Journal of Cleaner Production 447 (2024) 141427

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Environmental impacts of different single-use and multi-use packaging systems for fresh fish export

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ARTICLE INFO

Handling Editor: Kathleen Aviso

Keywords:
Single-use box
Multi-use tub
Fish packaging
Expanded polystyrene
Polyethylene
Life-cycle assessment

ABSTRACT

The production and pollution of plastic present a significant threat to global ecosystems, where annual plastic emissions in aquatic ecosystems are projected to triple between 2020 and 2030. Currently, plastics are widely used for food packaging but depending on the polymers, properties, the recyclability ratio of the plastics varies. Polymers, such as polyethylene (PE), polyurethane (PUR), and expanded polystyrene (EPS), are widely used for packaging and transporting foods such as fresh fish, where multi-use fish tubs often consist of PE and/or PUR and single-use boxes of EPS. This study evaluated the environmental impacts of reusable tubs of different volumes and sizes made of PE/PUR vs single-use EPS boxes, transporting 1000 tons (T) of fresh fish from Iceland to Europe, per year based on life cycle assessment methodology. This is to identify the packaging solution with the lowest environmental impact. The overall results show that multi-use tubs had lower environmental impacts when transporting 1000 T of fresh fish from Iceland to Europe per year, even during first year of usage. For Global warming impacts, producing and using EPS boxes for transporting 1000 T of fresh fish was 141 T CO_2-eq and ranged from 4 to 46 T CO_2-eq for variating multi-use packaging solutions for one year. The weight of the raw materials (plastics) and size of the tubs were key factors affecting the environmental impacts when transporting the tubs.

1. Introduction

The impacts of plastic production and pollution pose a global threat to ecosystems worldwide (Borrelle et al., 2020). Estimations from the conventional plastic sector in 2015 were around 1.7 Gt CO_2-eq for greenhouse gas emissions (GHGs) globally, which equals 3.5% of the total global GHGs and are expected to increase further to 6.5 Gt CO_2-eq by 2050 due to growing demand of plastics, which would account for 15% of the total GHGs in 2050 (Zheng and Suh, 2019). This highlights the importance of reducing the impacts of plastics along their life cycle, to limit their environmental impacts within the next years, as simultaneously, waste management infrastructure is inadequate, and plastic waste is projected to increase tenfold by 2025 (Jambeck et al., 2015). While waste management needs to be improved, circularity of plastic packaging and products made from recycled raw materials could lower the environmental impacts from plastic production and use.

From 1950 to 2015, 6.3 Gt of plastic were generated, of which only 9% was recycled, 12% incinerated, and the remaining 79% either stored in landfills or released directly into nature (Rhodes, 2018), emphasizing the low recyclability ratio of plastics during this period. Furthermore, in 2015, packaging had the highest waste-to-production ratio of primary waste generated at 97%, due to its short lifetime in use (Rhodes, 2018). This highlights the importance of finding alternative solutions for packaging materials and/or increase the reuse/recycling of plastic packaging along with prolonged lifetime usage. While infrastructure is being developed in developing countries, industrialized nations can take immediate action by reducing waste and limiting the use of single-use plastics (Jambeck et al., 2015). It is however worth mentioning that the proportions of plastics recycled vary geographically, in accordance with plastic types and applications (Hopewell et al., 2009). When looking specifically at Iceland, about 25% of all plastics are recovered and sent for recycling. Ögmundarson et al. (2022) show the environmental benefits of different disposal routes and for toxicity impacts, emissions of toxic fumes from incineration were assessed with preexisting waste incineration processes in ecoinvent as well as landfilled

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https://doi.org/10.1016/j.jclepro.2024.141427
Received 4 December 2023; Received in revised form 20 February 2024; Accepted 22 February 2024
Available online 29 February 2024

List of abbreviation/acronyms/symbols

Abbreviations/acronym/symbols	*Meaning*
CO_2-eq	CO_2 - equivalent
EPS	Expanded polystyrene
FU	Functional unit
GHG	Greenhouse gas emissions
Gt	Gigatonne
ISO	International Organization for Standardization
Kg	Kilogram
L	Liters
LCA	Life Cycle Assessment
PE	Polyethylene
PET	Polyethylene terephthalate
PP	Polypropylene
PS	Polystyrene
PUR	Polyurethane
T	Tonne
UK	The United Kingdom
°C	Degree Celsius

plastics. In this study, the same approach was used to assess the impacts of landfilled plastics and toxicity due to incineration.

Plastic is a highly versatile material and is commonly used for food packaging (Geueke et al., 2018) due to its low weight, strength, durability, and cost-effectiveness compared to other materials (Hopewell et al., 2009). It also acts as a preservation method, ensuring that consumers receive the product in a safe manner without compromising food quality (Raheem, 2013). Depending on the end-product, properties of plastic materials vary depending on the functional group of the polymer and are therefore used for different purposes in various applications (Zumdahl et al., 2016). Plastic packaging can consist of single polymers such as polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polystyrene (PS), while combinations of single polymers are called multi-layers and are currently not recycled into new food packaging (Geueke et al., 2018), highlighting the potential to increase recyclability when polymers are not blended. Polyurethane (PUR) and PS foams are widely used in flotation and packaging industries (Lee, 2016), with nearly 0.28 Mt of PUR produced annually (Sonnenschein, 2021) and nearly 16 Mt of PS (Fernández, 2022). Expanded polystyrene (EPS) is considered particularly useful for transportation of chilled-goods and fragile materials (Marten and Hicks, 2018), such as fresh fish (Margeirsson et al., 2011), and can be recycled from packaging with clear economic benefits and without loss of performance (Samper et al., 2010) although depending on geographical area (Hopewell et al., 2009). PUR is mostly disposed of in landfills, although other methods such as mechanical recycling or chemical recycling are available but have limitations with regards to high temperature, pressure, and potentially dangerous chemicals (Kemona and Piotrowska, 2020).

