Journal of Cleaner Production 476 (2024) 143738

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Can reusable packaging revolutionise e-commerce? Unveiling the environmental impact through a comparative carbon footprint analysis

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ARTICLE INFO

Handling Editor: Cecilia Maria Villas Bôas de Almeida

Keywords:
e-commerce
Reusable packaging
Single-use packaging
Carbon footprint
Sustainability
Circular economy

ABSTRACT

E-commerce is a rapidly growing, evolving sector. Its environmental impact has also increased, with shipping packaging being a key contributor. The sector is, however, struggling to tackle this environmental impact, as well as to follow new packaging regulations. Previous studies on reusable packaging have predominantly been qualitative or concentrated on material selection, overlooking essential elements of supply chain design and consumer behaviour. Industry reports attempting to quantify the sustainability of reusable packaging have produced varied results that lack generalisability or transferability to other contexts. Consequently, it is difficult to determine the actual environmental sustainability of reusable packaging in e-commerce. In this research, we assess the carbon footprint of reusable packaging in e-commerce, through a comparison of eight case studies. A multiple case study approach is followed, employing an embedded design where more than one unit of analysis is explored in each case. We evaluate the CO_2 emissions of all processes related to the circular supply chain of reusable packaging employing a method that can evaluate different solutions and situations and a sensitivity analysis. Findings highlight three specific factors influencing the carbon footprint of reusable packaging: (1) reusable packaging material, (2) return and reuse rate, and (3) supply chain design (i.e., centralised versus decentralised design, travel distance, transport mode). For the same type of reusable packaging, we found that polyester generates 215% more CO_2 emissions than cardboard in production and waste management. However, by analysing the same reusable packaging and supply chain, these same emissions can drastically increase if the return and reuse rate decreases. Changes in the return and reuse rate mainly linked, among others, to customer behaviour and involvement. Furthermore, for the same reusable packaging and return and reuse rate, a decentralised supply chain can reduce the CO_2 emissions compared to a centralised structure. Interestingly, reusable packaging is environmentally sustainable long before it reaches its maximum life cycle. Most of the analysed solutions were more environmentally friendly than a cardboard box when they reached 10% of their estimated life cycle.

1. Introduction

With the exponential growth in e-commerce and the number of packages delivered in recent years (Halldorsson and Wehner, 2020), environmental impacts along the online supply chain are rising (Zimmermann and Bliklen, 2020). The literature has highlighted the role of packaging in this impact (e.g., Fernández Briseño et al., 2020; Zimmermann and Bliklen, 2020). Its contribution to the total CO_2 emissions of online deliveries can account for a share of about 10–30 per cent (Zimmermann and Bliklen, 2020). From a holistic perspective, the packaging system in e-commerce is subdivided into the levels of primary packaging (i.e., the packaging directly surrounding the product) and secondary or shipping packaging (i.e., containing several primary packages and/or serving as transport packaging) (Freichel et al., 2020).

Online consumers are increasingly demanding a change in shipping packaging, related to their environmental concerns (Pålsson and Olsson, 2023). The packaging industry is also facing changes in policies and regulations with regards to usability and lifespan, in an attempt to promote a circular approach (Pålsson and Olsson, 2023). To tackle this problem, an interesting solution is the use of reusable shipping

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https://doi.org/10.1016/j.jclepro.2024.143738
Received 2 October 2023; Received in revised form 16 July 2024; Accepted 19 September 2024
Available online 28 September 2024

packaging for online orders (Baskoro, 2020; Vadakkepatt et al., 2021). It is already implemented by some companies in Europe (e.g., Hipli, Re-zip, Kopack). This innovative solution reduces unnecessary packaging waste, as the container can be used multiple times unlike single-use packaging (Baskoro, 2020). Whether it creates an environmental benefit overall depends, among other things, on customer involvement in returning the reusable packaging back to its supplier (Bocken et al., 2022).

Literature that reflects on the environmental impact of shipping packaging has shown modest interest in reusable packaging as a solution to reduce this impact (e.g., Zimmermann and Bliklen, 2020). However, few valid and comparable findings exist as to the environmental performance of reusable packaging systems in online retail (Baskoro, 2020). The current knowledge is also ambiguous (Pålsson and Olsson, 2023). The studies disagree on whether reusable packaging can be a sustainable solution and which factors influence these results (BOOX, 2020; Re-zip, 2021). Disagreements arise because these studies have analysed different packaging solutions and contexts (e.g., different supply chain configurations and consumer behaviour), without taking these differences explicitly into account (Pålsson and Olsson, 2023). Furthermore, the literature has focused on comparing packaging solutions based on production and hypothetical scenarios of use cycles, but very rarely have they considered the reverse supply chain for both types of solution, as well as consumer behaviour aspects.

In view of this situation, the objective of this paper is to identify when the implementation of reusable packaging in e-commerce can be environmentally sustainable. To this end, we analyse and compare eight European case studies mature enough for robust data collection. Furthermore, we develop and implement a method that can be used to evaluate different solutions and situations, to tackle the problems encountered in previous papers. We propose the following research question:

RQ1. Under which circumstances does reusable packaging present an environmental benefit in an e-commerce context?

This article continues with a literature review in the second section, which discusses the main trends supporting the use of reusable packaging. The third section outlines our methodology for the case studies, which are elaborated on in the fourth section. The fifth section discusses the findings, while the last section presents conclusions and lines of future research.

2. Literature review

2.1. E-commerce and its environmental impact

The success of e-commerce lies in its convenience and variety (Lim and Srai, 2018), based on its wide range of products, very competitive prices, a high-quality customer experience, and a premium logistics and service levels, among others (Mangiaracina et al., 2015). This logistics offering implies a redesign of the supply chain with respect to the offline channel, mainly concerning the storage and preparation of orders, and delivery to consumers (Colla and Lapoule, 2012). The wide range of products and the reduced number of products per order make managing inventory difficult, requiring real-time inventory control. Furthermore, they also increase the difficulty of order preparation. Thus, the selection of the type of preparation becomes a key decision. Related to delivery, home and fast deliveries (e.g., same-day delivery) with short delivery windows (Nogueira et al., 2022) hinder the implementation of efficient distribution strategies. Strategies that, in addition, do not exist in the in-store service.

As e-commerce continues its rise, the convenience offered generates wide-ranging environmental effects (Mangiaracina et al., 2015). Different factors are responsible for this impact. In this sense, logistics decisions related to transport and packaging are key components of this environmental impact (Mangiaracina et al., 2015). Fast deliveries trigger a higher number of trips, and a lower loading factors of courier trucks and consolidation rate of shipments (Nogueira et al., 2022; Mangiaracina et al., 2015). At the same time, the overuse of packaging compared to the offline channel, as well as the poor choice of materials and formats negatively impacts the environment (Nogueira et al., 2022; Mangiaracina et al., 2015). Thus, these factors have an important impact on the environment. Inefficiency in transportation, linked to a higher number of trips with lower loading factors, means an increase in polluting emissions, congestion in cities, noise pollution and global warming, among others (e.g., Rai, 2019). Thus, for example, transport associated with e-commerce is responsible for 36.4% of total transport emissions (Rai, 2019). Furthermore, the inappropriate use of packaging implies an inadequate management of resources, increasing the waste produced by e-commerce (Zimmermann and Bliklen, 2020).

In this sense, contribution of packaging to the total CO_2 emissions of online deliveries can account for a share of about 10–30 per cent (Zimmermann and Bliklen, 2020). In this sense, Fernández Briseño et al. (2020) related 45 per cent of the carbon footprint of online orders to packaging. Furthermore, this share is subject to different factors (Escursell et al., 2021). The main ones focus on the material selection, the management of the formats and the filling volume (Escursell et al., 2021). Thus, the greatest impact comes from the use of polluting materials and a failure to optimise package volume and shape (Escursell et al., 2021). Policies and regulations have been developed to tackle this impact, focusing on usability and lifespan, and following a circular approach (Pålsson and Olsson, 2023). For example, the Spanish government has launched a new law on waste and circular economy (Ley 7/2022, 2022). It aims to prevent the generation of packaging waste and to minimise its environmental impact, with an even greater focus on retailers.

2.2. Reusable packaging

In this situation, reusable packaging can be a solution to reduce the impact of online packaging on sustainability and comply with these new regulations (Pålsson and Olsson, 2023). However, the earliest studies that compare the environmental impact of reusable and single-use packaging did not frame the comparison in an e-commerce context. On the contrary, a review of research on disposable versus reusable packaging found that most studies focus on food products, take-away food, beverages, or industrial packaging (Pålsson and Olsson, 2023). From this perspective, some of the studies are dedicated to the impact of material selection when designing and producing reusable packaging. Such analyses focus on the emissions produced by production and waste management of different types of materials. The most common material comparisons are plastic and cardboard (Lai et al., 2022; Pålsson and Olsson, 2023).

Other authors have developed Life Cycle Assessments of the implementation of reusable packaging in different situations. Saraiva et al. (2016) compared the impact of reusable packaging made from high-density polyethene and single-use cardboard boxes for transporting mango fruits. When no reuses were considered, most of the environmental evaluations were clearly in favour of cardboard packaging. However, reusable packaging became less pollutant after four uses than single-use packaging. Greenwood et al. (2021) compared the environmental impacts of single-use, refillable, and returnable containers for takeaway meals. They indicated that reusable containers outperform single-use plastic containers on most measures of environmental impact such as global warming, land use, and water use.

In an e-commerce context, Zimmermann and Bliklen (2020) conducted a comparative analysis of CO_2 emissions for single-use and reusable packaging. Their analysis considered the most important processes: production, direct logistics, reverse logistics, and waste management. Based on an ideal use case, results showed that a reusable shipping bag could offer an environmental advantage after a few cycles, compared to a single-use low-density polyethylene (LDPE) bag. In the case of reusable polypropylene boxes, the break-even point lies between

32 and 81 cycles, depending on whether recycled material is used.

Apart from scientific studies, some companies providing reusable packaging have developed Life Cycle Assessments for their solution. BOOX (2020) compared the impact of production, direct and reverse logistics, and waste management between their reusable box made of polypropylene and a traditional cardboard box. After one thousand shipments, the reusable solution emitted 67% fewer CO_2 emissions than the traditional cardboard box. Later, Re-zip, 2021 and Re-zip (2022) compared up to three reusable solutions with traditional ones, analysing the CO_2 emissions and the water consumption of production, transport, and waste management. After ten shipments, a polypropylene bag emitted 42% fewer CO_2 emissions than a traditional mailing bag. Using a cardboard bag as a reusable solution emitted 79% fewer CO_2 emissions than the same traditional mailing bag. Furthermore, comparing a cardboard box as a reusable solution and a traditional cardboard mailing package, the reusable solution emitted 87% fewer CO_2 emissions than the traditional one.

Other, less detailed assessments can be found. Hey Circle (https://www.heycircle.de/impact) assures that after forty cycles, their polypropylene reusable box emits 43% fewer CO_2 emissions than a traditional cardboard box. Furthermore, Hipli (https://hipli.fr/impact/) claims that, after a hundred uses, their polypropylene reusable bag emits 83% fewer CO_2 emissions than a traditional mailing bag.

Although these studies are informative, they have focused on very specific solutions and situations. They have analysed different packaging types and contexts (e.g., different case studies, supply chain configurations, and consumer behaviour), without taking them explicitly into account (Pålsson and Olsson, 2023). They have also considered different operations. Thus, some have focused on the impact of production, transport (direct and reverse logistics) and waste management (e.g., Re-zip, 2022), while others have only paid attention to certain processes such as production or transport (e.g., https://hipli.fr/impact/). Furthermore, the information used for such analyses is not always correctly or sufficiently detailed, making comparisons impossible.

In this sense, the limited literature and these specific industry studies make it difficult to establish definite conclusions on the circumstances in which reusable packaging is actually more sustainable than single-use alternatives. Thus, the question of whether and in which contexts reusable packaging is environmentally sustainable has not yet been answered.

