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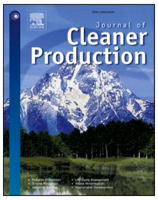

Life cycle assessment of reusable plastic food packaging

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ABSTRACT

The present study focuses on the cradle-to-grave life cycle assessment (LCA) of a reusable takeaway food container. The system boundary includes the production, transport, use, and end of life (EoL) stages of container, considering recycling and incineration, including all the inputs (material and energy) and outputs (emissions). Scenarios (10, 30, and 100 uses of a reusable container with EoL) were proposed and compared with a single-use container. The primary data was collected from industry and secondary data was taken from the literature and the Ecoienven 3.9.1 database. The functional unit (FU) was “one use of a container”, and the ReCiPe 2016 Midpoint (H) method was used. The results showed that with a centralised collection and washing system, the global warming potential (GWP) for a single-use container (0.020 kg CO_2 eq./FU) per FU had higher GWP than 10 uses (0.015 kg CO_2 eq./FU), 30 uses and 100 uses (0.007 kg CO_2 eq./FU) of the reusable container (EoL recycling). The GWP of a single-use container is 1.3 times higher than 10 uses of the container which results in a minimum six uses of the reusable container, providing a benefit over single-use container (EoL recycling). In EoL incineration, 10 uses scenario led to a decrease in the GWP of 46%, while 100 uses resulted in a significant reduction in the GWP of 83% compared to single-use per FU. It was found that the efficiency of the return system for empty containers significantly influenced the results. This study also quantified potential plastic waste for various scenarios.

1. Introduction

The global food packaging market was USD 363.8 billion in 2022 and is expected to reach USD 511.99 billion by 2028 (FPM, 2023). In 2020, the turnover of the European plastics industry showed a slight decrease compared to the previous year, mainly due to the impact of the Covid-19 crisis (Lamba et al., 2021). Plastic packaging is a major consumer of virgin materials, using up to 40% of plastics in Europe (Coelho et al., 2020). The virgin plastic produced is only used once, and it is not recovered after its use phase, meaning that it ends up as a waste material, causing pollution to water, land bodies, and oceans. Europe produces nearly 30 million tonnes of plastic waste annually, and the amount is increasing. Food packaging accounts for almost 60% of the plastic waste produced. Furthermore, the production of plastic contributes to greenhouse gas emissions (GHG) (Sæter et al., 2020). Plastic plays an important and growing role in modern society and a significant role in food safety and hygiene and can help in reducing food waste. However, the use of plastic packaging has both positive and negative impacts (Matthews et al., 2021), as mentioned in Fig. 1. The positive impact of plastic packaging stems from its light weight, which reduces transport costs (Schulze, 2016). Apart from financial benefits, plastics provide longevity, water resistance, high elasticity, durability, strength, and resistance to corrosion and can extend product shelf-life (Lamba et al., 2021).

Bertoluci et al. (2014) and Verghese et al. (2015) have debated the protective function of food packaging and highlighted the importance of environmental benefit. However, plastic entails a high production volume, short usage time (mostly single use), littering and waste management problems (Geueke et al., 2018). The environmental problems related to packaging waste have led to both legislation and research focusing on packaging prevention (Beitzen-Heineke et al., 2017). The European Union (EU) has implemented regulations for reduction of single-use plastics in food packaging since 2022. These regulations aim to decrease the environmental impact of disposable plastics by mandating the use of more sustainable materials and encouraging the use of reusable packaging. This policy shift is aligned with EU’s larger

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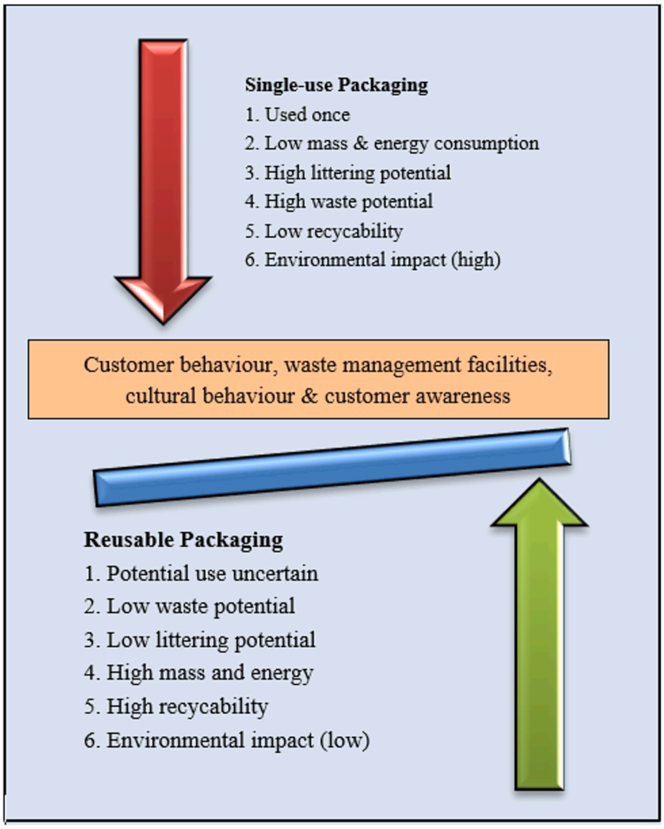

Fig. 1. Potential benefits and drawbacks of using different kinds of food packaging (single-use and reusable).

goal of promoting circular economy principles and reducing overall plastic waste.

Several changes to plastic use in the packaging industry have either already been implemented or are undergoing legislative processes. The EU aims that by 2030, “all plastics packaging placed on the EU market should be either reusable or recyclable in a cost-effective manner” (EUROPARC, 2018). According to the EU directive, the best methods to deal with plastic waste are to prevent and reduce their occurrence, reuse, and recycling (European Commission, 2018). Recycling has become an important pillar of the European economy and has high potential for growth due to the ecological legislation (Frackowiak et al., 2016). The plastics roadmap for Finland introduced several actions, including the avoidance of unnecessary plastics consumption, the reuse of packaging material, improvement of recycling efficiency, and finding alternative solutions to minimise the environmental impact of plastic (Ministry of the Environment, 2019).