To date, most plastics used in transportation of foods are single-use and have a short lifespan (Geueke et al., 2018). Reusable systems have shown promise, such as a comparison between a reusable plastic box and a single-use cardboard box, transporting vegetables, from cradle-to-grave showed 60% GHG emission reduction when using the reusable plastic box (Krieg et al., 2018), emphasizing the GHG reduction potential with using re-useable systems. Nevertheless, the potential has to be assessed on the product level for each application to identify the potential of reusing the products as product design, material combination, transport distances, lifetime as well as benchmark differ between single-use products (Krieg et al., 2018). There, geometric characteristics such as size, shape, and volume of the products are important in handling and processing operations (Rao et al., 2014) and can be limited through optimized design, possibly affecting the environmental impacts. Consequently, it is imperative to fundamentally transform the current linear plastic economy to a framework, limiting the single-use plastic with short life (Borrelle et al., 2020). Literature assessing environmental impacts of single-vs re-useable containers for transport of fresh fish is currently unavailable expressing the novelty of this study and evident knowledge gap in this field. Moreover, a limited number of LCA studies have been published comparing single- and re-useable packaging solutions except with focus on comparison of different packaging materials (Albrecht et al., 2013; Del Borghi et al., 2021; Foschi et al., 2020).

The main goal of this study was to assess and compare the environmental impacts of the current packaging solutions (base case) for fresh fish export from Iceland to Europe, each year for 8 years, from cradle-to-grave. Furthermore, to assess two new designs of packaging solutions (*Scenario 1* and *Scenario 2*) and compare them to the current packaging (*Base-case*) to investigate if the new designs lower the environmental impacts from fresh fish export from Iceland to Europe. The effects of packaging depth on both quality and weight loss of fresh fish during storage are not accounted for in the present study, and although weight loss of increased packaging depth is known, no significant differences have been found in quality of superchilled, un-iced, gutted salmon (Tryggvason et al., 2020).

2. Materials and methods

This Life Cycle Assessment followed the ISO14040/44 (ISO, 2006a, 2006b), including goal and scope, inventory analysis, impact assessment, and interpretation phase (Hauschild et al., 2018).

2.1. Research objectives

The study had two objectives:

1) To assess the environmental impacts of different fresh fish packaging solutions to be able to transport 1000 T of fresh fish, from cradle-to-grave, including single-use and multi-use packaging every year for 8 years (*Base case*).
2) To identify the environmental benefits of various fresh fish packaging solutions using different raw materials, volume, weight, and lifetime of the assessed scenarios (*Scenario 1* and *Scenario 2*).

The functional unit (FU) assessed was "*The environmental impacts of packaging, when transporting 1000 T of fresh fish from Iceland to the UK, from cradle-to-grave, every year for eight years*". The functional unit included both the production of the packaging solutions and yearly usage of the multi-use containers investigated.

2.2. Data collection and system modelling

Packaging materials studied included different polymers; polyethylene (PE), polyurethane (PUR), and expanded polystyrene (EPS). The design of the packaging solutions differentiated in weight, volume and raw materials, and multi-use vs. single-use where PE and PUR were reusable, but EPS were single-use.

The base case included *cradle-to-grave* and was representative of the packaging solutions already used by industry which include 50 kg PE 460 L, 42 kg PUR 460 L, 38 kg PE Twin 290 L and EPS 41 L, all manufactured with 100% virgin raw materials. In addition, two scenarios were assessed, *cradle-to-cradle*, for new packaging in their early design stages; exploring environmental impact reduction potential, against already established designs and virgin raw materials, with new designs and varying ratios of recycled materials.

2.2.1. Multiple usage packaging solutions

For all of the multiple usage packaging solutions assessed in this study, the manufacturing process employed rotational molding, where virgin plastic was inserted into a sealed mold, which rotated biaxially within an oven (Sæplast, 2023). As the mold was heated, the raw material underwent a phase transition from solid to liquid, adhering to the inner surface of the mold (Sæplast, 2023), with the help of a blowing agent. Once the plastic has transitioned to a liquid state, the mold is removed from the oven, and cooled down (Sæplast, 2023).

Multiple use packaging solutions included 50 kg PE 460 L, 42 kg PUR 460 L, 38 kg PE Twin 290 L which represent base case, where 44 kg PE 460 L (*Scenario 1*) and 6 kg PE Twin 41 L (*Scenario 2*) represent possible future designs.

2.2.2. Single usage packaging solutions

The single usage packaging studied were EPS boxes, 41 L. The raw material was pre-expanded, followed by a heat treatment by steam, heating the raw materials up to 80–100 °C (Hardarson, 2023). The integration of a blowing agent instigated the expansion of the material into a box, which was subsequently cooled down (Hardarson, 2023).