As mentioned by Pålsson and Olsson (2023) in their literature review, some factors should be considered when assessing the sustainability of a reusable packaging system. First, Zimmermann and Bliklen (2020) and Bocken et al. (2022) pointed out the importance of the retailer using reusable packaging. They mentioned the importance of their size, as well as the product on offer (e.g., type, size, number of products per purchase, fragility). Bocken et al. (2022) also mention the impact of customer behaviour on the sustainability of reusable packaging, linked to the return rate. Customers are thus responsible for closing the supply chain, as they are the ones who make the decision whether or not to return the reusable packaging (Bocken et al., 2022).

Zimmermann and Bliklen (2020) note the importance of the reusable packaging solution. Its type and material, as well as its volume and protection capacity, must be considered. Furthermore, the number of cycles that reusable packaging can assume is important, as well as the rejects because of premature defects (Megale Coelho et al., 2020).

Last, multiple authors have reflected on the importance of supply chain design when trying to attain sustainability using reusable packaging. In this sense, different variables arise when designing the reusable supply chain. Thus, Megale Coelho et al. (2020), Zimmermann and Bliklen (2020) and Bocken et al. (2022) mention the impact of production, reusable packaging stock, distance between facilities, transportation mode and capacity, supply chain strategy, and recycling process (i.e., separate collection rate and recycling rate). The distance between facilities will depend on which actors intervene in the process (e.g., producer, provider, retailer, and end-customer) and where each actor is located (e.g., Mission Reuse, 2023). Supply chain strategies will be defined on the basis of the cleaning process (i.e., centralised or decentralised) and whether it is a dependent or independent structure.

Regarding cleaning strategy, it is important to mention Fashion For Good (2021) and Mission Reuse (2023), two global organisations working at a policy level to implement sustainable solutions in fashion and packaging, respectively. They have differentiated the reusable supply chain according to the cleaning process. In a centralised process, the packaging is transported to a facility to be cleaned. This is a single facility, regardless of where the retailer and the end-customer are located, and it is the provider's responsibility. For the decentralised structure, the packaging is transported to a facility for cleaning. However, this facility can be the retailer's or the provider's responsibility and is located near the retailer and/or the end-customer.

Mission Reuse (2023) also defined the concepts of dependent and independent supply chains. Dependent supply chains require collaboration with logistics providers for the delivery and collection of packaging. In independent supply chains, the customer is responsible for collecting and returning the packaging.

As mentioned before, the available literature suggests differences in terms of environmental impact between reusable and single-use packaging in e-commerce. Furthermore, most studies did not focus on e-commerce, nor did they create an evaluation method for reusable packaging that can be used as a method of comparison between different solutions and cases. Thus, literature has not yet defined whether (and under which circumstances) reusable packaging is environmentally sustainable. Taking the factors previously detailed into account, this study contributes by investigating the environmental impact associated with the use of reusable packaging in e-commerce, comparing its impact with single-use packaging and creating, at the same time, a method that can be used to evaluate different solutions and situations.

3. Methodology

The objective of this paper is to identify when the implementation of reusable packaging in e-commerce can be sustainable from a carbon dioxide (CO_2) emissions perspective. CO_2 is a greenhouse gas and the primary driver of global climate change. Our research responds to an open and underexplored topic. We analyse it empirically through a case study approach (Eisenhardt, 1989; Yin, 2018), following the example of other authors (e.g., Lim and Srai, 2018; Rai et al., 2022).

This method was chosen for the following reasons. First, case studies allow us to understand practical and real problems in their natural context (Yin, 2018; Eisenhardt, 1989). Furthermore, they are an ideal research method for exploring and explaining phenomena and their current circumstances (Yin, 2018). Second, case studies are tailor-made for exploring processes that are little understood (Hartley, 1994), which is the case for our subject under study. Third, case studies allow for a variety of data sources and a range of different data collection methods to be covered (Miles and Huberman, 1994; Yin, 2018). They are therefore an effective technique for developing in-depth analysis (Eisenhardt and Graebner, 2007).

In addition, to further explore this last reason, we have developed a case study approach, in which more than one unit of analysis is explored in each case (Yin, 2018). This design enables in-depth analysis of individual cases based on more detailed data collection, combining within-case and cross-cases analyses (Yin, 2018).

3.1. Case selection

As mentioned by Meyer (2001), case selection, sampling time, and data collection procedures are important when developing the case study design. First, we selected a theoretical sampling procedure (e.g., Sharma et al., 2021), in which cases are chosen purposefully rather than randomly. Europe constitutes the case of interest in this study due to the constant growth of e-commerce in this territory (Eurostat, 2022), as well as its strong innovative character (European Commission, 2020). Furthermore, the European Commission is working on new regulations to promote reusable packaging (European Commission, 2022). Through our desk research, we identified twelve providers of reusable packaging in Europe and interviewed eight of them. As we studied almost all relevant players in the European market, the findings of our research are based on input from each case study, as well as the collective set of cases.

In response to the research question, we employed an embedded design. This implies that more than one unit of analysis is explored in each case (Yin, 2018). We analysed the reusable packaging solution and circular supply chain for each provider. Furthermore, as the research question focuses on assessing the sustainability level of the solution proposed by each case study, an e-retailer working with each provider was selected. In this sense, we explored the most mature e-retailers for each reusable packaging provider. Additionally, the supply chain of this e-retailer using reusable packaging was analysed to assess its CO_2 emissions. Thus, we quantified the emissions of the most relevant processes: production, direct and reverse logistics, and waste management (including those produced in the cleaning process) (Zimmermann and Bliklen, 2020).

3.2. Data collection

We selected data collection procedures that allow for triangulation (Yin, 2018). Case studies typically rely on archives, interviews, questionnaires, and observations to collect data (Eisenhardt, 1989). Our field research combines two data collection methodologies: (1) desk research and (2) eight semi-structured interviews with reusable packaging providers in Europe. The desk research and contact with the providers was developed through March 2023. Data collection and analysis took place between April and June 2023.

During the desk research stage, we conducted a literature review about reusable packaging in e-commerce as a base for the next stage. This review identified the key characteristics of reusable packaging, the processes integrated into its supply chain and the factors to be considered when quantifying its environmental impact.

A detailed analysis of various data sources (e.g., annual reports, websites, etc.) was also developed. Information was compiled to establish the context for each company (providers and retailers). Thus, for each provider, information about business model, reusable packaging solution (e.g., type of packaging, reusable supply chain), sales, experiencing selling reusable packaging, and environmental impact was collected. For each retailer, information about the type of product sold, sales, experience selling online, reusable packaging solution (e.g., type of packaging, reusable supply chain, consumer relationship, etc.), and environmental impact was also collected. Subsequently, this information was organised and classified in a spreadsheet file. Thus, this structured information served both as a basis for the interviews and for the evaluation of the findings (as an element for the triangulation).

After the interviews, various data collected from the companies were also analysed (e.g., Life Cycle Assessment reports and annual reports). More information on their reusable packaging solutions (e.g., type, weight, material, size), their circular supply chain (e.g., type, distances), and their environmental impact was compiled. This information was structured in a spreadsheet file. Thus, this data was classified according to the methodology used and the processes considered in the analysis. This structured information served for the evaluation of the findings (as an element for the triangulation).

The second stage included semi-structured interviews with each provider. Following requests sent by e-mail, eight providers agreed to be interviewed. Table 1 provides information on the providers and e-retailers interviewed. The interviews (held on video conferencing platforms) lasted on average 45 min, were undertaken in English, French, or Spanish, depending on the origin of the interviewed company, and were structured along five different topics: (1) reusable packaging solution, (2) e-retailers using this solution, (3) reusable supply chain, and (4) a successful case study. Related to the fourth theme, four types of data

Table 1
Overview of providers and e-retailers interviewed.

Company	Product type	Company size	Country of origin	Country in which they offer their services	Interviewee's position	Interview date	Instrument	Duration	Language
Provider 1	Mailing bag	Medium	France	Europe	Co-founder	April 06, 2023	Google Meet	45 min	French
Retailer 1	Different type of products	Big	France	France					
Provider 2	Mailing bag	Small	France	France	COO	April 06, 2023	Teams	35 min	French
Retailer 2	Fashion	Big	France	France					
Provider 3	Mailing bag and box	Small	Spain	Europe	Development Lead	March 28, 2023	Google Meet	50 min	Spanish
Retailer 3	Cosmetic	Big	France	Spain					
Provider 4	Mailing bag and box	Medium	Denmark	Europe	Project manager	April 05, 2023	Google Meet	50 min	English
Retailer 4	Ecological products	Medium	Denmark	Denmark					
Provider 5	Box	Small	France	France	Business Developer	March 27, 2023	Google Meet	45 min	French
Retailer 5	Different type of products	Big	France	France					
Provider 6	Box	Small	USA	UK	CEO	April 12, 2023	Zoom	40 min	English
Retailer 6	Cosmetic	Big	USA	UK					
Provider 7	Glass jar	Small	Belgium	Belgium	CEO	April 13, 2023	Google Meet	50 min	English
Retailer 7	Bakery	Small	Belgium	Belgium					
Provider 8	Mailing bag and box	Medium	Germany	Austria, Switzerland, Germany	CEO	May 25, 2023	Google Meet	45 min	English
Retailer 8	Fashion	Big	Germany	Germany					

were collected: (1) reusable packaging (i.e., type of solution, cycles, weight, material, stock necessities and discarded rate), (2) sales (i.e., orders per month), (3) customer behaviour (i.e., product returns per month and return rate of reusable packaging), (4) supply chain (i.e., distance between actors, mode of transport, occupancy, and the number of orders delivered through the different actors). The topics covered in the interviews are available in the complementary material.

3.3. Data analysis

For the first three interview topics, a thematic data analysis was performed by cross-referencing the main themes and complementarity among the results was sought. The same interviewer conducted, transcribed, and analysed the interviews to ensure that their context was captured adequately. Spreadsheet files were used to manage, store, and organise the data.

For the fourth topic, all data was collected and structured into a spreadsheet file. The data collected about each retailer is available in the complementary material. Then, we calculated the CO_2 emissions of all relevant processes of the supply chain: production, transport, waste collection, and waste management. For transport, we considered the flows between producer and provider, provider and retailer, retailer and end-customer, end-customer and provider, end-customer and retailer, retailer and provider, provider and cleaning facility, and cleaning facility and provider. For flows concerning the end-customer, both the transport from the costumer's home to the collection point (if applicable) and the transport from the collection point to the retailer or provider have been considered. We also assessed the CO_2 emissions for each case study assuming the possible use of single-use packaging. After that, we compared and analysed the findings.

CO_2 emissions were calculated based on secondary data from the literature review. Table 2 shows the specific data used to conduct all calculations. Using this data, CO_2 emissions from production were calculated based on the material and the quantity used to produce the reusable packaging and the emissions generated during the production of each material. The same applied to emissions from waste management. Furthermore, CO_2 emissions from the cleaning process were calculated based on the electricity and cleaning agent consumed (e.g., Postacchini et al., 2018). CO_2 emissions from transport were calculated based on the specifications of the vehicle used, the distance travelled and the load. Finally, emissions from the waste collection were calculated based on previous studies on the topic (e.g., de la Barrera and Hooda, 2016; Lee et al., 2017; Vanderreydt et al., 2021). More information about the calculation process can be found in the complementary material.

Although each case study might use the same material with different characteristics (in the production process) or different types of truck or van, we were unable to collect these specific characteristics for each case study. In this situation, we used an approximation.

These findings were contrasted with other respondents and with structured secondary data on the issues to enable richer analysis (Eisenhardt, 1989). Thus, internal validity was achieved via triangulation with the interviewees, who received a summary of the preliminary results and made some minor suggestions, which were carried out.

