging: A Relative Cost Approach," *Journal of Business Logistics* 26 (2005): 169–197, https://doi.org/10.1002/j.2158-1592.2005.tb00198.x.

32. L. Zampori and R. Pant, *Suggestions for Updating the Product Environmental Footprint (PEF) Method* (Publications Office of the European Union, 2019), https://doi.org/10.2760/424613.

33. M. Mahmoudi and I. Parviziomran, "Reusable Packaging in Supply Chains: A Review of Environmental and Economic Impacts, Logistics System Designs, and Operations Management," *International Journal of Production Economics* 228 (2020): 107730, https://doi.org/10.1016/j.ijpe.2020.107730.