2.2.3. Stackability and comparison of the packaging solutions

The system modeling depended mainly on the stacking abilities of the packaging solutions into multi-modal shipping-containers. Volume or weight limits the amount of fish which can be loaded into the multi-modal containers, indicating that higher efficiency in stacking of the tubs/boxes into the shipping-containers result with lower count of those containers, decreasing the environmental impacts. The larger multi-use containers (460 L PE/PUR tubs) reached the weight limits earlier than limits due to volume, whereas for single-use EPS boxes (41 L), the opposite was observed. Therefore, both volume and weight need to be considered in this study.

The dimensions of the tubs/boxes, which included weight, volume capacity and fish weight capacity are presented in Table 1. This data was collected primary from the manufacturing company for our calculations. Furthermore, the number of tubs/boxes needed to fulfill the FU each year, along with the configuration of the different designs are presented in Fig. 1, where twin tubs were designed to maximize volume utilization on the return trip home by stacking more efficiently. Fig. 1 demonstrates packaging needed to transport the same amount of product 900 kg of whole fish, as it is approximately the weight that fits into three 460 L tubs and four 290 L tubs, although the FU is still 1000 T.

2.2.4. Analyzed scenarios

Two scenarios were modeled and analyzed in this study, which are two tubs that differed in design and/or raw materials. The tub's design in Scenario 1 was a 44 kg PE 460 L tub, already at designing stages in the manufacturing company. For *Scenario 1*, different ratios of virgin and recycled PE in the raw materials were modeled, which were 100%, 90%, 70%, and 50% virgin PE material where the rest was recycled material. This is conducted to assess the impact of different ratios of virgin and recycled materials on the overall environmental impacts for the FU.

Scenario 2 included a reusable 6 kg PE 41 L tub, the size of an EPS box but with raw materials possible to recycle. This design included only 100% virgin raw materials, as the inner shell should consist of 100% virgin PE, according to current regulations (Commission Regulation, 2022/1616; 10/2011, 1935/2004).

Table 1
Different fish packaging solutions and parameters affecting the FU.

Different parameters per tub or box	PE 460 L	PE 460 L	PUR 460 L	PE Twin 290 L	PE Twin 41 L	EPS 41 L
Weight (kg)	44	50	42	38	6	0.7
Volume capacity (L)	430	400	400	290	41	41
Weight (kg) of fish possible	323	300	300	220	22	22
Tubs/boxes for the FU, per year[a]	261	278	278	379	3788	45,455

[a] All reusable packaging are used once per month on average.

2.3. LCA system boundaries

The system boundaries show which variables were included in the current assessment (Fig. 2) for both multiple usage tubs and single usage boxes. The system boundaries of all assessed packaging types were defined to include the life cycle stages raw materials, electricity, transport and cleaning, and end-of-life phase.

Raw materials for the multiple usage tubs included toner, blowing agent and the polymer used, which was either PE only for PE tubs, or a blend of both PE and PUR for PUR tubs (70%, and 30%, respectively), but the recycling process is currently mainly in the UK. The raw materials used for single-use box were EPS only.

The energy used for molding of the tubs and boxes was electricity, as the molding of the tubs and EPS boxes take part in Iceland.

The transport was set to be 2000 km, to estimate the transport to the UK, equal for each assessed tub or box type. Furthermore, export included a container ship with a refrigeration unit (the reference flow), and in case of multiple usage, non-refrigeration unit back. The multiple use tubs were estimated to include one round-trip per month including the reference flow (export) and cleaning with water, soap and sterilizing agents, and electricity usage in the UK as geographical.

The end-of-life phase differentiated for the raw materials used in the tubs/boxes (Fig. 2). Current relevant legislation 2022/1616; 10/2011, and 1935/2004 do not allow the recycled material used in the PE tubs to contact food. Therefore, no more than approximately 30% of the recycled PE can be re-routed into the molding of the PE-tub, lowering the virgin raw material need, and the remaining 70% can be recycled and used in other applications. The PUR-tubs are an example of multilayer packaging, which is usually incinerated or landfilled depending on geographical locations (Kaiser et al., 2018). EPS can be recycled depending on geographical location, but the recycling ratios were around 27% in Europe in year 2013 (EUMEPS, 2013) and above 30% in 2019 (Lassen et al., 2019). The reason why the recyclable ratio of PUR tubs is mostly 0% compared to 100% for the PE tubs, is due to the blending of PUR and PE in the PUR tubs and specified mechanical and/or chemical processes are required to recycle PUR tubs and is therefore costly both economically and environmentally (Kemona and Piotrowska, 2020).

Scenario 1 and *Scenario 2* followed the same end-of-life processes as the PE tubs in Fig. 2.

2.4. Life cycle impact assessment (LCIA)

The Life Cycle Assessment (LCA) calculations were conducted with the SimaPro version 9.1.0.8 software (PReConsultants, Amersfoort, Netherlands) in conjunction with the ecoinvent 3.8 life cycle inventory. SimaPro modeled the average amount or energy of each component seen in the system boundary (Fig. 1), including different scenarios of the PE in the raw materials. An average electricity and usage of raw materials were obtained by the company, primary, where an estimation of 2000 km for transportation was included for all of the tubs and boxes: a refrigeration unit in a sea container one way and sea container without the refrigeration unit back.1.