3.4. Presentation of the cases

In this section, Table 3 and Fig. 1 present the eight case studies (providers and e-retailers). For each provider, we describe its reusable packaging, business model, supply chain, return rate, and reuse rate. We identify the number of cycles that each reusable packaging has been proven to be useful. The business model can be based on a pay-per-use system, a pay-per-month system, or a deposit-refund system. For the first one, e-retailers must pay every time they use reusable packaging, regardless of its past uses. However, in the second model, e-retailers pay a fee every month for the packaging they keep in stock, regardless of how many times they reuse it. Finally, for the last model, e-retailers only pay the first time they use a package. Return rate refers to the percentage of packaging that is returned by the final consumer. Reuse rate is the percentage of packaging that can be used after being returned by the final consumer, meaning that it is in a suitable condition for further use. For each e-retailer, we describe its products, the reusable packaging in use, the number of orders delivered using reusable packaging, and its supply chain.

4. Findings

To assess the CO_2 emissions of reusable packaging, all relevant processes need to be considered: production, direct and reverse logistics, and waste management. As mentioned in the methodology, we assessed the impact of production and waste management based on the material used to create the reusable packaging. In this sense, three types of reusable packaging were identified: bags, boxes, and jars. These three solutions can be made from four different materials: polypropylene, polyester, cardboard, and glass.

All other processes were assessed based on emissions produced by

Table 2
Data used to conduct the CO_2 emissions analysis.

Process	Alternative	CO_2 emissions	Source
Production	Polypropylene	1.98 kg/kg	Ecoinvent (2022)
	Polyester	5.20 kg/kg	Ecoinvent (2022)
	Glass	0.58 kg/kg	Ecoinvent (2022)
	Cardboard	1.24 kg/kg	Ecoinvent (2022)
Transport	Plane	0.50 kg/km	European Environment Agency (2023)
	Truck	1.26 kg/km	European Environment Agency (2023)
	Van	0.33 kg/km	European Environment Agency (2023)
	Sustainable vehicle (electric vans, cargo bikes, electric motorbikes)	0 kg/km	European Environment Agency (2023)
	Passenger car	0.22 kg/km	European Environment Agency (2023)
	Collection vehicle	0.02 kg/km	Vanderreydt et al. (2021)
	Polypropylene	2.53 kg/kg	Ecoinvent (2022)
	Polyester	6.64 kg/kg	Ecoinvent (2022)
	Glass	5.76 kg/kg	Ecoinvent (2022)
	Cardboard	2.52 kg/kg	Ecoinvent (2022)
	Electricity	0.11 kg/kWh	International Energy Agency (2022)
	Polypropylene	2.53 kg/kg	Ecoinvent (2022)
Waste management	Polyester	6.64 kg/kg	Ecoinvent (2022)
	Glass	5.76 kg/kg	Ecoinvent (2022)
	Cardboard	2.52 kg/kg	Ecoinvent (2022)
	Electricity	0.11 kg/kWh	International Energy Agency (2022)
	Cleaning agent	1.71 kg/kg	Ecoinvent (2022)

Table 3
Relevant characteristics of providers and e-retailers interviewed.

Company	Product type	Maximum cycles	Country in which the packaging is produced	Business model	Product in use	Return rate	Reuse rate	Orders per month
Provider 1	Polypropylene bag	100	France	Pay-per-use system	Polypropylene bag	87%	99%	1,500,000
Retailer 1	Different type of products							
Provider 2	Polyester bag in 4 sizes	100	France	Pay-per-use system	Polyester bag	96%	99%	200
Retailer 2	Fashion							
Provider 3	Polypropylene bag and box	20 and 10	Spain	Pay-per-month system	Polypropylene bag	20%	85%	500
Retailer 3	Cosmetic							
Provider 4	Cardboard bag and box in 3 and 5 sizes	10	Denmark	Pay-per-use system	Cardboard bag	80%	70%	100
Retailer 4	Ecological products							
Provider 5	Polypropylene box in 5 sizes	250	France	Pay-per-use system	Polypropylene box	98%	90%	300
Retailer 5	Different type of products							
Provider 6	Polypropylene box	20	USA	Pay-per-use system	Polypropylene box	80%	99%	8000
Retailer 6	Cosmetic							
Provider 7	Glass jar	1000	Belgium	Deposit-refund system	Glass jar	80%	95%	600
Retailer 7	Bakery							
Provider 8	Polypropylene bag and box	50	Germany	Pay-per-month system	Polypropylene bag	97%	99%	1050
Retailer 8	Fashion							

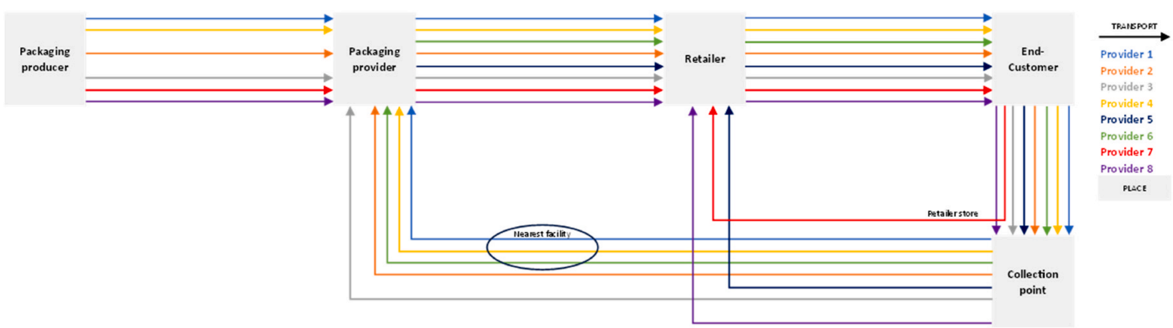

Fig. 1. Overview of the supply chain of the providers and retailers interviewed.

transport. This required the supply chain of each case study to be analysed. We therefore identified up to four alternative supply chains, classified into three main strategies, which are shown in Fig. 2. The first strategy, called 3rd-Party dependent B2C infrastructure with cleaning facility at provider, can result in two alternative supply chains: 3rd-Party dependent B2C infrastructure with centralised cleaning facility at provider and 3rd-Party dependent B2C infrastructure with decentralised cleaning facility at provider. The last two alternative supply chains are called 3rd-Party dependent B2C infrastructure with cleaning facility at retailer, and Independent B2C Return Infrastructure.

In the first strategy (3rd-Party dependent B2C infrastructure with cleaning facility at provider), providers and retailers utilise third-party logistical services to exchange packaging. Furthermore, the cleaning process and facility are the responsibility of the provider. As mentioned before, this strategy can result in two alternative supply chains depending on whether the cleaning process is centralised (i.e., only one central cleaning facility) or decentralised (i.e., different cleaning facilities in all important markets).

In the third alternative (3rd-Party dependent B2C infrastructure with cleaning facility at retailer), as in the previous one, providers and retailers utilise third-party logistical services to exchange packaging. However, in this alternative, the decentralised cleaning process and facility are the responsibility of the retailer.

In the last alternative (Independent B2C Return Infrastructure), the customer is responsible for collecting and returning the reusable packaging at a retailer's store or a collection point. Furthermore, the retailer is responsible for the cleaning process.

These four alternatives can be classified according to their inventory pooling system (decentralised system, centralised system, and echelon inventory system) (Kurata, 2014). Thus, the first two alternatives, where the provider is responsible for the cleaning process, represent a centralised system. Here, providers manage and keep the stock of reusable packaging and deliver it upon the request of the e-retailer (Kurata, 2014). The last two alternatives, where the retailer is responsible for the cleaning process, represent a decentralised system. Here, retailers manage and keep their stock of reusable packaging (Kurata, 2014). Only when this stock is insufficient, they request more packaging to the provider.

The cleaning process, a key factor in differentiating the available alternative supply chains, focuses on a process of checking the packaging and removing the labels with heat guns. In some of the analysed cases (e.g., Retailer 5 and Retailer 7), a cleaning process (with water and cleaning agent) is also required.

After defining the different alternatives, we first present the findings

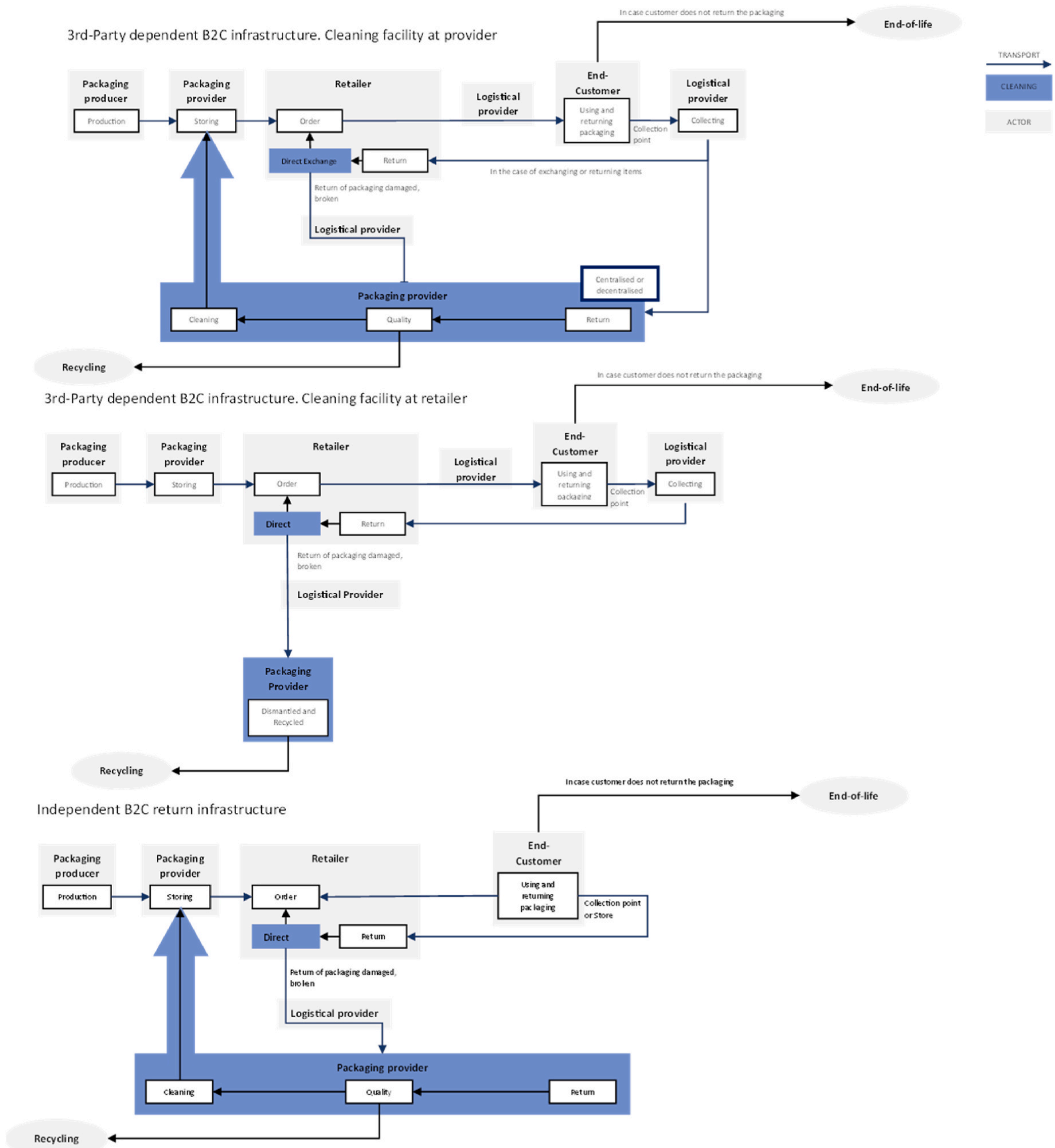

Fig. 2. Supply chain strategies. Adapted from Mission Reuse (2023)

per case study, identifying the reusable packaging solution and supply chain, and developing a cycle analysis. In this sense, we analyse the CO_2 emissions of reusable packaging through its life cycle. Then, we develop this same cycle analysis but through a sensitivity analysis, comparing the impact of all solutions using a similar situation. Through these explanations, numerical information will be used to support and argue the findings. However, the data comes from specific case studies, so caution is required in generalising these values.