The life cycle assessment (LCA) is one of the most recognised and widely used tool for assessing a product’s potential environmental sustainability in supporting decision making and policymaking (ISO, 2006). This study uses LCA to assess the environmental impact of a reusable polypropylene (PP) takeaway food container. The study considers the packaging product across the chain, from manufacturing to the use phase and end-of-life (EoL). It is impossible to determine the absolute number of uses for a reusable takeaway food container. Due to this uncertainty, the study proposes various scenarios for the potential number of uses of a reusable container in Finnish conditions.

In the literature, few studies have focused on the benefits of reusable takeaway food containers and their EoL options. Shokri et al. (2014) have highlighted environmental concerns associated with the use of food packaging boxes. However, most studies have focused on waste generation and management rather than applying a full life cycle perspective. Woods and Bakshi (2014); Van der Harst and Potting (2014) and Potting and Van der Harst (2015) analysed the environmental impacts of reusable cups and discussed the implementation of eco-design criteria in fast-food packaging. Gallego-Schmid et al. performed a study in 2018 and 2020 related to reusable plastic and glass, assessing the environmental impact of a Tupperware box compared with other boxes. Arunan and Crawford (2021) conducted a study related to a single-use box, bags, straw, and cups. Changwichan and Gheewala 2020 compared various food packaging materials and single-use and reusable packaging. Another study was conducted by Camps-Posino et al. (2021) in China of takeaway food container and its environmental impact, but this study considered very regional Chinese conditions and a specific pattern of food delivery on a regional scale that may not be relevant for the European market. Sæter et al. (2020) mentioned that reusable packaging has the potential to minimise plastic waste and energy consumption by creating long-life products and reducing the consumption of virgin material (Aryan et al., 2019, Yadav and Samadder 2018). Accorsi et al. (2022) studied the supply chain of reusable boxes in a secondary packaging system. Ramboll (2022) conducted a comparative study of single-use and reusable containers at a system level. It is important to assess the environmental benefits or drawbacks of reusable food packaging over other kinds of food packaging options available in the market, and thus is why the present study has been conducted. Reusable packaging can be one of the solutions as it reduces plastic waste, which is a major problem worldwide. Fig. 1 shows some of the differences between reusable and single-use food packaging and factors that affect the environmental load of such packaging. Although previously published LCA studies undertook a comparison based on the system level, they have not compared single-use container with reusable takeaway food container by using various scenario analysis and considering various sensitivity analysis parameters in Finland. This study is the first to focus on the environmental impact of a reusable takeaway food container in Finland with a cradle-to-grave approach considering unique delivery pattern of food packaging. This study will be very helpful for European readership and will provide significant evidence of reusable packaging for food in terms of the environmental impacts.

2. Methodology

This study follows the methodology and guidelines for conducting LCA of International Standardization Organization (ISO) 14040-14044: 2006. The procedure of the LCA was followed step by step: (a) the goal and scope of the study; (b) data collection and inventory analysis; (c) determination of environmental impacts; and (d) interpretation of results.

2.1. Goal and scope Definition

The goal of the study is to compare a reusable takeaway food container with a single-use takeaway food container. The LCA was conducted for the different life cycle stages of the containers, including production, transport, the use phase, and EoL. The reusable container was designed to be used many times, and there is no evidence concerning the container’s highest potential reuses. To identify the best potential uses of the container, we have therefore proposed various scenarios.

2.1.1. Functional unit

The environmental impact of a product is expressed by the functional unit (FU). This study considers “one use of a container” as the FU for the comparative analysis. The volume of the reusable takeaway food container is 1.2 L, and it is made of PP (lid and container). The total weight is 138 g (container 115 g and lid 23 g), the dimension of the container is 24 x 16 × 6 cm. The weight of the single-use container is 30 g and is made of PP (both lid and container). The single-use and reusable container hold the same quantity of food for every use.

2.1.2. *System boundary*

The system boundary of this study is “cradle-to-grave”, as shown in Fig. 2. This study considers all inputs (energy and material) and outputs (direct and indirect emissions) in the process. The assessment covered raw material extraction for PP, production of PP granules, manufacturing PP containers (single and reusable) from PP granules, transportation, reusable container washing, and EoL (single and reusable). The reusable container and single use container were assumed to be manufactured in Sweden and transported to Finland. The containers (single-use and reusable) were assumed to be distributed to grocery shops in Finland. The single and reusable container were assumed to be used by customers in towns for salad or food packaging (takeaway). The reusable container is assumed to be cleaned with a dishwasher after each use for hygiene. At its maximum potential uses, it is assumed to be recycled or incinerated with energy recovery. While single use container assumed to be recycled or incinerated after one use. The transportation distance for both containers considered same and based on theoretical analysis while data were taken from ecoinvent database 3.9.1. While washing data used in the study based on the literature and sources of data are given in Table 1.

2.2. *Life cycle inventory*

2.2.1. *Production*

The life cycle starts with the extraction of oil and natural gas as the basic resources for PP production. The PP granulate is extruded and thermoformed into a container in several steps. The PP production data were taken from Ecoinvent database 3.9.1, which is based on Plastics Europe data sets (secondary data). The container was assumed to be produced in Sweden; therefore, Swedish electricity mix was used as the input in PP production. Additionally, it was assumed that the containers were transported from Sweden to Finland. All the inputs required to produce the reusable container are listed in Table 1, along with their references. The size and material of the container was based on a primary data source provided by the Finnish industry.

Table 1

Inputs and outputs (material and energy) data for one reusable and single use container.