In the current study, the impact assessment method used was CML-IA baseline version 3.08. The following impact categories were included in the assessment: Abiotic depletion, Abiotic depletion (fossil fuels), Global warming (excluding biogenic carbons), Ozone layer depletion, Human toxicity, Freshwater aquatic ecotoxicity, Marine aquatic ecotoxicity, Terrestrial ecotoxicity, Photochemical oxidation, Acidification, and Eutrophication. Environmental hotspots were compared on weight of each tub, the polymers it consisted of (PE, PUR, EPS), and different ratios of virgin materials. Furthermore, the lifetime of the tubs is currently guaranteed by the manufacturer to be 8 years, although other options

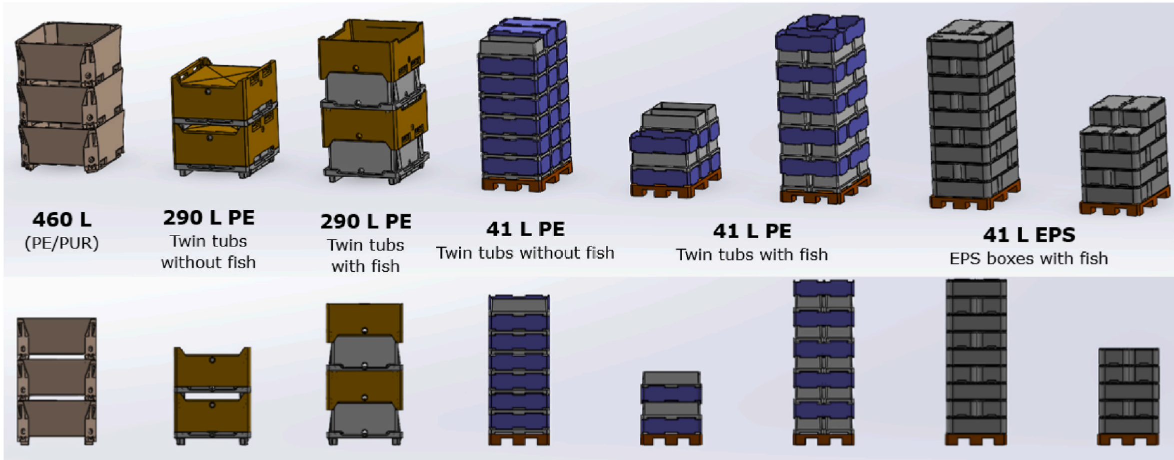

Fig. 1. Different packaging solutions with and without fish to demonstrate the stacking abilities, as each of the designs carry around 900 kg of whole fish. Further description of each of the packaging can be seen in Table 1. Note that twin tub design stacks more efficiently on the way back, and as EPS is a single-use box, there is no return trip.