4.1. Cycle analysis

Cycle analysis was developed by comparing the eight case studies to the two most widely used single-use packaging solutions: a cardboard box and a polypropylene mailing bag. Tables 4 and 5 illustrate the kg of CO_2 emissions per retailer and cycle, as well as the percentage of variation in CO_2 emissions between reusable and single-use packaging (i.e., cardboard box and mailing bag, respectively). Cycle 0 reflects the CO_2 emissions of production. From cycle 1 onwards, every cycle reflects the accumulated CO_2 emissions for the use of such packaging. It means that cycle 1 represents the CO_2 emissions for using one single-use packaging and one reusable packaging (taking reverse logistics into account). Cycle 2, however, represents the CO_2 emissions for using two single-use packaging and one reusable packaging shipped twice. From cycle 1 onwards, we considered the return rate and reuse rate, accounting for a percentage of the CO_2 emissions of the reusable packaging that cannot be used again.

In general, almost every retailer's solution generates fewer CO_2 emissions than single-use packaging at some point in its life cycle (break-even point). Moreover, all solutions that are more sustainable than single-use packaging achieved their break-even point long before completing their life cycle. Thus, comparing the cycle in which the break-even point is reached and the life cycle of each solution,

Table 4
Comparison between reusable packaging and cardboard box.

Cycle	Comparison between reusable and single-use packaging (cardboard box) CO_2 emissions											
	Retailer 1 Polypropylene bag 3rd-Party dependent infrastructure. Cleaning at provider (decentralised) Return rate: 87% Reuse rate: 99% Maximum cycles: 300			Retailer 2 Polyester bag 3rd-Party dependent infrastructure. Cleaning at provider (centralised) Return rate: 96% Reuse rate: 99% Maximum cycles: 100			Retailer 3 Polypropylene bag 3rd-Party dependent infrastructure. Cleaning at provider (centralised) Return rate: 20% Reuse rate: 85% Maximum cycles: 20			Retailer 4 Cardboard box 3rd-Party dependent infrastructure. Cleaning at provider (decentralised) Return rate: 80% Reuse rate: 70% Maximum cycles: 10		
	Single-use packaging (kg CO_2e)	Reusable packaging (kg CO_2e)	Variation (%)	Single-use packaging (kg CO_2e)	Reusable packaging (kg CO_2e)	Variation (%)	Single-use packaging (kg CO_2e)	Reusable packaging (kg CO_2e)	Variation (%)	Single-use packaging (kg CO_2e)	Reusable packaging (kg CO_2e)	Variation (%)
0	0.074	0.234	216%	0.074	0.650	779%	0.074	0.228	208%	0.074	0.050	−32%
1	0.723	0.773	7%	0.726	1.171	61%	0.464	0.555	20%	0.515	0.400	−22%
2	1.446	1.337	−8%	1.453	1.690	16%	0.927	1.098	18%	1.029	0.759	−26%
3	2.169	1.901	−12%	2.179	2.209	1%	1.391	1.641	18%	1.544	1.119	−28%
4	2.892	2.465	−15%	2.906	2.729	−6%	1.854	2.183	18%	2.059	1.478	−28%
5	3.615	3.030	−16%	3.632	3.248	−11%	2.318	2.726	18%	2.573	1.837	−29%
6	4.338	3.594	−17%	4.359	3.767	−14%	2.781	3.269	18%	3.088	2.196	−29%
7	5.060	4.158	−18%	5.085	4.286	−16%	3.245	3.812	17%	3.603	2.556	−29%
8	5.783	4.722	−18%	5.811	4.806	−17%	3.708	4.355	17%	4.117	2.915	−29%
9	6.506	5.286	−19%	6.538	5.325	−19%	4.172	4.898	17%	4.632	3.274	−29%
10	7.229	5.851	−19%	7.264	5.844	−20%	4.635	5.441	17%	5.147	3.634	−29%
Cycle	Comparison between reusable and single-use packaging (cardboard box) CO_2 emissions											
	Retailer 5 Polypropylene box 3rd-Party dependent infrastructure. Cleaning at retailer Return rate: 98% Reuse rate: 90% Maximum cycles: 250			Retailer 6 Polypropylene box 3rd-Party dependent infrastructure. Cleaning at provider (decentralised) Return rate: 80% Reuse rate: 99% Maximum cycles: 20			Retailer 7 Glass jar Independent B2C return infrastructure Return rate: 80% Reuse rate: 95% Maximum cycles: 1000			Retailer 8 Polypropylene bag 3rd-Party dependent infrastructure. Cleaning at retailer Return rate: 97% Reuse rate: 99% Maximum cycles: 50		
	Single-use packaging (kg CO_2e)	Reusable packaging (kg CO_2e)	Variation (%)	Single-use packaging (kg CO_2e)	Reusable packaging (kg CO_2e)	Variation (%)	Single-use packaging (kg CO_2e)	Reusable packaging (kg CO_2e)	Variation (%)	Single-use packaging (kg CO_2e)	Reusable packaging (kg CO_2e)	Variation (%)
0	0.231	0.990	328%	0.231	0.505	118%	0.074	0.086	17%	0.231	0.396	71%
1	1.290	1.365	6%	1.793	1.361	−24%	1.519	2.343	54%	1.366	0.722	−47%
2	2.580	1.835	−29%	3.585	2.322	−35%	3.037	4.603	52%	2.731	1.063	−61%
3	3.871	2.304	−40%	5.378	3.284	−39%	4.556	6.862	51%	4.097	1.404	−66%
4	5.161	2.774	−46%	7.171	4.245	−41%	6.075	9.122	50%	5.462	1.746	−68%
5	6.451	3.243	−50%	8.963	5.207	−42%	7.593	11.382	50%	6.828	2.087	−69%
6	7.741	3.712	−52%	10.756	6.168	−43%	9.112	13.641	50%	8.193	2.428	−70%
7	9.032	4.182	−54%	12.548	7.130	−43%	10.631	15.901	50%	9.559	2.770	−71%
8	10.322	4.651	−55%	14.341	8.091	−44%	12.150	18.161	49%	10.925	3.111	−72%
9	11.612	5.121	−56%	16.134	9.053	−44%	13.668	20.420	49%	12.290	3.452	−72%
10	12.902	5.590	−57%	17.926	10.015	−44%	15.187	22.680	49%	13.656	3.794	−72%

Table 5
Comparison between reusable packaging and mailing bag.

Cycle	Comparison between reusable and single-use packaging (mailing bag) CO_2 emissions					
	Retailer 1 Polypropylene bag 3rd-Party dependent infrastructure. Cleaning at provider (decentralised) Return rate: 87% Reuse rate: 99% Maximum cycles: 300			Retailer 2 Polyester bag 3rd-Party dependent infrastructure. Cleaning at provider (centralised) Return rate: 96% Reuse rate: 99% Maximum cycles: 100		
	Single-use packaging (kg CO_2e)	Reusable packaging (kg CO_2e)	Variation (%)	Single-use packaging (kg CO_2e)	Reusable packaging (kg CO_2e)	Variation (%)
0	0.069	0.234	239%	0.069	0.650	842%
1	0.573	0.773	35%	0.577	1.171	103%
2	1.146	1.337	17%	1.153	1.690	47%
3	1.719	1.901	11%	1.730	2.209	28%
4	2.292	2.465	8%	2.307	2.729	18%
5	2.866	3.030	6%	2.883	3.248	13%
6	3.439	3.594	5%	3.460	3.767	9%
7	4.012	4.158	4%	4.036	4.286	6%
8	4.585	4.722	3.0%	4.613	4.806	4%
9	5.158	5.286	2.5%	5.190	5.325	3%
10	5.731	5.851	2.1%	5.766	5.844	1.4%
12				6.920	6.883	−0.53%
20						
24	13.755	13.750	−0.04%			

Cycle	Comparison between reusable and single-use packaging (mailing bag) CO_2 emissions								
	Retailer 3 Polypropylene bag 3rd-Party dependent infrastructure. Cleaning at provider (centralised) Return rate: 20% Reuse rate: 85% Maximum cycles: 20			Retailer 4 Cardboard box 3rd-Party dependent infrastructure. Cleaning at provider (decentralised) Return rate: 80% Reuse rate: 70% Maximum cycles: 10			Retailer 8 Polypropylene bag 3rd-Party dependent infrastructure. Cleaning at retailer Return rate: 97% Reuse rate: 99% Maximum cycles: 50		
	Single-use packaging (kg CO_2e)	Reusable packaging (kg CO_2e)	Variation (%)	Single-use packaging (kg CO_2e)	Reusable packaging (kg CO_2e)	Variation (%)	Single-use packaging (kg CO_2e)	Reusable packaging (kg CO_2e)	Variation (%)
0	0.069	0.228	230%	0.069	0.050	−28%	0.069	0.396	474%
1	0.314	0.555	77%	0.365	0.400	10%	0.361	0.722	100%
2	0.627	1.098	75%	0.730	0.759	4%	0.722	1.063	47%
3	0.941	1.641	74%	1.095	1.119	2%	1.083	1.404	30%
4	1.255	2.183	74%	1.459	1.478	1%	1.444	1.746	21%
5	1.569	2.726	74%	1.824	1.837	1%	1.805	2.087	16%
6	1.882	3.269	74%	2.189	2.196	0%	2.166	2.428	12%
7	2.196	3.812	74%	2.554	2.556	0.1%	2.527	2.770	10%
8	2.510	4.355	74%	2.919	2.915	−0.1%	2.888	3.111	8%
9	2.824	4.898	73%	3.284	3.274	0%	3.249	3.452	6%
10	3.137	5.441	73%	3.649	3.634	0%	3.610	3.794	5%
12									
20							7.219	7.208	−0.16%
24									

considering a cardboard box, the break-even point is between 0.7% and 10% of the reusable packaging's life cycle. When compared to a mailing bag, the break-even point is between 8% and 80% of the reusable packaging's life cycle. This means that, in most cases, the capacity of reusable packaging to handle many return cycles (e.g., 100 cycles) is not a factor influencing the environmental sustainability of reusable packaging. That is, providers could try to create reusable packaging with a shorter life cycle (e.g., 10 cycles), using less or cleaner materials and processes to create them.

However, three factors do influence the environmental impact of reusable packaging: (1) reusable packaging material, (2) return and reuse rate, and (3) supply chain design.

4.1.1. *Reusable packaging material*

Comparing cycle 0 (i.e., the production process only), most reusable packaging pollutes more than single-use packaging. This is due to the use of more polluting materials (i.e., polypropylene or polyester) instead of cardboard. Therefore, (1) the material used to create the reusable packaging is a factor affecting the sustainability of such packaging.

As mentioned before, four different materials (i.e., polypropylene, polyester, cardboard, and glass) can be used to create reusable packaging. To compare the impact of the different materials, Table 6 shows a comparison between the first two cycles for each packaging.

Focusing on polyester, this material is, according to the literature, much more pollutant per kilogram of material than other materials such as cardboard or polypropylene. Retailer 2 is the only one using polyester to create its bags. In Table 6, it can be seen that the production process of Retailer 2 emits 178% more CO_2 emissions than that of Retailer 1. Retailer 1 is using polypropylene to create its bags, which are similar in size and protection to those of Retailer 2. Similar reusable packaging is also produced by Retailer 4. However, Retailer 4 is using cardboard instead of polyester or polypropylene. In this sense, compared to Retailer 4, the production process of Retailer 2 emits 1201% more CO_2 emissions. Furthermore, the production process of Retailer 2 emits 842% more CO_2 emissions than the production of a traditional mailing bag. In this sense, the use of polyester triggers an increase in CO_2 emissions.

On the contrary, the use of cardboard to produce the reusable

Table 6
Comparison between reusable and single-use packaging (kg of CO_2 emissions per process – first two cycles).