S. N	Material	Unit	Amount	Source/Reference
1.	**Production of reusable container**			
	Polypropylene (PP)	g/ container	138	Kamupak (2023)
	Electricity	kWh/ container	0.0213	(Industrial data 2020)
2.	**Production of single use container**			
	Polypropylene (PP)	g/ container	30	(Industrial data 2020)
	Electricity	kWh/ container	0.0048	(Industrial data 2020)
3.	**Transport (reusable and single use)**			
	Diesel	kg/tkm	0.054	(Ecoinvent database 3.9.1)
4.	**Industrial Washing (reusable container)**			
	Electricity	kWh/ container	0.0254	Van Lieshout et al. (2015) (Compare the market, 2023)
	Detergent	g/ container	0.067	
	Water	L/ container	0.338	
5.	**Recycling (End of life) (reusable and single-use container)**			
	Mass loss	%	20	Liljenström and Finnveden (2015) Note: 20% mass loss was incinerated in the process of recycling.
	Electricity consumption PP	kWh/kg	0.60	
	Mass recycled	%	80	
	Mass incinerated	%	20	
6.	**Incineration (End of life) (reusable and single-use container)**			
	Electricity recovery from PP	kWh/kg	−2.26	Vantaa Energy (2023)
	Heat recovery from PP	MJ/kg	−30.6	

2.2.2. *Washing*

Alternatively, after each use of the container, it was assumed that the container would be washed using an industrial dishwasher. The washing data used in the study were based on literature because such a washing

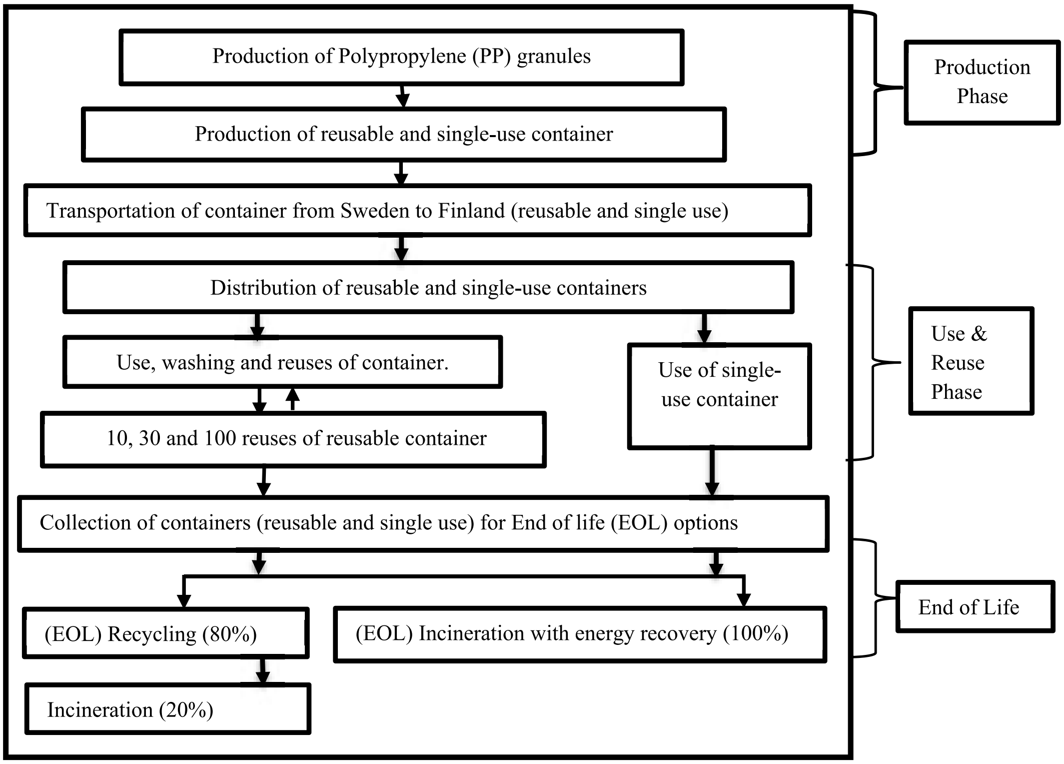

Fig. 2. Simplified system boundary of reusable and single-use food packaging take away containers.

system does not yet exist in Finland (Table 1). The washing phase assumed an industrial dishwasher at its highest capacity. It was assumed that the capacity of the industrial washing machine would be about 1420 dishes/h (depending on the size of the container). The power consumption was estimated to be an average of about 36 kWh (FFD, 2022). For one cycle washing unit if the onetime dishwasher capacity was 1420/h dishes, consuming 36 kWh of electricity, 480 L of water, and 0.096 kg of detergent per cycle (Van Lieshout et al., 2015). The details of the per container per use input in the dishwashing machine are given in Table 1. It was assumed, there were centralised washing facilities 10 km (round trip) from the selling points (Table 2).

2.2.3. *Transport*

Currently, assumed transport system does not exist in Finland; this is based on a theoretical analysis. In terms of logistics, the urban structure has been estimated to be like Helsinki city, in Finland. The transport stage was considered in the comparative analysis, as shown in Table 2. The transport of the container from Sweden to Finland was assumed to be done by ship, as shown in Table 2. The distribution of the containers to various shops in Finland was considered to entail 10 km. The containers were then ready for use, it was assumed that customers picked up food with the container from the shop, and the used container was assumed to be returned on foot to the shop, so zero emissions were considered in all scenarios (for returning the used container). The dirty container then needed to be delivered to the washing point, and a cleaned container was assumed to be delivered for the customers use the distance round trip were considered to be 10 km. The transport of the container within the city and its collection for washing was assumed to be done by lorry with the minimum capacity of 7.5 metric ton, using EURO 6 and calculation have been done per FU. The secondary data used for all kind of transportation was taken from Ecoinvent database 3.9.1, as mentioned in Table 2. At the EoL, the container was sent to waste management facilities, and the distance of the journey was assumed to be 10 km. The details of the distances involved in various transports are given in Table 2, with all the data that was taken from Ecoinvent database 3.9.1.

Table 2
Inputs and assumptions related to various transports per FU.