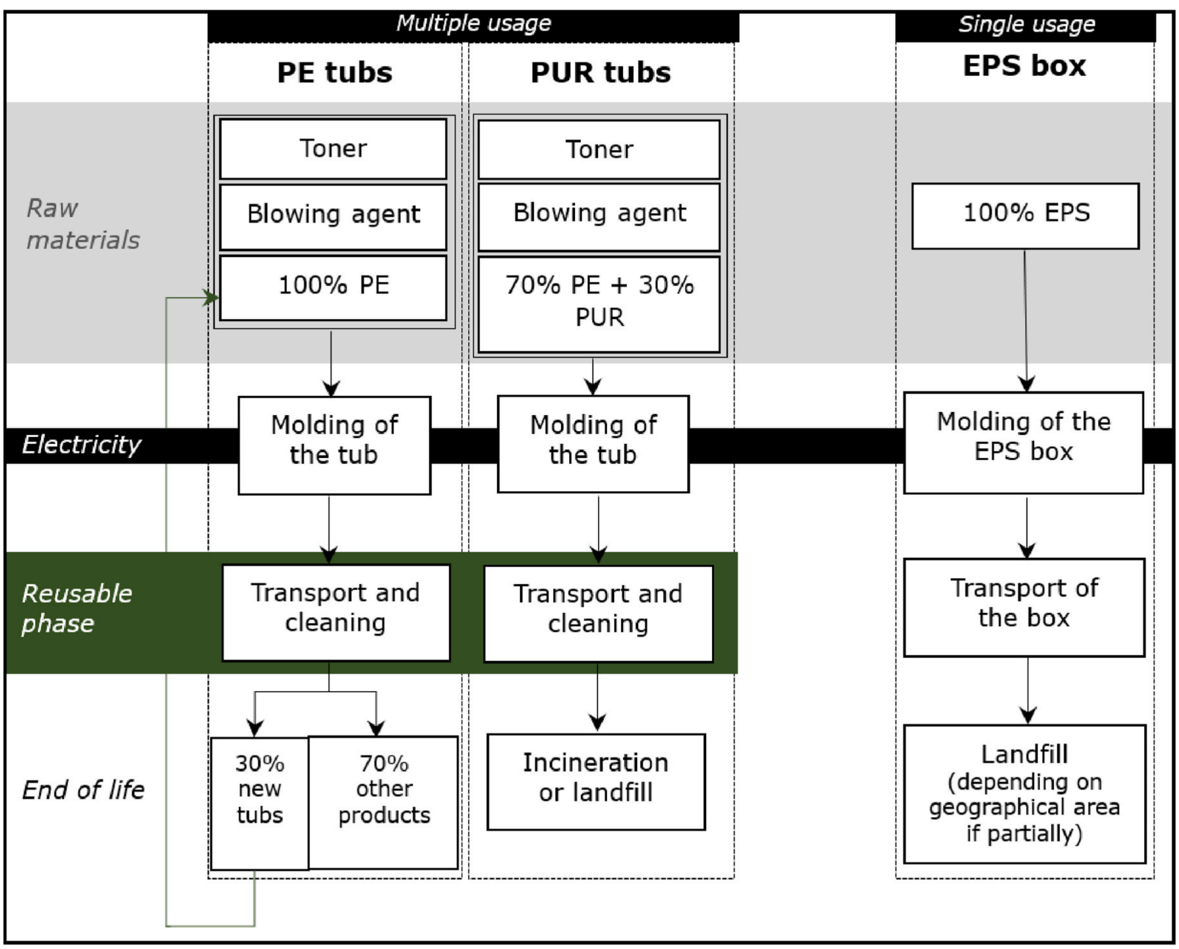

Fig. 2. System boundaries for multi and single-use tubs and boxes, where the multi-use tubs were made from polyethylene (PE) and polyurethane (PUR) and expandable polystyrene (EPS) were single-use. The PE and PUR tubs are reusable, highlighted green in the figure, while EPS boxes are not. End of life is 100% recyclable for the PE tubs, as the polymer used in the raw material is only PE. EPS boxes can be recycled partially, depending on the geographical area. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

were explored, as these tubs can last 20+ years.

2.5. Sensitivity analysis

To evaluate the sensitivity of the results, five sensitivity scenarios were identified, summarized, and described in Table 2. The sensitivity

Table 2
Sensitivity scenarios in different packaging solutions.

Sensitivity scenarios	Description
End-of-life for multi-use packaging, tubs	•Tubs tend to have a longer life-time than is guaranteed, and hence not necessarily give a fair comparison •Multi-use tubs could be "lost" upon return
Re-packaging upon arrival to the customer	•It could be that when the tubs arrive to their destination, the customer uses EPS 41 L box anyways, as it is easier to handle smaller box
Cleaning of the multi-use packaging, tubs	•Cleaning was estimated but can vary depending on the status of the tub when collected
42 kg PUR 460 L tubs real average weight	•Improper handling can lead to holes in the outer PE layer, which can increase the weight of the tub from water absorption (Sigurdsson, 2023)

analysis included various factors that could potentially influence the comparison of the different packaging solutions.

End-of-life for the multi-use packaging such as the tubs (including 6 kg PE 41 L) could alter the results, as lifespan of the fish tubs can exceed 8 years. The environmental impacts of their production would decrease when distributed over longer lifetime, and on the contrary, shorter lifetime increase the environmental impacts of the tub production. Measurements of tubs that are nearly 20 years old have shown to retain their initial capability and, if used properly, could further increase their lifespan. In that case, environmental impacts for multi-use containers could potentially be reduced further. However, the implementation of a smart design for the tubs may lead to a reduction in the reuse ratio of fresh fish export as customers could repurpose those tubs for other uses. As examples multi-use tubs have been spotted moving concrete, storing machine parts, resulting in a higher loss of tubs. In this case, environmental impacts would increase with higher demand for new tubs. Cleaning of the multi-use tubs can vary a lot and can be dependent on various factors such as the tub itself, weather, the usage, if used with a lid or not.

The weight of a single PUR 460 L tub is 42 kg when produced, but in case of holes or cracks in the tub, the insulating PUR-layer can absorb water, entrapping the water within the structural matrix resulting in increased weight of the tub (Sigurdsson, 2023). This water absorption due to damage in the PUR tub may result in less product being exported due to max load limitations of containers, lowering the efficiency of each export trip. This can result in less product being exported, depending on the number of PUR tubs being damaged.

2.6. Statistical analysis

To analyze the environmental impacts of the tubs and boxes with variating lifetime, calculations were conducted with Microsoft Office 365's Excel software (Microsoft, Redmond, WA, USA), and results presented as mean values.

3. Results and discussions

3.1. Production and yearly usage of the packaging solutions

The environmental impacts of the production and the yearly usage of the tubs and boxes were compared across the impact categories covered in the CML-IA baseline version 3.08. (Table 3). The EPS 41 L boxes had the highest overall impact in both production and yearly usage per FU across all assessed impact categories. A single 460 L tub (PUR or PE) resulted having generally higher overall environmental impacts compared to a single EPS 41 L box, taking into consideration the necessary quantity of packaging units to meet the FU. At the same time, the EPS 41 L boxes have the highest environmental impacts in usage and production. The 44 kg 460 PE 50/50 (with 50% virgin materials) was shown to have the lowest impacts in all of the impact categories (Table 3), except for Freshwater- and Marine aquatic ecotoxicity, possibly due to impacts from recycling of PE. This indicates that higher ratio of recycled PE in the raw materials increased the impacts for Freshwater- and Marine aquatic ecotoxicity. However, when the virgin material decreases down to 70% or 50%, advised practice includes adding a plastic bag to the tub to ensure that the inner layer of the shell is guaranteed to be a 100% virgin material, and follows the current legislation (Commission Regulation, 2022/1616; Commission Regulation 10/2011; Regulation, 1935/2004). Nonetheless, plastic bags can increase environmental impacts depending on their size and materials (Lewis et al., 2010). The results show that plastic bag increased environmental impacts by <6% particularly for the impact categories Abiotic depletion, Photochemical oxidation, and Abiotic depletion (fossil fuels). Abiotic depletion refers to the exhaustion of natural resources, such as minerals and fossil fuels (Van Oers and Guinée, 2016), and photochemical oxidation which are processes involving light, nitrogen oxide and various volatile organic compound, and can have significant impacts on the environment (Krueger et al., 2023) (*Appendix* Table X1).