	Activity	Retailer 1 Polypropylene bag 3rd-Party dependent infrastructure. Cleaning at provider (decentralised) Return rate: 87% Reuse rate: 99%			Retailer 2 Polyester bag 3rd-Party dependent infrastructure. Cleaning at provider (centralised) Return rate: 96% Reuse rate: 99%			Retailer 3 Polypropylene bag 3rd-Party dependent infrastructure. Cleaning at provider (centralised) Return rate: 20% Reuse rate: 85%		
		Single-use packaging (cardboard box) (kg CO_2e)	Single-use packaging (mailing bag) (kg CO_2e)	Reusable packaging (kg CO_2e)	Single-use packaging (cardboard box) (kg CO_2e)	Single-use packaging (mailing bag) (kg CO_2e)	Reusable packaging (kg CO_2e)	Single-use packaging (cardboard box) (kg CO_2e)	Single-use packaging (mailing bag) (kg CO_2e)	Reusable packaging (kg CO_2e)
First cycle	Production	0.074	0.069	0.234	0.074	0.069	0.650	0.074	0.069	0.228
	Direct logistics	0.321	0.321	0.321	0.325	0.325	0.325	0.062	0.062	0.006
	Reverse logistics	0.058	0.009	0.176	0.058	0.009	0.155	0.058	0.009	0.044
	Cleaning process	0.000	0.000	0.003	0.000	0.000	0.007	0.000	0.000	0.001
	Waste produced	0.270	0.174	0.039	0.270	0.174	0.033	0.270	0.174	0.276
	Total	0.723	0.573	0.773	0.726	0.577	1.171	0.464	0.314	0.555
Second cycle	Production	0.094	0.069	0.030	0.094	0.069	0.026	0.094	0.069	0.216
	Direct logistics	0.321	0.321	0.316	0.325	0.325	0.298	0.062	0.062	0.006
	Reverse logistics	0.058	0.009	0.176	0.058	0.009	0.155	0.058	0.009	0.044
	Cleaning process	0.000	0.000	0.003	0.000	0.000	0.007	0.000	0.000	0.001
	Waste produced	0.270	0.174	0.039	0.270	0.174	0.033	0.270	0.174	0.276
	Total	0.743	0.573	0.564	0.747	0.577	0.519	0.484	0.314	0.543

	Activity	Retailer 4 Cardboard box 3rd-Party dependent infrastructure. Cleaning at provider (decentralised) Return rate: 80% Reuse rate: 70%			Retailer 5 Polypropylene box 3rd-Party dependent infrastructure. Cleaning at retailer Return rate: 98% Reuse rate: 90%		Retailer 6 Polypropylene box 3rd-Party dependent infrastructure. Cleaning at provider (decentralised) Return rate: 80% Reuse rate: 99%	
		Single-use packaging (cardboard box) (kg CO_2e)	Single-use packaging (mailing bag) (kg CO_2e)	Reusable packaging (kg CO_2e)	Single-use packaging (cardboard box) (kg CO_2e)	Reusable packaging (kg CO_2e)	Single-use packaging (cardboard box) (kg CO_2e)	Reusable packaging (kg CO_2e)
First cycle	Production	0.074	0.069	0.050	0.231	0.990	0.231	0.505
	Direct logistics	0.113	0.113	0.113	0.034	0.034	0.536	0.536
	Reverse logistics	0.058	0.009	0.142	0.181	0.154	0.181	0.182
	Cleaning process	0.000	0.000	0.004	0.000	0.040	0.000	0.002
	Waste produced	0.270	0.174	0.091	0.844	0.148	0.844	0.136
	Total	0.515	0.365	0.400	1.290	1.365	1.793	1.361
Second cycle	Production	0.094	0.069	0.025	0.231	0.116	0.231	0.106
	Direct logistics	0.113	0.113	0.097	0.034	0.012	0.536	0.536
	Reverse logistics	0.058	0.009	0.142	0.181	0.154	0.181	0.182
	Cleaning process	0.000	0.000	0.004	0.000	0.040	0.000	0.002
	Waste produced	0.270	0.174	0.091	0.844	0.148	0.844	0.136
	Total	0.535	0.365	0.359	1.290	0.469	1.793	0.962

	Activity	Retailer 7 Glass jar Independent B2C return infrastructure Return rate: 80% Reuse rate: 95%		Retailer 8 Polypropylene bag 3rd-Party dependent infrastructure. Cleaning at retailer Return rate: 97% Reuse rate: 99%		
		Single-use packaging (cardboard box) (kg CO_2e)	Reusable packaging (kg CO_2e)	Single-use packaging (cardboard box) (kg CO_2e)	Single-use packaging (mailing bag) (kg CO_2e)	Reusable packaging (kg CO_2e)

(*continued on next page*)

Table 6 (*continued*)

	Activity	Retailer 7 Glass jar Independent B2C return infrastructure Return rate: 80% Reuse rate: 95%		Retailer 8 Polypropylene bag 3rd-Party dependent infrastructure. Cleaning at retailer Return rate: 97% Reuse rate: 99%		
		Single-use packaging (cardboard box) (kg CO_2e)	Reusable packaging (kg CO_2e)	Single-use packaging (cardboard box) (kg CO_2e)	Single-use packaging (mailing bag) (kg CO_2e)	Reusable packaging (kg CO_2e)
First cycle	Production	0.074	0.086	0.231	0.069	0.396
	Direct logistics	1.117	1.117	0.109	0.109	0.109
	Reverse logistics	0.058	0.890	0.181	0.009	0.195
	Cleaning process	0.000	0.034	0.000	0.000	0.000
	Waste produced	0.270	0.216	0.844	0.174	0.022
	Total	1.519	2.343	1.366	0.361	0.722
Second cycle	Production	0.074	0.022	0.295	0.069	0.016
	Direct logistics	1.117	1.098	0.106	0.109	0.076
	Reverse logistics	0.058	0.890	0.181	0.009	0.195
	Cleaning process	0.000	0.034	0.000	0.000	0.000
	Waste produced	0.270	0.216	0.844	0.174	0.022
	Total	1.519	2.260	1.426	0.361	0.308

packaging can have a positive impact in CO_2 emissions. Thus, although in most cases the difference in CO_2 emissions between the production of reusable packaging and single-use packaging is relevant, for Retailer 4 this process emits less in the case of reusable packaging. This happens because it is using less quantities of cardboard (−32%) to produce its reusable packaging, making its solution better from a production perspective.

Analysing the use of glass, i.e., the case of Retailer 7 exemplifies how the use of this material to produce its reusable packaging brings the emissions of production closer between reusable and single-use packaging.

Thus, the comparison of the production process using four different materials to produce reusable packaging (i.e., polyester, polypropylene, cardboard, and glass) points out the importance of material selection in creating sustainable solutions.

4.1.2. *Return and reuse rate*

Related to the production process, if retailers have a high return and reuse rate, from the second cycle onwards, the CO_2 emissions from the reusable packaging production process will be lower than the emissions from the production of single-use packaging. This is due to the low number of new reusable packaging units that retailers need to produce every month.

Therefore, (2) return and reuse rate is the second factor affecting the sustainability of reusable packaging.

This factor impacts the sustainability of reusable packaging in terms of CO_2 emissions, influencing whether this solution is more sustainable or not than single-use packaging. For example, this factor explains why, for Retailer 3, reusable packaging is not more sustainable than single-use packaging in terms of CO_2 emissions. The lower return and reuse rate of Retailer 3 is triggered by low customer involvement in the return process of reusable packaging. In this respect, only 20% of Retailer 3 customers who receive reusable packaging decide to return it. This lower return and reuse rate (i.e., only 17% of reusable packaging is returned by the end customer to the provider and can be used again) means that reusable packaging must continue to be produced every month. Thus, CO_2 emissions from the second cycle onwards are kept at similar levels to those of the first cycle. This situation can be observed in Table 6. As an illustration, comparing the production process of Retailer 3 and Retailer 1, the difference in CO_2 emissions goes from −3% in the first cycle to 610% from the second cycle onwards. As mentioned above, the reusable packaging of both retailers has similar characteristics, but their return and reuse rate is completely different.

Thus, in general, a low return and reuse rate means that a larger number of packaging needs to be produced each month, as reusable packaging sent in the previous month are not reused. In this situation, emissions from the production process will be similar in all cycles. This makes it impossible to reduce emissions cycle by cycle, making single-use packaging more beneficial than reusable packaging.

But not only production is affected by the return and reuse rate. The waste produced by reusable packaging is, in general, less pollutant than that produced by single-use packaging (see Table 6). This happens because reusable packaging is not being thrown away in every cycle. In this sense, the return and reuse rate must be high to ensure this situation. Again, Retailer 3 is an example of this. Its return and reuse rate is low enough to make the waste produced by reusable packaging more pollutant than that produced by single-use packaging.

Thus, these previous analyses justify the influence of the return and reuse rate on production and waste produced, highlighting the impact of this rate on the environmental sustainability of reusable packaging.

4.1.3. *Supply chain design*

A lower return and reuse rate is not the only factor that can influence this situation. Observing Tables 4 and 5, it is evident that there are important differences in CO_2 emissions depending on the supply chain strategy chosen. So, the last factor affecting the environmental sustainability of reusable packaging is the (3) supply chain design. First, it is clear that the use of a 3rd-Party dependent B2C infrastructure, where the provider is responsible for a centralised cleaning process, has a major impact on CO_2 emissions. In this sense, the two retailers using this design, Retailer 3 and Retailer 2, have greater problems in making reusable packaging more sustainable than single-use packaging, with Retailer 3 being unable to achieve this. This centralised cleaning process means that all returned reusable packaging must go to the provider's central facility, regardless of where the retailer is located. From there, reusable packaging must go back to the retailer's facility. This leads to an increase in the number of kilometres travelled by packaging and in CO_2 emissions.

From the opposite point of view, the use of 3rd-Party dependent B2C infrastructure where the cleaning process is the responsibility of the retailer should be mentioned. In this design, used by Retailer 5 and Retailer 8, the e-retailer is responsible for managing the delivery and return of reusable packaging to and from the customer. Additionally, reusable packaging does not have to go all the way to the provider, to come back the next month. This supply chain design means a reduction in kilometres travelled compared to the previous strategy.

Differences between these supply chain designs can be observed in Table 6. In the case of direct logistics, the emissions of the first cycle are identical for reusable and single-use packaging, because all packaging (regardless of their type) must be delivered to the provider and retailer once. When assessing the second cycle (and onwards), direct logistics' emissions drop between 0% and 64%, or 16% on average, due to all the reusable packaging that does not have to go from the producer to the provider and from the provider to the retailer. Retailers using a 3rd-Party dependent B2C infrastructure, where the provider is responsible for the cleaning process (e.g., Retailer 1, Retailer 2, Retailer 3, Retailer 4, Retailer 6) and all the reusable packaging must travel from provider to retailer in every cycle, perceive a smaller dropout from the first to second cycle. In contrast, Retailer 5, and Retailer 8, using a 3rd-Party dependent B2C infrastructure, where the retailer is responsible for the cleaning process and just the new reusable packaging must travel from provider to retailer in every cycle, perceives a bigger dropout from first to the second cycle. In this sense, a smaller dropout means that CO_2 emissions remain similar in all cycles, making it difficult for reusable packaging to emit fewer emissions than single-use packaging.

As a supply chain design, Independent B2C Return Infrastructure is only used by Retailer 7. This design, as mentioned before, means that end-customers must collect their online orders and return their reusable packaging at a store. Thus, dedicated trips to stores are developed by customers using, mainly, diesel cars. This situation, compared with delivery and collection by van with a high occupation rate, triggers the CO_2 emissions. This can be observed in Table 6. For example, for Retailer 7, reverse logistics accounts for 38% of CO_2 emissions in the first cycle. This percentage drops to 13% for Retailer 6, where consumers do not have to return the packaging at a retailer's store. This supply chain design, where the responsibility for reverse logistics lies with the customer, does not allow reusable packaging to be more environmentally sustainable than single-use packaging.