From	To	Distance (km)	Transport means	Type of vehicle use
Sweden to Finland	Manufacturer to customer	500	Ship	By water (Transport, freight, sea, bulk carrier for dry goods {GLO}| transport, freight, sea, bulk carrier for dry goods.)
Distribution of containers within Helsinki	Shop	10	Lorry	Transport, freight, lorry, unspecified {RER}| transport, freight, lorry, all sizes, EURO 6 to generic market[a].
Collection of containers for washing	Washing to shop (Both way)	10	Lorry	Transport, freight, lorry, unspecified {RER}| transport, freight, lorry, all sizes, EURO 6 to generic market[a].
Customer transport in all scenarios (S1 to S10)	Home or office to shop	1	Walk	Emission considered by walk zero
Customer transport (sensitivity analysis)	Home or office to shop (one way)	1	Car	Emission considered by petrol car.
End of life (EoL)	Waste management facility	10	Lorry 21 t	Municipal waste collection service by 21 metric ton lorry {GLO}| market

[a] **Note:** The lorry considered here is easily available in European market with a capacity between 7.5 and 32 metric ton (Euro 6).

2.2.4. *End of life options (EoL)*

The study considered recycling and incineration with energy recovery as waste management options. It was assumed that the container (reusable and single use) would either be recycled or incinerated, using 0.60 kWh/kg of energy for recycling (Liljenström and Finnveden, 2015) and would experience 20% mass loss (incinerated 20%) when recycled. The study did not consider possible contamination in the container (reusable and single use), resulting in its disposal by the customer after one use, and how this influenced the waste processing of the contaminated container. This study did not consider landfilling as a possible waste management option because landfilling is prohibited for plastic waste in Finland (Statistics Finland, 2019). The Finnish electricity mix grid was used as the source of energy for washing, incineration, and recycling. The energy recovery credit was used per reusable container for incineration −0.311 kWh, and heat recovery was used −4.23 MJ per container.

2.3. *Scenario analysis*

Various scenarios were proposed based on the potential uses of the reusable container and its end-of-life options (recycling or incineration). The different scenarios were proposed: (a) Scenario S1: container used 10 times with recycling; (b) Scenario S2: container used 10 times with incineration; (c) Scenario S3: container used 30 times with recycling; (d) Scenario S4: container used 30 times with incineration; (e) Scenario S5: container used 100 times with recycling; (f) Scenario S6: container used 100 times with incineration; (g) Scenario S7: single-use container with recycling (h) Scenario S8: single-use container with incineration; (i) Scenario S9: reusable container used once with recycling; and (j) Scenario S10: reusable container used once with incineration.

2.3.1. *Allocation*

To evaluate the environmental impact on various scenarios (10, 30, and 100) per FU, production and EoL emissions were divided by the corresponding container uses. While washing emissions remain constant per FU in scenarios (10, 30 and 100). There is no mass loss occurred during the number of uses in various scenarios (10, 30 and 100) (Fig. S1). Although there is a possibility of microplastic waste generation during washing stage, it is minimal, not included in the study, and does not impact the final results.

2.3.2. *Potential plastic waste generation*

The potential plastic waste generation for the different scenarios were quantified in this study compared to single-use container. In this context, the waste generation was determined as the amount of plastic waste per one use of the food container, i.e., the same FU was used as in the case of the GWP. If the container was used only once, the waste generation would simply be equal to the mass of plastic included in the packaging material of one container. In the case of reusable container, the mass of the plastic in one container would then be divided by the number of uses of the container.

2.4. *Life cycle environmental impact assessment*

The life cycle environmental impact assessment translates the inventory data into their potential contributions to a range of environmental impact category. The GWP (kg CO_2 eq.), marine ecotoxicity (kg 1,4-DCB eq.), and other impact categories were assessed in accordance with the characterisation factors reported in the ReCiPe 2016 (World-H) midpoint method (Huijbregts et al., 2017) using SimaPro 9.5 software (PRé Sustainability, 2023). The ReCiPe 2016 (World-H) midpoint method is well suited for a global perspective (Huijbregts et al., 2017).

2.5. Sensitivity analysis

The sensitivity analysis was performed using various parameters and factors that could affect the results. (i) The first factor considered for the sensitivity analysis was the use of a residential dishwasher (RW). The inputs were considered to be 1.5 kWh of electricity, 15 L of water, and 20 g of detergent, with a capacity of 20 containers per cycle (Compare FPM 2023). (ii) To simulate real situations in customer transport facilities, a sensitivity analysis was performed for a distance of 1 km using a petrol car, a diesel car, an electric car, and an electric scooter driven by customers to return a reusable container. (iii) Sources of energy play a significant role, and the study considered the different sources (European mix grid and global mix grid) of electricity for senstivity analysis. The average global electricity mix was based on fossil fuel electricity (63%) generation. This analysis helps understand the GWP of the process at the European and Global levels.

3. Results and discussion

3.1. Scenario and comparative analysis

The results of the scenario analysis (10, 30, and 100 with EoL recycling) per FU for the GWP are shown in Fig. 3. The reusable container used 10, 30, and 100 times resulted in 24%, 54%, and 64% reduction in the GWP compared to a single-use container per FU. The GWP decreased by 39% when the reusable container was used 30 instead of 10 times, and the GWP decreased by 23% when the reusable container was used 100 instead of 30 times. Significant differences were found in the GWP reduction in various scenarios per FU EoL recycling. This was because of the reduction of energy and raw material consumption in reusable container production per FU. In addition, credit was given for replacing virgin PP with recycled PP in the recycling stage, which reduced the burden on the production and EoL stages.

The use of recycled material played a significant role in reducing GWP. Galleo-Schmid et al. (2020) and Arunan and Crawford (2021) found this is an ongoing debate because post-consumer recycled plastic cannot currently be used in food packaging without a special permit for safety reasons. Recycled material should be used for other purposes such as in containers for non-food packaging products that helps in reducing the virgin PP production emissions and is beneficial for the environment. A reusable takeaway container can be reused many times for food packaging, which also reduces the burden of EoL facilities (inputs and outputs) compared to a single-use container. However, a reusable food container used only once and then recycled at the end of its life had a greater environmental impact in terms of the GWP (0.083 kg CO_2 eq./FU) than single-use packaging (0.020 kg CO_2 eq./FU). To minimise the GWP, reusable containers need to be used more than 6 times, for surpassing the impact of single-use packaging.