For the multi-use containers, yearly cleaning and transportation of the tubs include twelve transport trips per year, including return. The ratios of recycled PE did not influence the results of yearly usage of the

Table 3
The overall environmental impacts of the production and the yearly usage of the PUR/PE fish tubs and the EPS 41 L boxes to transport 1000 tonnes of fresh fish. Red color indicates higher environmental impacts for each of the impact categories. The different ratios of virgin PE used in the molding of the tubs range from 100% to 50% virgin PE in the raw materials where the remains are recycled PE.

Production of the tubs and boxes		**EPS**	**6 kg PE 41 L**	**42kg PUR 460 L**	**50 kg PE 460 L**		**44 kg PE 460 L**				**38 kg PE Twin 290 L**	
Impact category			100/0		100/0	90/10	100/0	90/10	70/30	50/50	100/0	90/10
Abiotic depletion	kg Sb eq	8.2E-02	2.9E-01	1.6E-01	1.8E-01	1.4E-01	1.5E-01	1.2E-01	6.5E-02	9.7E-03	1.8E-01	1.9E-01
Abiotic depletion (fossil fuels)	MJ	2.6E+06	1.6E+06	8.3E+05	9.5E+05	7.6E+05	7.8E+05	6.3E+05	3.2E+05	3.8E+03	9.8E+05	9.3E+05
Global warming (GWP100a)	**kg CO_2 eq**	**1.3E+05**	**4.5E+04**	**2.4E+04**	**2.7E+04**	**2.2E+04**	**2.3E+04**	**1.8E+04**	**9.2E+03**	**2.9E+02**	**2.8E+04**	**3.0E+04**
Ozone layer depletion (ODP)	**kg CFC-11 eq**	**3.4E-03**	**6.9E-04**	**3.6E-04**	**4.1E-04**	**3.3E-04**	**3.4E-04**	**2.7E-04**	**1.3E-04**	**-1.1E-05**	**4.3E-04**	**6.4E-04**
Human toxicity	kg 1,4-DB eq	2.5E+04	1.4E+04	7.2E+03	8.3E+03	7.0E+03	6.8E+03	5.7E+03	3.5E+03	1.5E+03	8.5E+03	1.2E+04
Fresh water aquatic ecotox.	kg 1,4-DB eq	2.0E+04	6.0E+03	2.4E+03	2.7E+03	5.0E+03	2.2E+03	4.1E+03	7.6E+03	1.2E+04	2.8E+03	9.3E+03
Marine aquatic ecotoxicity	kg 1,4-DB eq	6.8E+07	2.3E+07	1.2E+07	1.3E+07	2.7E+07	1.1E+07	2.3E+07	4.5E+07	6.9E+07	1.4E+07	2.4E+07
Terrestrial ecotoxicity	kg 1,4-DB eq	1.1E+02	2.5E+01	1.3E+01	1.5E+01	1.4E+01	1.3E+01	1.2E+01	1.0E+01	8.7E+00	1.6E+01	2.4E+01
Photochemical oxidation	kg C_2H_4 eq	1.9E+02	1.4E+01	7.6E+00	8.6E+00	6.9E+00	7.1E+00	5.7E+00	2.8E+00	-3.6E-02	8.9E+00	8.8E+00
Acidification	**kg SO_2 eq**	**4.5E+02**	**1.7E+02**	**9.0E+01**	**1.0E+02**	**8.2E+01**	**8.4E+01**	**6.7E+01**	**3.4E+01**	**6.2E-01**	**1.1E+02**	**1.0E+02**
Eutrophication	kg PO_4 eq	8.1E+01	2.9E+01	1.5E+01	1.7E+01	1.3E+01	1.4E+01	1.1E+01	4.4E+00	-1.9E+00	1.8E+01	2.5E+01

Yearly usage		**41 L**	**41 L**	**460 L**	**460 L**	**460 L**	**290 L**
Impact category		**EPS**	**6 kg PE**	**42 kg PUR**	**50 kg PE**	**44 kg PE**	**38 kg PE Twin**
Abiotic depletion	kg Sb eq	3.3E-02	2.3E-03	3.2E-02	3.6E-02	3.0E-02	3.6E-02
Abiotic depletion (fossil fuels)	MJ	8.8E+04	2.0E+03	1.1E+05	1.2E+05	9.9E+04	1.2E+05
Global warming (GWP100a)	**kg CO_2 eq**	**6.8E+03**	**3.4E+02**	**8.5E+03**	**9.6E+03**	**8.0E+03**	**9.8E+03**
Ozone layer depletion (ODP)	**kg CFC-11 eq**	**1.1E-03**	**2.0E-05**	**1.3E-03**	**1.5E-03**	**1.2E-03**	**1.6E-03**
Human toxicity	kg 1,4-DB eq	2.6E+03	1.8E+02	3.4E+03	3.8E+03	3.2E+03	3.9E+03
Fresh water aquatic ecotox.	kg 1,4-DB eq	2.0E+03	5.8E+02	2.8E+03	3.0E+03	2.6E+03	2.8E+03
Marine aquatic ecotoxicity	kg 1,4-DB eq	3.4E+06	2.8E+05	3.8E+06	4.3E+06	3.6E+06	4.3E+06
Terrestrial ecotoxicity	kg 1,4-DB eq	7.9E+00	2.0E+02	3.1E+02	3.2E+02	2.9E+02	2.2E+02
Photochemical oxidation	kg C_2H_4 eq	3.4E+00	1.5E-01	4.7E+00	5.3E+00	4.4E+00	5.4E+00
Acidification	**kg SO_2 eq**	**1.2E+02**	**1.5E+00**	**1.7E+02**	**1.9E+02**	**1.6E+02**	**2.0E+02**
Eutrophication	kg PO_4 eq	1.8E+01	4.1E+00	2.8E+01	3.1E+01	2.6E+01	3.0E+01

tubs, as the design remained the same. The PE 41 L tub showed the overall lowest impact (Table 3) in yearly usage except for Terrestrial ecotoxicity where EPS boxes had the lowest impact. This could be explained by that the EPS material production has less Terrestrial ecotoxicity impacts than the PE and PUR. The environmental impacts from yearly usage of the larger multi-use tubs were relatively similar, as well as the production phase of the multi-tubs.