Another aspect related to supply chain design that has an impact on CO_2 emissions is the actor producing the reusable packaging. Providers who produce their packaging (e.g., Retailer 2) do not have to account for the emissions of the transport from producer to provider. This allows the direct logistics to have a lower impact on CO_2 emissions. However, the emissions of the direct logistics in the first and second cycle are similar. It means that there is not a large emission reduction in the second cycle, as in other supply chain designs. That is because, if the provider produces the packaging, the expected reduction in the production of packaging for the second cycle will not reduce the trips and kilometres related to the transport of this packaging from the producer to the provider.

Analysing the supply chain design, when assessing reverse logistics, it is important to mention that this operation is usually more pollutant in reusable packaging than in single-use packaging. In this sense, in a reusable supply chain, packaging must be delivered from the customer's home or a collection point to the retailer's or provider's facilities. In contrast, single-use packaging is collected by waste collection systems (i.e., more efficient and less pollutant per package). However, analysing Table 6, the reverse logistics of Retailer 3 and Retailer 5 are less pollutant in reusable packaging than in single-use packaging. For Retailer 3, the use of sustainable vehicles to develop the reverse logistics is the reason for this situation. For Retailer 5, their supply chain (mentioned in the previous paragraphs), as well as the proximity between customers and retailer and their high return and reuse rate (88%), facilitate that collecting the waste of single-use packaging produces more emissions than the whole reverse logistics of the reusable packaging.

It is also important to mention that the large differences in direct and reverse logistics CO_2 emissions between case studies are related to different travel distances and transport modes. In this sense, the average distance travelled by reusable packaging was 1741 km. However, when comparing the case studies with more and less distance (Retailer 6 and Retailer 7), the difference reaches 5393%. Excluding Retailer 6 (distance includes ocean crossings) and Retailer 7 (customers must collect and return the reusable packaging at a store), the difference between the case studies with more and less distance reaches 404%. Thus, by increasing the number of kilometres travelled, CO_2 emissions linked to direct and reverse logistics increase. This situation is also mediated by the transport mode used. Thus, some cases are using planes to ship their orders, increasing the CO_2 emissions of their direct and reverse logistics, while others are using sustainable vehicles (e.g., electric vans). For example, for Retailer 3, who is using electric vans, cargo bikes, and electric motorbikes, direct logistics for reusable packaging is 90% less pollutant than the same process for single-use packaging.

It is therefore clear that the supply chain design, and the different elements around it (e.g., travel distances and transport modes), impact on the environmental sustainability of reusable packaging.

One element not mentioned about Table 6 is the cleaning process. In this sense, despite the need to clean and/or recondition reusable packaging for its next use, the impact of this process on CO_2 emissions is very low. This is because not all retailers need to wash their reusable packaging. Furthermore, the reconditioning process is very fast and not very electricity intensive.

Finally, as an overview, this section described how three factors influence the environmental impact of reusable packaging: (1) reusable packaging material, (2) return and reuse rate, and (3) supply chain design. In this sense, the use of carboard, a higher return and reuse rate, and the implementation of a decentralised supply chain can reduce the environmental impact of reusable packaging.

4.2. Sensitivity analysis

To further investigate how certain factors influence the sustainability of reusable packaging, a sensitivity analysis was carried out. Through this analysis, the impact of factors (1) - material used to create the reusable packaging - and (3) - supply chain design - is further analysed. Thus, the sensitivity of the results to changes in these factors is developed. To do that, the number of online orders, the return and reuse rate, and the location of the retailer and end-customer remain constant. At the same time, each type of reusable packaging and supply chain strategy are evaluated.

Specifically, the environmental impact of serving Retailer 1 was calculated through each provider's strategy. Retailer 1 was selected for being the most mature e-retailer in the use of reusable packaging, as well as for its high number of online orders being shipped using reusable packaging. For each provider, the type of reusable packaging used, and the supply chain strategy were maintained. However, the number of online orders, the return and reuse rate, and the location of the retailer and end-customer were adapted from Retailer 1.

First, the impact of different supply chain strategies was evaluated. To do that, direct and reverse logistics should be assessed.

The use of an Independent B2C infrastructure (Retailer 7) has a major negative impact on emissions related to direct logistics. Generally, direct logistics in the first cycle is the same for reusable and single-use packaging. However, for e-retailers using this strategy, observing Table 7, reusable packaging's CO_2 emissions are much higher than those of single-use packaging in the first cycle. Here, the dedicated journeys from end-customers to the retailer's stores create this impact. Furthermore, these same dedicated customer journeys of Retailer 7 also make its

Table 7
Sensitivity analysis.

	Activity	Retailer 1 Polypropylene bag 3rd-Party dependent infrastructure. Cleaning at provider (decentralised) Return rate: 87% Reuse rate: 99%				Retailer 2 Polyester bag 3rd-Party dependent infrastructure. Cleaning at provider (centralised) Return rate: 96% Reuse rate: 99%			
		Single-use packaging (Small cardboard box) (kg CO_2e)	Single-use packaging (Polypropylene mailing bag) (kg CO_2e)	Single-use packaging (Cardboard mailing bag) (kg CO_2e)	Reusable packaging (kg CO_2e)	Single-use packaging (Small cardboard box) (kg CO_2e)	Single-use packaging (Polypropylene mailing bag) (kg CO_2e)	Single-use packaging (Cardboard mailing bag) (kg CO_2e)	Reusable packaging (kg CO_2e)
First cycle	Production	0.074	0.069	0.012	0.234	0.074	0.069	0.012	0.650
	Direct logistics	0.321	0.321	0.321	0.321	0.306	0.306	0.306	0.306
	Reverse logistics	0.058	0.009	0.009	0.176	0.058	0.009	0.009	0.287
	Cleaning process	0.000	0.000	0.000	0.003	0.000	0.000	0.000	0.007
	Waste produced	0.270	0.174	0.043	0.039	0.270	0.174	0.043	0.108
	Total	0.723	0.573	0.385	0.773	0.708	0.558	0.370	1.358
Second cycle	Production	0.074	0.069	0.012	0.030	0.074	0.069	0.012	0.085
	Direct logistics	0.321	0.321	0.321	0.316	0.306	0.306	0.306	0.282
	Reverse logistics	0.058	0.009	0.009	0.176	0.058	0.009	0.009	0.287
	Cleaning process	0.000	0.000	0.000	0.003	0.000	0.000	0.000	0.007
	Waste produced	0.270	0.174	0.043	0.039	0.270	0.174	0.043	0.108
	Total	0.723	0.573	0.385	0.564	0.708	0.558	0.370	0.768

	Activity	Retailer 3 Polypropylene bag 3rd-Party dependent infrastructure. Cleaning at provider (centralised) Return rate: 20% Reuse rate: 85%				Retailer 4 Cardboard box 3rd-Party dependent infrastructure. Cleaning at provider (decentralised) Return rate: 80% Reuse rate: 70%			
		Single-use packaging (Small cardboard box) (kg CO_2e)	Single-use packaging (Polypropylene mailing bag) (kg CO_2e)	Single-use packaging (Cardboard mailing bag) (kg CO_2e)	Reusable packaging (kg CO_2e)	Single-use packaging (Small cardboard box) (kg CO_2e)	Single-use packaging (Polypropylene mailing bag) (kg CO_2e)	Single-use packaging (Cardboard mailing bag) (kg CO_2e)	Reusable packaging (kg CO_2e)
First cycle	Production	0.074	0.069	0.012	0.228	0.074	0.069	0.012	0.050
	Direct logistics	0.562	0.562	0.562	0.006	0.587	0.587	0.587	0.587
	Reverse logistics	0.058	0.009	0.009	0.006	0.058	0.009	0.009	0.144
	Cleaning process	0.000	0.000	0.000	0.003	0.000	0.000	0.000	0.007
	Waste produced	0.270	0.174	0.043	0.038	0.270	0.174	0.043	0.024
	Total	0.964	0.814	0.626	0.281	0.989	0.839	0.651	0.811
Second cycle	Production	0.074	0.069	0.012	0.030	0.074	0.069	0.012	0.007
	Direct logistics	0.562	0.562	0.562	0.001	0.587	0.587	0.587	0.560
	Reverse logistics	0.058	0.009	0.009	0.006	0.058	0.009	0.009	0.144
	Cleaning process	0.000	0.000	0.000	0.003	0.000	0.000	0.000	0.007
	Waste produced	0.270	0.174	0.043	0.038	0.270	0.174	0.043	0.024
	Total	0.964	0.814	0.626	0.077	0.989	0.839	0.651	0.740

	Activity	Retailer 5 Polypropylene box 3rd-Party dependent infrastructure. Cleaning at retailer Return rate: 98% Reuse rate: 90%			Retailer 6 Polypropylene box 3rd-Party dependent infrastructure. Cleaning at provider (decentralised) Return rate: 80% Reuse rate: 99%		
		Single-use packaging (Medium cardboard box) (kg CO_2e)	Single-use packaging (Big cardboard box) (kg CO_2e)	Reusable packaging (kg CO_2e)	Single-use packaging (Medium cardboard box) (kg CO_2e)	Single-use packaging (Big cardboard box) (kg CO_2e)	Reusable packaging (kg CO_2e)

(*continued on next page*)

Table 7 (*continued*)

	Activity	Retailer 5 Polypropylene box 3rd-Party dependent infrastructure. Cleaning at retailer Return rate: 98% Reuse rate: 90%			Retailer 6 Polypropylene box 3rd-Party dependent infrastructure. Cleaning at provider (decentralised) Return rate: 80% Reuse rate: 99%		
		Single-use packaging (Medium cardboard box) (kg CO_2e)	Single-use packaging (Big cardboard box) (kg CO_2e)	Reusable packaging (kg CO_2e)	Single-use packaging (Medium cardboard box) (kg CO_2e)	Single-use packaging (Big cardboard box) (kg CO_2e)	Reusable packaging (kg CO_2e)
First cycle	Production	0.153	0.231	0.990	0.153	0.231	0.505
	Direct logistics	0.099	0.099	0.099	0.509	0.509	0.509
	Reverse logistics	0.120	0.181	0.196	0.120	0.181	0.545
	Cleaning process	0.000	0.000	0.039	0.000	0.000	0.002
	Waste produced	0.557	0.844	0.165	0.557	0.844	0.084
	Total	0.928	1.355	1.489	1.338	1.766	1.645
Second cycle	Production	0.153	0.231	0.129	0.153	0.231	0.066
	Direct logistics	0.099	0.034	0.077	0.509	0.536	0.509
	Reverse logistics	0.120	0.181	0.196	0.120	0.181	0.545
	Cleaning process	0.000	0.000	0.039	0.000	0.000	0.002
	Waste produced	0.557	0.844	0.165	0.557	0.844	0.084
	Total	0.928	1.290	0.607	1.338	1.793	1.206

	Activity	Retailer 7 Glass jar Independent B2C return infrastructure Return rate: 80% Reuse rate: 95%			Retailer 8 Polypropylene bag 3rd-Party dependent infrastructure. Cleaning at retailer Return rate: 97% Reuse rate: 99%			
		Single-use packaging (Medium cardboard box) (kg CO_2e)	Single-use packaging (Big cardboard box) (kg CO_2e)	Reusable packaging (kg CO_2e)	Single-use packaging (Small cardboard box) (kg CO_2e)	Single-use packaging (Polypropylene mailing bag) (kg CO_2e)	Single-use packaging (Cardboard mailing bag) (kg CO_2e)	Reusable packaging (kg CO_2e)
First cycle	Production	0.153	0.074	0.086	0.231	0.069	0.012	0.396
	Direct logistics	0.851	0.851	48.784	0.158	0.158	0.158	0.158
	Reverse logistics	0.120	0.058	0.979	0.181	0.009	0.009	0.014
	Cleaning process	0.000	0.000	0.001	0.000	0.000	0.000	0.000
	Waste produced	0.557	0.270	0.113	0.844	0.174	0.043	0.070
	Total	1.680	1.253	49.962	1.415	0.410	0.222	0.639
Second cycle	Production	0.153	0.074	0.011	0.231	0.069	0.012	0.052
	Direct logistics	0.851	0.851	48.574	0.106	0.158	0.158	0.085
	Reverse logistics	0.120	0.058	0.979	0.181	0.009	0.009	0.014
	Cleaning process	0.000	0.000	0.001	0.000	0.000	0.000	0.000
	Waste produced	0.557	0.270	0.113	0.844	0.174	0.043	0.070
	Total	1.680	1.253	49.678	1.362	0.410	0.222	0.221

reverse logistics' emissions higher in reusable packaging than in single-use packaging.