The results obtained from the EoL incineration option differ from recycling, as shown in Fig. 3. The results showed that in all scenarios, a reusable container used once had higher GWP (0.349 kg CO_2 eq./FU) than the other scenarios. While the single-use container had higher impact on the GWP (0.0754 kg CO_2 eq./FU) compared to reusable container (10, 30 and 100 scenarios). The GWP decreased with an increasing number of uses of the container. The GWP decreased by 46% when a reusable container was used 10 times compare to a single-use container. The GWP reduced by 56% when the container was used 30 times instead of 10 times. Finally, the GWP was reduced by 30% when it used 100 times instead of 30 times. There was 83% decrease in the GWP when the container was used 100 times compare to single use container (EoL incineration).

Gallego-Schmid et al. (2018) studied 50 reuses of plastic and glass food packaging containers from cradle to grave, finding GWP (0.466 kg CO_2 eq.) per use for plastic container and 0.544 kg CO_2 eq. per use of glass container. These values exceed the GWP per FU observed in the present study. This study found that many uses of the reusable container and recycling the material could play a crucial role in reducing the GWP. Gallego-Schmid et al. (2020) and Arunan and Crawford (2021) found similar results. According to Chakori et al. (2021), a reduction in packaging waste is possible by changing the structure of supply chains, consumption habits, and policies. The differences in results are dependent on many factors such as system boundary, FU, source of data, assumptions and used process.

The impact of potential customer behaviour is shown in Fig. 3 in scenarios S9 (reusable container used once EoL: recycling) and S10 (reusable container used once EoL: incineration). The results showed that if a reusable container was not used at least six times, single use was better than the reusable container per FU. However, reusable container used once and recycled produced 315% higher GWP than the single-use container, while incineration had 363% higher GWP than the single-use container.

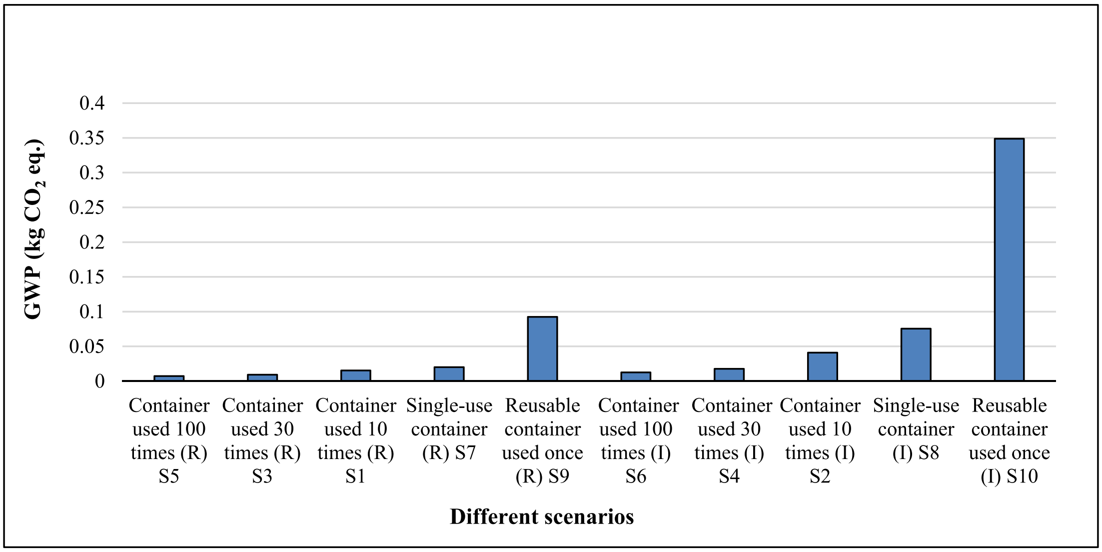

Fig. 3. Environmental impact of different scenarios on the GWP per FU with EoL: (R) recycling and (I) incineration.

3.2. environmental impact on other impact categories

The results of the scenario analysis (10, 30, and 100 with EoL recycling and incineration) per FU for different impact categories are shown in Figs. S2–S13. The reusable container, when used once, had higher impact on freshwater ecotoxicity (0.002 kg 1,4-DCB eq.) (Fig. S2), marine ecotoxicity (0.003 kg 1,4-DCB eq.) (Fig. S3) and fossil resource scarcity (0.033 kg oil eq.) (Fig. S4) compared to the single-use container impact on freshwater ecotoxicity (0.0003 kg 1,4-DCB eq.), marine ecotoxicity (0.0005 kg 1,4-DCB eq.) and fossil resource scarcity (0.0071 kg oil eq.) at the EoL recycling. While the reusable container, when used 10, 30, and 100 times resulted in lower environmental impact than the single-use container due to a reduction in production and EoL stage emissions. The reusable container, when used 10, 30, 100 times for EoL (recycling and incineration), had a higher impact on marine eutrophication (Fig. S5), freshwater eutrophication (Fig. S6), ionizing radiation (Fig. S7), human carcinogen toxicity (Fig. S8), mineral resource scarcity (Fig. S9), and human non-carcinogen toxicity, (Fig. S10) compared to single use, primarily due to washing stage emissions. However, in EoL incineration of a reusable container used once and single-use container, negative values were observed due to energy recovery credits from incineration. These credits result from replacing Finnish heat (produced in Finland by burning wood chips, natural gas, oil, coal, and peat) with PP incineration. Additionally, it was found that increasing the number of uses of container (10, 30 and 100 EoL recycling and incineration) led to an increase in impact on terrestrial acidification (Fig. S11), terrestrial ecotoxicity (Fig. S12) and land use (Fig. S13) due to washing emissions.

3.3. Contribution analysis of different scenarios

Fig. 4a, shows the contribution of different stages in the life cycle of the reusable container, including production, washing, transport, recycling (80%), and incineration (20%), for various scenarios. It was found that washing (0.006 kg CO_2) had a higher GWP than the production (0.002 kg CO_2), transport, and EoL stages in “scenario 100”, while in “scenario 30 and 10”, production had higher GWP than washing. The GWP of reusable container is reduced due to a decreased impact on production and EoL stages [recycling (80%), and incineration (20%)], attributed to its multiple uses per FU.