3.2. Varying lifetime of multiple usage packaging solutions compared to single usage packaging solutions

The reusable packaging solutions were compared with single-use EPS boxes, assuming different lifetimes of the multiple usage packaging solutions, where 8 years is the guaranteed lifespan of the tubs (Fig. 3).

For the impact categories Global warming, Ozone layer depletion and Acidification, EPS 41 L had the highest environmental impacts, exceeding all the reusable packaging materials, even as soon as after the first year. This is based on the assumption that all the multi-use tubs/boxes were produced during the first year (Fig. 3; blue line and blue y-axes). Higher ratio of recycled material generally resulted in lower impacts, although varying in magnitude, as energy is needed for the recycling process of the polymer and is dependent on location. As the tubs are assumed to be recycled mainly in the UK, the average electricity grid mix for the UK were used in the recycling-steps. This partially explains the higher impacts of the 10% recycled PE tub (44 kg PE 460 L 90/10) compared to 100% virgin PE tub (44 kg PE 460 L 100/0). Due to stacking efficiency of the PE Twin tubs (38 kg PE Twin 290 L) and the 6 kg PE 41 L tub, the difference was lesser when comparing the different recycling ratios on the PE 460 L tubs. In addition, with increased lifetime, the 6 kg PE 41 L tub resulted in the lowest overall environmental impacts. However, impacts from recycled materials could decrease if the recyclable processes of PE were moved to a geographical location with a higher percentage of renewable energy sources. Along with using renewable energy sources in recycling processes, standardizing commodity plastics to be recyclable would limit the end-of-life scenarios for both EPS and PUR, limiting the global virgin plastic demand (Borrelle et al., 2020).

The 42 kg PUR 460 L tubs generally gave higher impact compared to 44 kg PE 460 L tubs. The PE tubs are recyclable as they only consist of one polymer, PE, whereas PUR tubs are comprised of 70% PE and 30% PUR and are generally not recycled (Fig. 2). However, the tub's weight was essential for lowering the environmental impacts of the tubs due to the assessed impacts related to repeated transportation of the reusable containers. Therefore, reducing the tub weight would lower the environmental impacts of all the packaging solutions even further than discussed. Furthermore, with the longer lifespan of the tubs, less difference was observed when comparing the packaging solutions except for 44 kg PE 460 L 50/50 with a plastic bag, as the bag inside the tub is single-use and therefore new bags must constantly be produced and disposed of.

The recycling ratios of EPS vary depending on geographical location (EPS branchen, 2022; EUMEPS, 2013) and hence Fig. 4 shows examples ranging from 0% recycled EPS to 50% recycled EPS, compared to other packaging solutions already available in the industry (base-case). Higher environmental gain comes from recycling a higher ratio of the EPS boxes, and although recycling 50% of all EPS is rather optimistic, the aim should be set high. It though must be noted that although higher recycling rates decrease the Global warming impacts of EPS boxes, the impacts of other reusable packaging solutions remain lower, independent of their lifetime.

When comparing the multi-tubs, eco-design principles for transport boxes (less material usage, longer lifetimes etc.) showed promise. Further reduction of material usage for these packaging solutions could be explored and increased the potential recycling ratio of single and multi-use tubs by only using easily recyclable single material plastics in the packaging solutions. In addition, considering use of novel materials such as bioplastics should be explored (Spierling et al., 2018; Venkatachalam et al., 2018). Bioplastics would require a change in regulations to enable the industry to move forward with higher ratios of recyclable raw materials which, shown in this study, can reduce environmental impacts of food containers. However, before that happens tubs with recycled material only will have to be tested and compared with virgin material only both with regards to strength and food safety. Furthermore, along with regulations for the producers of the tubs and