In those retailers using a 3rd-Party dependent B2C infrastructure where the centralised cleaning process is the responsibility of the provider (Retailer 2), reverse logistics for reusable packaging has higher CO_2 emissions than for single-use packaging. This is because reusable packaging must travel more kilometres to arrive at the cleaning facility and to go back to the retailer. The exception to this is Retailer 3. Thus, even though Retailer 3 is using that same supply chain strategy (3rd-Party dependent B2C infrastructure where the centralised cleaning process is the responsibility of the provider), the usage of sustainable vehicles for deliveries and collections of reusable packaging means that the impact of direct and reverse logistics is greatly reduced compared to other retailers using the same supply chain strategy.

On the contrary, for retailers using 3rd-Party dependent B2C infrastructure where the cleaning process is the responsibility of the retailer (i.e., Retailer 5 and Retailer 8), the impact of reverse logistics for reusable packaging is lower than the impact for single-use packaging (small cardboard box). This is because this reverse logistics only has to account for the kilometres between the customer and the retailer, removing the transport between the customer and the provider.

Now, the importance of supply chain design is more evident. After isolating the impact of supply chain strategy selection, e-retailers should focus on implementing decentralised structures, in which customer and packaging travels are kept to a minimum and the use of sustainable vehicles is promoted.

As far as materials are concerned, comparing the same situation, it is more evident now that the use of polyester to create similar packaging has a bigger impact on the sustainability of reusable packaging, especially when compared to other materials such as cardboard or glass. For example, Retailer 1 and Retailer 2 uses similar packaging with respect to size, shape, and weight. However, Retailer 1 uses a polypropylene packaging and Retailer 2 a polyester packaging. Thus, for the first cycle, Retailer 2 is emitting 178% more CO_2 emissions in the production of reusable packaging compared Retailer 1. For similar packaging, the production of polyester emits more CO_2 emissions than the production of polypropylene. In this sense, the selection of the material used to produce the reusable packaging becomes even more relevant. For the same type of packaging, there are already better solutions from the point of view of CO_2 emissions, such as reusable packaging made of cardboard (Retailer 4).

Lastly, in this sensitivity analysis, the comparison of reusable packaging with single-use packaging has been expanded by including more single-use packaging alternatives. For retailers using reusable bags, a comparison between small cardboard boxes, polypropylene mailing bags, and cardboard mailing bags is presented. For retailers using reusable boxes or jars, a comparison between medium and big carboard boxes is implemented. The comparison of reusable packaging with single-use packaging which uses less material (e.g., cardboard mailing bag, small or medium cardboard box) or less polluting materials (e.g., cardboard mailing bag versus polypropylene mailing bag) allows further detailing the situations where, from an environmental perspective, reusable packaging is a better option than single-use packaging.

Usually, reusable packaging is a better solution compared to small cardboard boxes and polypropylene mailing bags, but its advantage vanishes when compared with cardboard mailing bags. In this sense, using a less polluting material (cardboard) in a smaller quantity (−81% compared to polypropylene reusable packaging) is the justification for this change. This is the case of Retailer 1 and Retailer 4.

When comparing reusable packaging and medium cardboard boxes (Retailer 5, Retailer 6, and Retailer 7), reusable packaging is generally better than single-use packaging (medium and big cardboard boxes). The exception is Retailer 7. Here, supply chain design prevents reusable packaging from being environmentally sustainable.

Thus, even if the selection of single-use packaging is optimised (e.g., use of a less polluting material in a smaller quantity), a good choice of reusable packaging (material selection and supply chain design) will make the latter more sustainable in terms of CO_2 emissions.

4.3. Economic analysis

Even though reusable packaging can be environmentally sustainable, for e-retailers to implement these solutions, it should also be economically sustainable. Thus, an economic analysis of the eight case studies is presented. Figs. 3 and 4 represent a comparison between reusable packaging and two different single-use packaging: a cardboard box and a mailing bag. These figures present the cost of purchase for e-retailers, comparing the use of reusable packaging or single-use packaging. Thus, the monthly purchase cost of all the packaging needed for each e-retailer is represented in the following figures.

In general, reusable packaging tends to be more expensive than single-use packaging. For example, one polypropylene bag used by Retailer 1 is 36% more expensive than one cardboard box. Thus, the implementation of reusable packaging is an effort for e-retailers.

However, the right business model can reduce or erase this effort. In general, providers tend to use a pay-per-use system, where e-retailer must pay every time they use a reusable packaging, regardless of whether it is new or not. It means that e-retailers will pay for the same number of packaging, regardless of whether it is reusable or not. Thus, as reusable packaging is more expensive than single-use packaging, the monthly cost of using reusable packaging will be much higher (e.g., Retailer 2).

Another option is to use a pay-per-month system, where e-retailers only pay a fee every month for the packaging they keep in stock, regardless of how many times they reuse it. Here, e-retailers will pay only for their stock and not for all delivered orders. Thus, cost can be reduced when comparing reusable packaging and single-use packaging. That is the case of Retailer 8. Here, the use of reusable packaging is cheaper than the use of a cardboard box. This reduction of costs will be true if the return and reuse rate is very high and therefore stock is low (compared to the number of orders). The example of Retailer 3 can explain this. Retailer 3 uses a pay-per-month system. However, its reuse

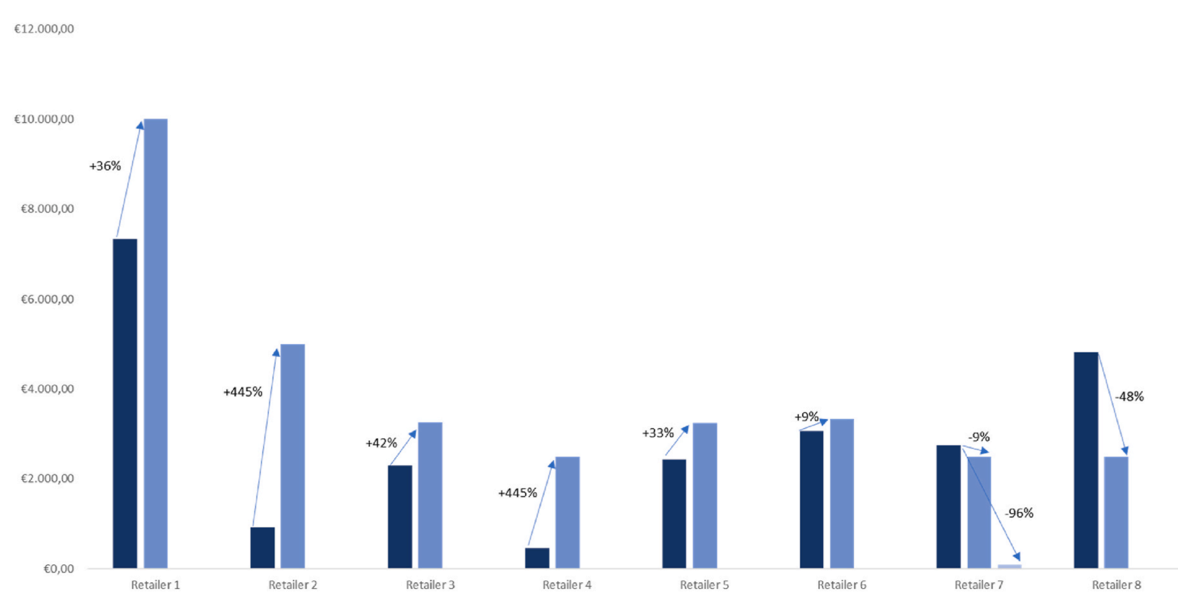

Fig. 3. Cost comparison between reusable packaging and single-use packaging (cardboard box).

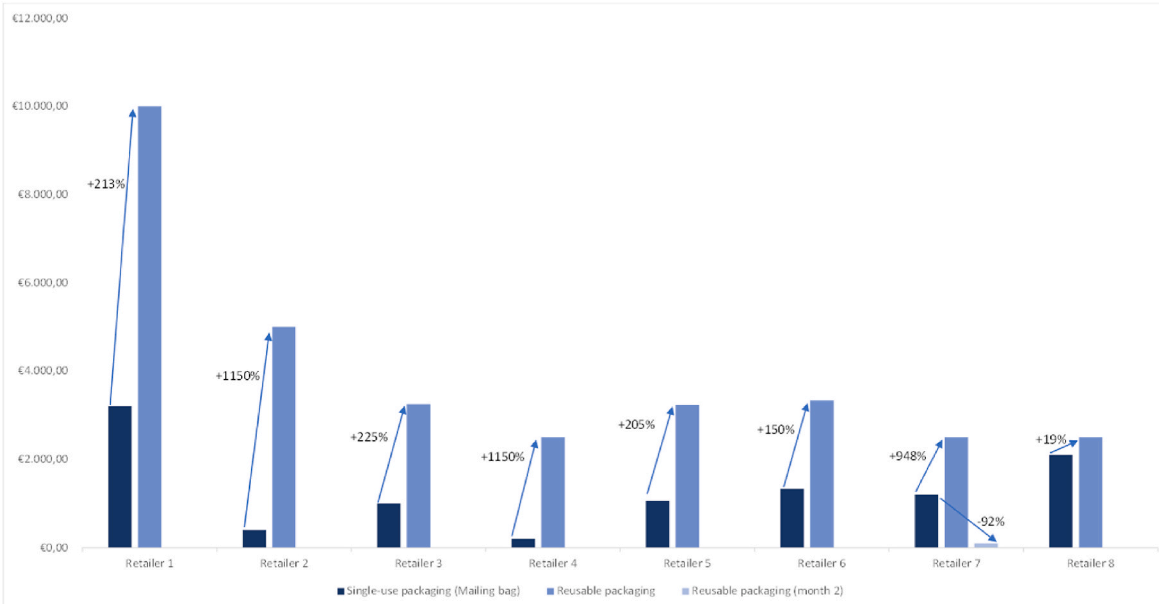

Fig. 4. Cost comparison between reusable packaging and single-use packaging (mailing bag).

and return rate is just 17%. This means that it needs a higher stock compared to its number of orders. Thus, it needs to pay for almost the same number of reusable packaging as if it was using a single-use packaging.

Lastly, for the deposit-refund system, e-retailers only pay the first time they use the reusable packaging. Thus, if a high return and reuse rate is ensured, the system will be cheaper than the use of single-use packaging. This is because that, after the first month, in each new cycle/month, the e-retailer will only need to pay for the reusable packaging that they could not reuse (e.g., because it is damage, or the customer did not return in). That is the case of Retailer 7. As it needs to pay for all the stock of reusable packaging in the first month, this solution is only cheaper compared to cardboard boxes. However, after this month, the savings with the use of reusable packaging are significant. Thus, unlike other business models in which every month retailers must pay the same (if the number of orders and the return and reuse rate remains the same), this system implies a high investment in the first month, which dissipates after the second month (if the return and reuse rate is high).

Following this analysis, to ensure that e-retailers see an economic benefit in this solution, providers should commit to a pay-per-month system or a deposit-refund system. Furthermore, a high return and reuse rate is essential to ensure this cost reduction.

5. Discussion

The findings from this study, and those from the previous literature have established the most relevant issues that providers and retailers should consider when trying to implement an environmentally sustainable reusable packaging system in e-commerce.