The contribution analysis results for various scenarios with EoL incineration are shown in Fig. 4b. Transport’s contribution was smaller than the other life cycle stages of the container. Production and incineration were the main contributors to the GWP for single-use and reusable container used once, as Fig. 4b shows.

3.4. Sensitivity analysis

3.4.1. residential washing of container

Fig. 5a and b shows the changes in results due to the change in the washing facilities of the reusable container per FU. The industrial washing (IW) capacity and facilities reduced 92% of the GWP (0.006 kg CO_2) compared to the residential dishwasher (RW) GWP (0.075 kg CO_2 eq.) per FU. According to Gallego-Schmid et al. (2018), efficient washing could reduce or save up to 70% of energy, 30% of detergent, and 60% of water compared to the RW. Using RW had a higher impact on the GWP than IW, as show in Fig. 5a and b. The GWP of the single-use container (0.020 kg CO_2/FU) can be higher than the reusable container if the washing facility is inefficient. Studies have found that the washing phase accounts for 22%–67% of the total impact of the reusable plastic container and 17%–55% for the glass container (Gallego-Schmid et al., 2018). This study found that the RW contribution to the GWP was greater than IW at EoL recycling per FU. IW contributed 12%, 29%, and 57% to the GWP in Scenarios 10, 30, and 100 respectively EoL recycling. In contrast, using RW led to a higher contribution of 61%, 83%, and 94% in the same scenarios per FU, EoL recycling.

3.4.2. environmental impact of transport

Fig. 6a and b shows the impact on GWP when customers used a petrol car to return a reusable container at a distance of 1 km. It shows that the use of a petrol car for one km journey by the customer increased the GWP more than a single-use container in all the scenarios. The study found that customer transport had the highest GWP compared to the other stages of the container life cycle stages (such as production, washing, and end of life). Specifically, Fig. 6b shows that using a petrol car for customer transport for one km journey increased the impact on GWP (0.192 kg CO_2 eq./FU), surpassing that of a single-use container (0.075 kg CO_2 eq./FU). This study therefore concludes that the return

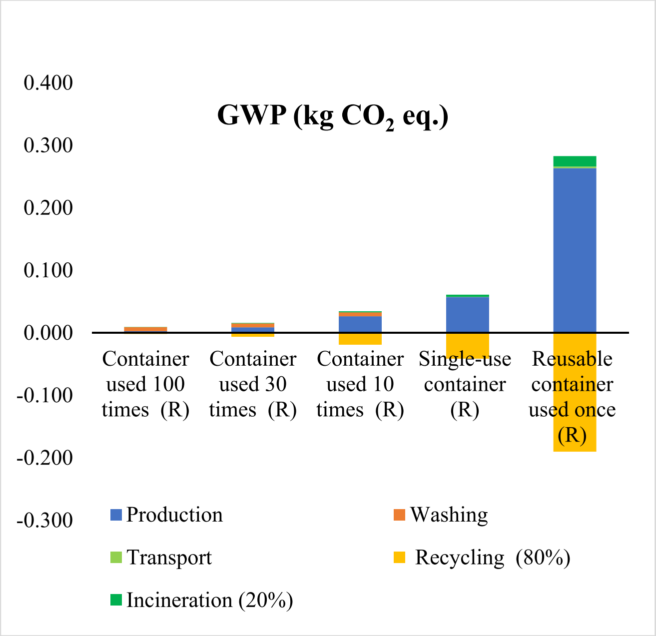

Fig. 4a. Contribution of different stages of container to the GWP per FU at end of life: (R) recycling.

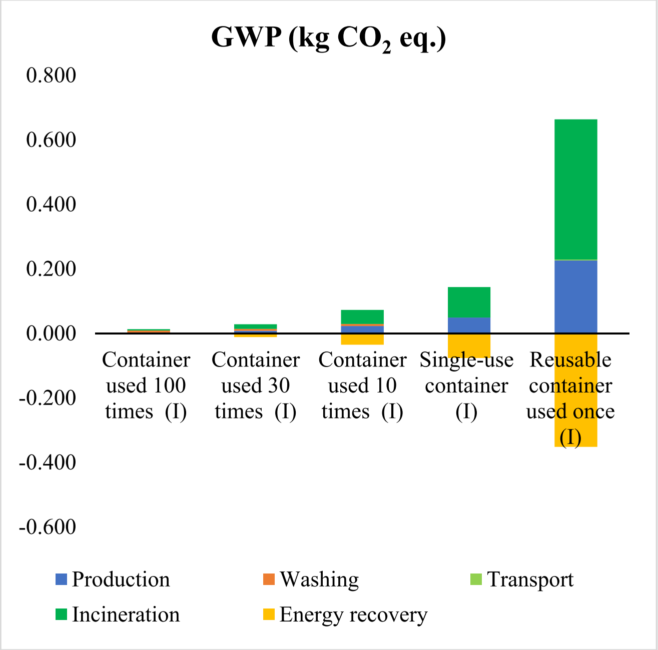

Fig. 4b. Contribution of different stages of container on GWP per FU at end of life: (I) incineration.

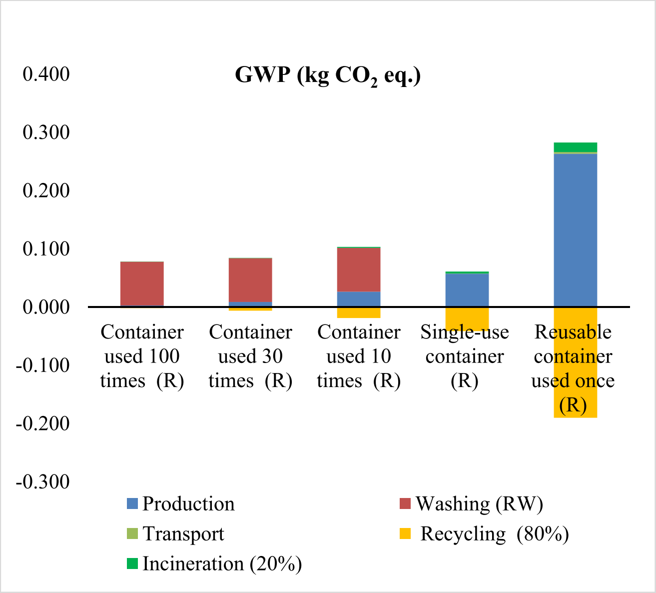

Fig. 5a. GWP per FU residential washing (RW) instead of industrial washing (IW) facility at end of life: (R) recycling.

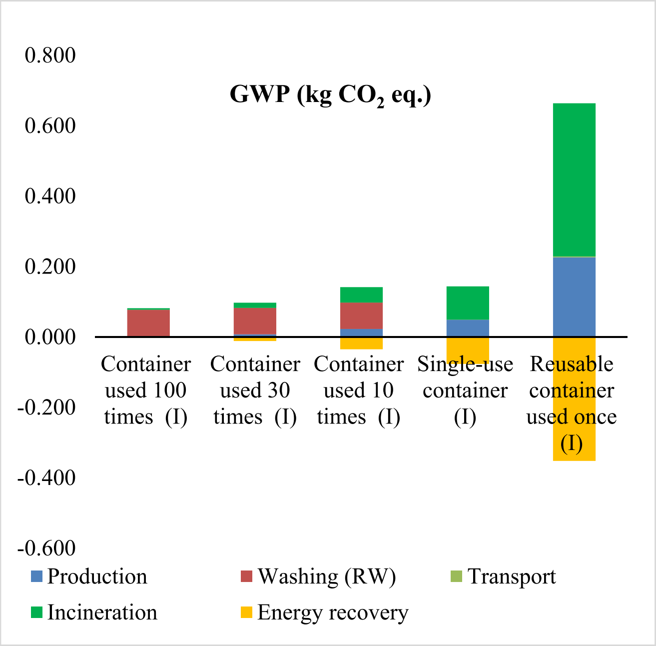

Fig. 5b. GWP per FU residential washing (RW) instead of industrial washing (IW) facility at end of life: (I) incineration.

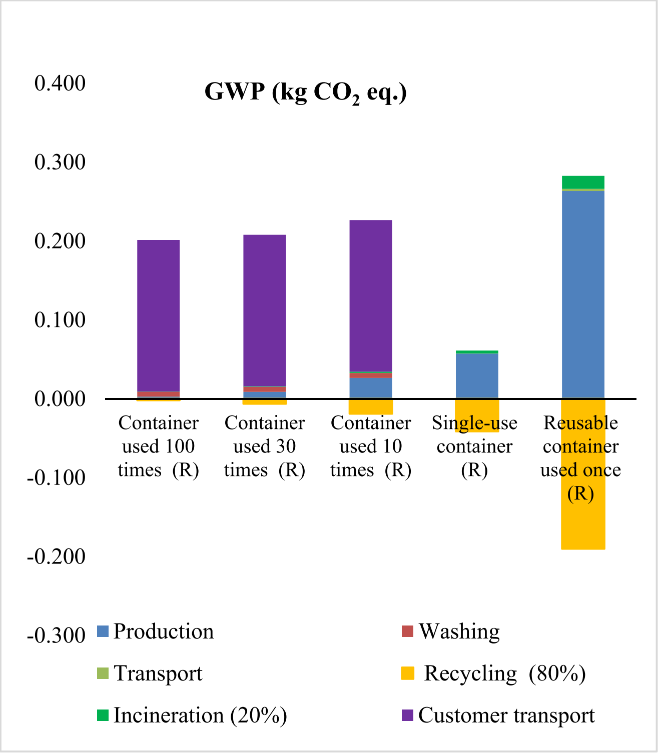

Fig. 6a. Impact on the GWP per FU, assuming an additional 1 km journey by a petrol car to return the container after use at the end of life: (R) recycling.

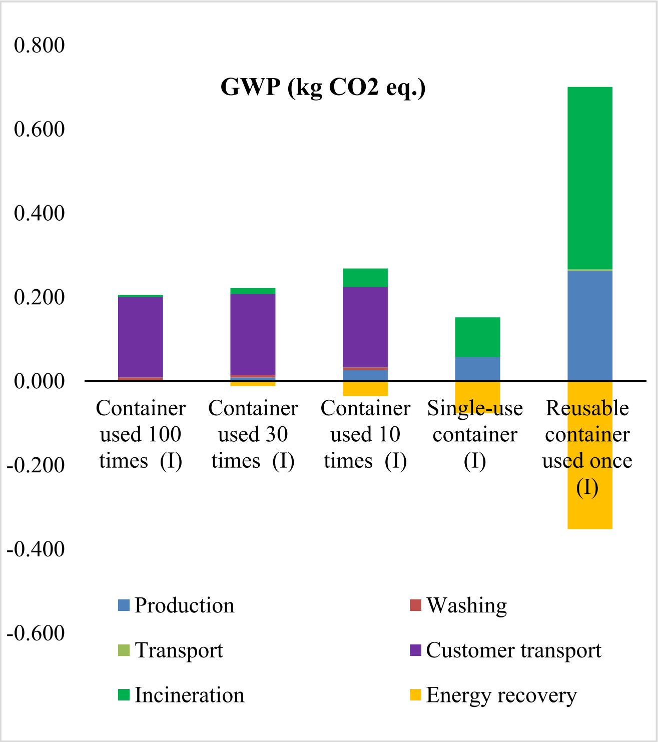

Fig. 6b. Impact on GWP per FU, assuming an additional 1 km journey by a petrol car to return the container after use at the end of life: (I) incineration.

system for the empty container has a critical role in the GWP of reusable container. These results are influenced by many factors, including customer behaviour if customer purchases other groceries at the same time when returning the container. In this case, the environmental load will be allocated to the various activities. Fig. 6a and b illustrate the condition where 100% of the GWP related to customer transport was attributed to the reusable container. However, if the customer returns the container on foot, reusable container (which is used at least 6 times) is better than the single-use container EoL recycling. It was found that returning a reusable container by petrol car within 100 m distance, a reusable container that is used seven times is better than a single-use container EoL incineration. The results of using different types of vehicles (diesel car, petrol car, electric car, bus, and electric scooter) used for customer transport for a journey of one km are shown in Fig. S14. Using an electric scooter (0.03 kg CO_2 eq.) and bus (0.10 kg

CO_2 eq.) have lower GWP than using a petrol (0.19 kg CO_2 eq.), diesel (0.17 kg CO_2 eq.), or electric car (0.11 kg CO_2 eq.). The transportation used can depend on various climate and weather conditions. For example, during the winter season, roads are slippery in Finland because of snow. Therefore, electric scooter can be an efficient option during summer. Juan et al. (2016) found similar results for a diesel van covering the same distance, showing that it produced about 54 times CO_2 emissions released by an electric vehicle.