Three key factors (i.e., reusable packaging material, return and reuse rate, and supply chain design) are involved in the sustainability of reusable packaging systems in e-commerce. However, before focusing on them, the reluctance of online retailers to use reusable packaging to deliver their online orders may be one of the biggest difficulties for the implementation of these systems. As mentioned by Centola et al. (2018), when implementing new sustainable systems, behavioural change is always complex. However, the right business model can facilitate this transition. Although research has focused on a deposit-refund system (Zimmermann and Bliklen, 2020; Bocken et al., 2022), where e-retailers only pay the first time they use a package, most cases we analysed use a pay-per-use system. Here, the e-retailer must pay every time they use a reusable packaging, regardless of whether it is new or not. However, as shown in the findings, this system increases costs for e-retailers (as a unit of reusable packaging tends to be more expensive than a unit of single-use packaging). To tackle this problem, some providers selected the option presented in the literature, using a deposit-refund system with a service fee or a pay-per-month system. In addition to the economic benefits demonstrated by this study, it is necessary to mention the importance of economy of scale to reduce costs in the use of reusable packaging.

To be able to develop this solution, supply chain design must be done in a certain way. Thus, this design is decisive for the establishment of reusable packaging systems that are environmentally sustainable from a CO_2 emissions perspective. It is important to mention that this selection should always be subordinated by the specific case of analysis. It means that the appropriate solution will depend on the context of each case (e.g., Zimmermann and Bliklen, 2020). However, considering the business model, to attract retailers through a deposit-refund system, providers and retailers should opt for a decentralised pooling system (Kurata, 2014). This decentralised structure can be achieved through a 3rd-Party dependent B2C infrastructure with a cleaning facility at a retailer or an independent B2C return infrastructure. In this sense, the latter alternative involves the use of passenger cars by end-consumers to collect and return reusable packaging, which has a high impact on CO_2 emissions. Thus, the most recommendable option from a carbon footprint perspective is a 3rd-Party dependent B2C infrastructure with a cleaning facility at a retailer. This leaner structure provides operational ease that facilitates the adoption of reusable packaging from a retailer and provider perspective. In this sense, it leads to a considerable reduction in the kilometres that reusable packaging must travel. In addition to this operational ease, this structure enables the environmental sustainability of the use of reusable packaging.

From a centralised pooling system perspective, this same benefit (e.g., leaner structure) occurs when implementing a 3rd-Party dependent B2C infrastructure, where the decentralised cleaning process is the responsibility of the provider. In this system, the provider implements multiple and identical supply chains in each country of operations, creating a warehouse to store the packaging and a cleaning facility to clean and refurbish it (Mission Reuse, 2023). However, when creating decentralised facilities in different countries, providers struggle to replicate their supply chains due to the different idiosyncrasies that each country has. In this regard, replication should be replaced by a solution adapted to the specific case in some countries.

Additionally, when opting to clean locally at the retailer's or a decentralised provider's facility, to promote implementing an environmentally and economically sustainable system, it is interesting to create partnerships with logistics providers (e.g., Bocken et al., 2022). These partnerships should be focused on facilitating packaging returns for the customer (e.g., collection points), leading to a higher return rate, and reducing the cost of return for the provider and the retailer. As well as such partnerships with logistics providers, it is also interesting to create them to extend the supply chain and the uses of reusable packaging. For example, one of the companies allows end-consumers to use reusable packaging for shipping their sales made through second-hand clothing platform Vinted. A higher return rate and an extended supply chain would trigger greater reuse of reusable packaging, facilitating its environmental sustainability.

Thus, the extended supply chain, as well as the partnerships with logistics providers, can encourage the end-customer to adopt reusable packaging, which is one of the most important factors in the sustainability of the system (Zimmermann and Bliklen, 2020). Customers are responsible for closing the reusable supply chain, as they are the ones who make the decision whether to return reusable packaging (Bocken et al., 2022). However, to keep the return rate as high as possible, the best solution according to the interviewees is to make the use of reusable packaging an option for the end-customer, who can choose it at the check-out. Furthermore, providers and retailers are opting for a no-fee system, where the end-customer receives a discount for returning the packaging. Another option not mentioned in the literature is to charge a deposit to the customer a couple of weeks after the online order has been delivered and if the reusable packaging has not been returned. To facilitate this return process, providers and retailers should ensure continuous communication with end-customers (Bocken et al., 2022). To do so, interviewees mentioned the importance of creating online applications that ease returns at collection points. In this sense, when comparing the return rate of the different cases within the sample, implementing a proper customer communication system can help increase the return rate. Despite all this effort, convincing the end-customer to use reusable packaging, as well as to return it once chosen, remains one of the major difficulties of this system (Bocken et al., 2022) and one of the most important factors for its environmental sustainability.

To ensure that the end-customer can choose the use of reusable packaging at the check-out, interviewees mentioned the importance of developing IT integration between the e-retailer and the provider. This integration can be a long process. Moreover, it must ensure three things: that end-customers can visualise whether their order can be delivered using reusable packaging (due to volume or weight characteristics); that providers can reach out to end-customers if they do not return the packaging; and that all packaging is localised in real-time.

Finally, another important aspect is legislation. The packaging industry is facing changes in policies and regulations about usability and lifespan, in an attempt to favour a move in a circular direction (Pålsson and Olsson, 2023). These new regulations are facilitating the arrival of new reusable packaging solutions, as well as forcing retailers to change their perspective on shipping packaging. In these regulations, institutions are paying attention to the material used to create the packaging. In this sense, polypropylene is the favourite choice for the creation of durable reusable packaging (up to 300 cycles) (Zimmermann and Bliklen, 2020). However, given that maximised life cycle is not a determinant for the sustainability of the solution (as mentioned in the previous section), and that return rates remain low, the use of other materials, such as cardboard, is becoming an interesting solution. Although the life cycle is reduced (10 cycles maximum), so are the CO_2 emissions for its production and the price for the retailer, making it a more economically and environmentally profitable solution.

In general, three key factors (reusable packaging material, return and reuse rate, and supply chain design) are decisive in creating reusable packaging systems that are environmentally sustainable. Thus, insights from the eight case studies analysed facilitate decision making on these factors (e.g., a decentralised strategy as a better supply chain design). Furthermore, multiple elements around these factors are decisive in achieving this objective (e.g., business model selection, communication with the end-customer, IT integration with the provider …).

6. Conclusions

This paper investigates when the use of reusable packaging can be a sustainable alternative in e-commerce. Thus, the CO_2 emissions of all processes related to the supply chain of reusable and single-use packaging were analysed for eight case studies in Europe. E-commerce is growing rapidly, but the sector is struggling with the environmental impact of shipping packaging, as well as following new packaging regulations. Some studies have analysed the use of reusable packaging as a solution to this problem, but the variety of results cannot allow to generalise or transfer them to other contexts, making it impossible to determine the actual environmental sustainability of reusable packaging in e-commerce.

For this research, a method that can be used to evaluate different solutions and situations by calculating CO_2 emissions was developed and implemented. This method was applied to eight different case studies where different reusable packaging solutions, supply chain designs, and consumer behaviour were identified. We evaluated the CO_2 emissions of all processes related to the supply chain of reusable and single-use packaging: production, direct and reverse logistics, and waste management. In this sense, through a cycle, sensitivity, and economic analysis, the findings indicate that three specific factors influence the sustainability of reusable packaging: (1) reusable packaging material, (2) return and reuse rate, and (3) supply chain design.

In this sense, the material used to produce the reusable packaging, and the selection of certain materials (e.g., polyester), impacts on CO_2 emissions related to production and waste management of reusable packaging. For instance, for the same type of reusable packaging and supply chain design, it is found that polyester generates 215% more CO_2 emissions than cardboard in production and waste management. Furthermore, a low return and reuse rate affects the production and waste management, increasing the CO_2 emissions of these processes due to the need to produce more reusable packaging each month. The use of centralised supply chain design means an increase in the number of kilometres travelled by reusable packaging, increasing CO_2 emissions from direct and reverse logistics. Last, the use of more polluting modes of transport (e.g., planes, passenger vehicles) as opposed to sustainable vehicles also leads to an increase in these emissions.

Thus, as theoretical implications, this study implemented a method that assessed all process through the calculation of CO_2 emissions. The implementation of this method presents a complete analysis (cycle, sensitivity, and economic analysis) of the environmental impact of reusable packaging, determining the importance of three key factors. In this sense, in contracts to previous literature and through the comparison of eight case studies, we analysed different packaging solutions and contexts, taking into consideration and evaluating these circumstances. Thus, clear knowledge about when the use of reusable packaging is sustainable and which factors influence it was provided.

So far, these factors are not sufficiently considered in practice. As practical implications, this study establishes the basis for companies to implement the use of reusable packaging in an environmentally sustainable way. Thus, the findings indicate that the sustainability of reusable packaging in e-commerce needs a thorough process design with attention to these three factors (reusable packaging material, return and reuse rate, and supply chain design). These findings have made it possible to establish recommendations on the design of these factors. In this sense, when possible, a decentralised supply chain where packaging is cleaned at the retailer's facility (or at the provider's facility) is the best option to reduce the distance travelled by reusable packaging. Furthermore, as the life cycle is not determinant for the sustainability of the solution, the use of other materials, such as cardboard, to create reusable packaging is becoming an interesting solution. Communication with the end-consumer, as well as the creation of an easy and seamless return process, are also necessary measures to improve the return rate. Finally, the method presented in this paper can be used to evaluate different solutions and alternatives by calculating CO_2 emissions.

In more detail, the involvement of customers in the use of reusable packaging is decisive for its environmental sustainability. Customers are responsible for closing the reusable supply chain, as they are the ones who make the decision whether to return reusable packaging. In addition, in most cases, this decision requires an effort to travel to a collection point or a store to return the packaging. Thus, a system created without the involvement of customers, and which does not facilitate the return of packaging will trigger a decline in the return rate. In this sense, the findings reveal a difference between 20% and 98% in return rates. This difference in consumer behaviour is related to the difficulty of returning the reusable packaging to the provider due to the creation of supply chains that do not offer facilities for consumers (e.g., delivery points far away from the consumer, lack of information or online applications to facilitate the process). This will prevent the system from being sustainable from a CO_2 emissions perspective. Thus, the findings determined that this reuse rate is part of one of the three factors that affects the environmental sustainability of this solution.

Finally, these findings come from a study based on eight case studies from Europe, compared to previous studies that only focused on one specific case study. However, as the study is limited to eight providers and e-retailers, further research could use a larger worldwide sample to analyse whether, outside Europe, the sustainability of reusable packaging is dependent on other factors. Furthermore, due to the impact of consumer behaviour (e.g., return rate) on the sustainability of reusable packaging, research on consumer behaviour would be necessary. In this sense, it is important to know what consumers' attitudes towards the use of reusable packaging are, as well as which elements can facilitate the adoption of this solution. For this last point, research focusing on consumer response to the reusable packaging selection system, the return process, and incentives could be of great interest. As the physical internet begins to gain prominence in research and business, it would be appropriate to analyse how this system could facilitate the implementation of reusable packaging in e-commerce. Finally, a detailed study of CO_2 emissions produced by the transport of raw materials to create the packaging could also be of interest.

Funding

This work was supported by a grant from the "Ministerio de Universidades para la Formación de Profesorado Universitario" [FPU22/02741] and by a grant from the Research Foundation – Flanders [FWO Grant 12ZX923N]. Funding for open access charge: Universidade de Vigo/CRUE-CISUG.

CRediT authorship contribution statement

Iria González Romero: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Heleen Buldeo Rai:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Ángel Ortiz Bas:** Validation, Supervision, Investigation, Conceptualization. **J. Carlos Prado Prado:** Validation, Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Iria Gonzalez Romero reports financial support was provided by Government of Spain Ministry of Universities. Iria Gonzalez Romero reports financial support was provided by CRUE-CISUG. Heleen Buldeo Rai reports financial support was provided by Research Foundation Flanders. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

I have shared our data at the Attach File step

Acknowledgments

This work was supported by a grant from the "Ministerio de Universidades para la Formación de Profesorado Universitario" [FPU22/02741] and by a grant from the Research Foundation – Flanders [FWO Grant 12ZX923N].

Funding for open access charge: Universidade de Vigo/CRUE-CISUG.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.143738.

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