The results of the sensitivity analysis demonstrate the important role of factors such as consumer behaviour, infrastructure and efficiency of the return and reuse system of the containers, and factors related to the location and travelling distances. The baseline scenario of this study shows that the reuse system can potentially reduce the GWP related to takeaway food container. However, it should also be noted that such a reduction is possible only if no major additional emission arises from the return of the containers. For example, Fig. 6a and b shows that only a little additional travel by private transport (1 km by petrol car) when returning the reusable container can easily produce multiple emissions compared to the production of the single-use container. Such a scenario is likely to be realistic in scarcely populated areas with limited public transport options. It is therefore critical that an efficient and centralised return system be developed to achieve any environmental benefits when replacing single-use containers with reusable containers for takeaway meals. In practice, such a system should be comparable to the current system for the collection and recycling of packaging material.

3.4.3. change in geographical regions and electricity

The LCA results for the reusable container are sensitive to the source of electricity. A sensitivity analysis was conducted by simulating the use of alternative electricity sources, namely the European electricity mix (denoted the “medium-voltage RER market”) and the global electricity mix (denoted the “medium-voltage GLO market”) by replacing the Finnish electricity (denoted the “medium-voltage FI market” in the Ecoinvent 3.9.1 database). The composition of the Finnish electricity mix is nuclear (27.4%), biomass (25%), hydro (19.2%), wind (9.7%), solar power (0.3%), and imported electricity from Sweden and Norway (18.4%) (Energy Statistics Finland, 2022), while the composition of the Swedish electricity mix is hydro (43%), nuclear (31%), wind (17%), solar (1%) and biomass-based electricity (Statista, 2022; Yadav et al., 2020).

EoL Recycling showed higher change in the GWP than incineration (due to energy recovery from incineration) for all the scenarios as shown in Figs. S15 and S16. Based on the Finnish energy mix, the use of European (GWP: 0.020 kg CO_2 eq.) and global electricity (GWP: 0.029 kg CO_2 eq.) resulted in an increase of the GWP 29% and 90% respectively in 10 reuses scenario EoL recycling.

3.5. Generation of plastic waste

The results for plastic waste are shown in Fig. 7. The highest potential plastic waste was found in reusable container used once, and the single-use container showed higher plastic waste than 10, 30, and 100 uses scenarios. We can therefore conclude that if the reusable container is not efficiently used, it will not improve the plastic waste problem but make it worse compared to single use.

4. Conclusions

A comparative life cycle assessment of reusable food packaging was performed to determine the potential magnitude of the reduction of the GWP of reusable packaging and its significance against single-use packaging, considering various parameters. Customer behaviour, the type of vehicle used by the customer and distance, and the source of electricity were identified as the major determinants of the GWP. The study revealed that the impact of the production stage decreased with an increase in the number of uses, while the opposite was the case for the washing stage. The use phase is the main hotspot of the reusable container. To reduce single-use littering and plastic waste pollution, it is important to promote reusable food packaging, and pick-up centres should be designed at a walking distance, as proposed in the baseline scenarios. Policymakers should consider local people’s need, conditions, and behaviour instead of implementing a single policy across the country. The future study can focus on the littering potential of reusable container and examine how microplastic waste ends up in rivers and oceans, exploring its impact on the marine ecosystem.

CRediT authorship contribution statement

Pooja Yadav: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Frans Silvenius:** Writing – review & editing, Data curation. **Juha-Matti Katajajuuri:** Writing – review & editing, Funding acquisition. **Ilkka Leinonen:** Writing – review & editing, Supervision, Project administration, Conceptualization.

Declaration of competing interest

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

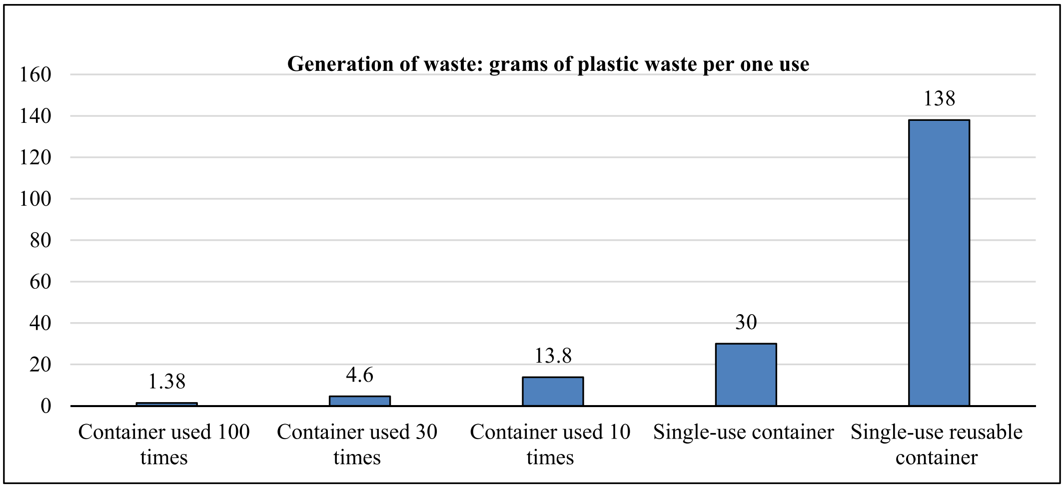

Fig. 7. Generation of plastic waste for different scenarios.

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Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.141529.

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