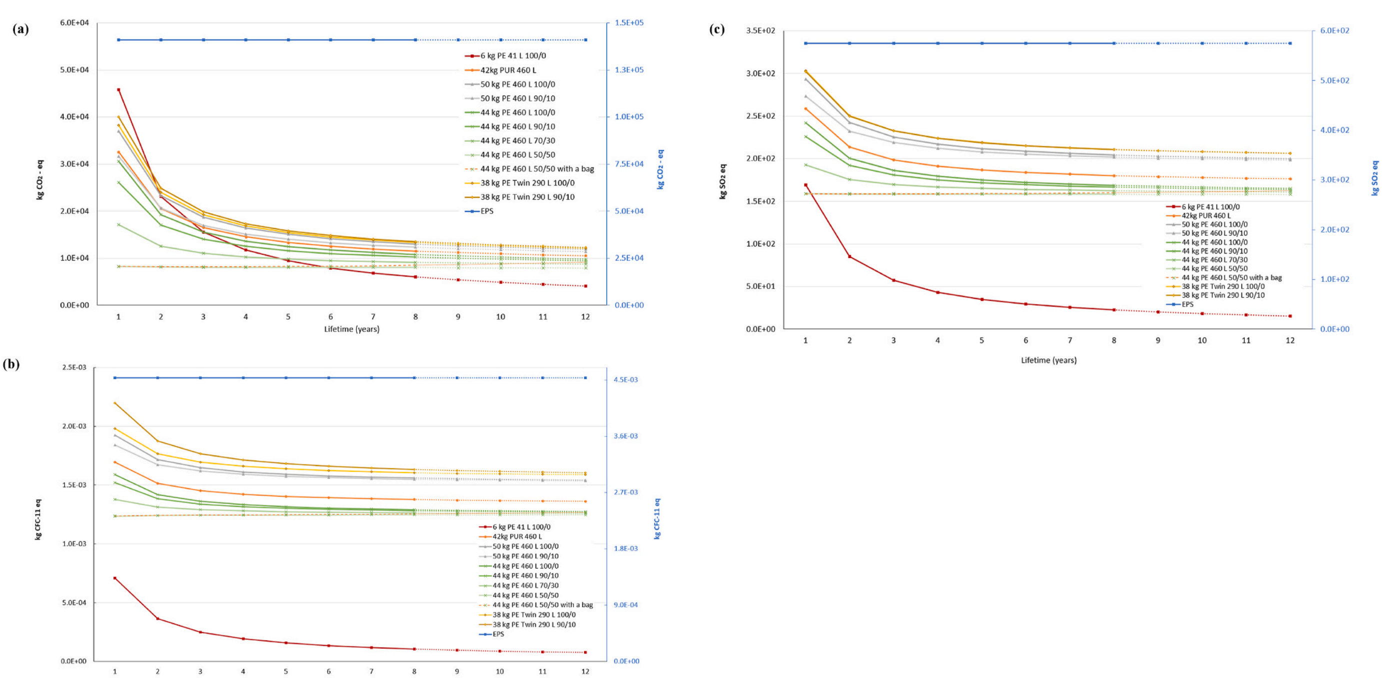

Fig. 3. Results for Global warming (a), Ozone layer depletion (b), and Acidification (c), during 8 years in lifetime (including estimations for 12 years). The blue y-axes only applies for EPS boxes. Figure (a), (b), and (c) show all the packaging solutions, including Base-case, Scenario 1 and 2, described in the legend. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

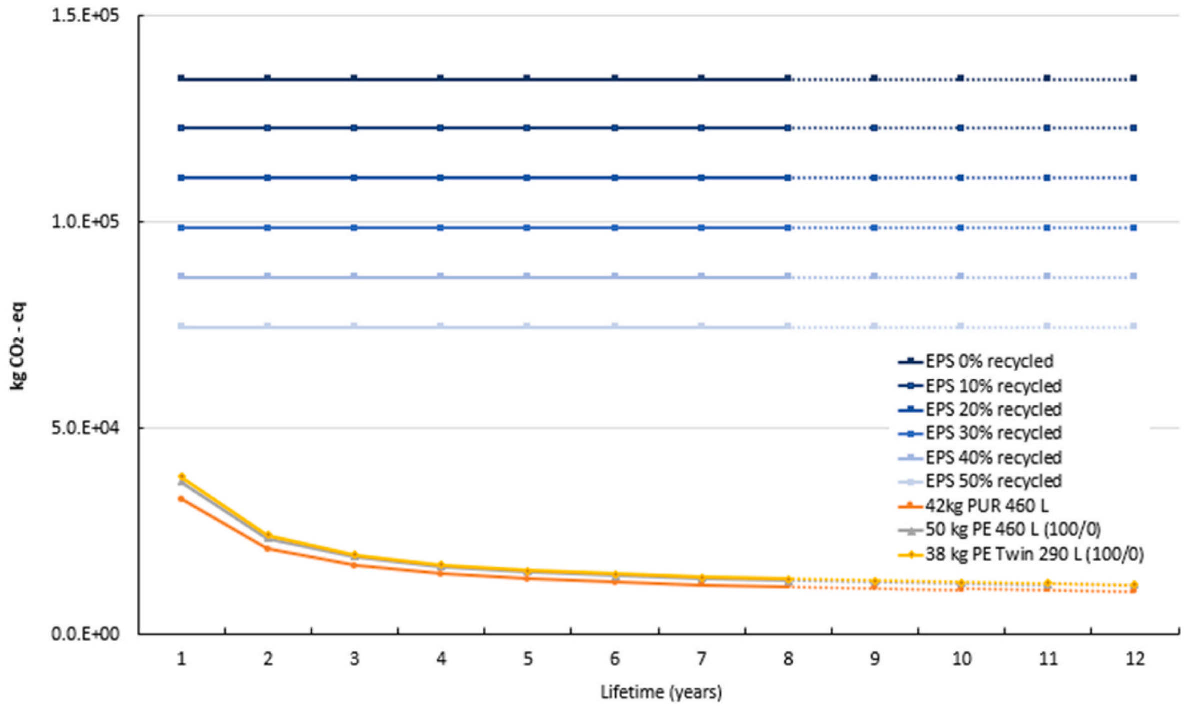

Fig. 4. Recycling ratios of EPS boxes compared to the base-case of the FU, when assessing Global warming (CO_2-eq).

boxes, extended producer responsibility of the products' life cycle is needed as it has shown to reduce environmental impacts of plastic products (Directive, 2018/852).

4. Conclusions

The environmental impacts of different single-use and multi-use packaging for fresh fish export were investigated with the functional unit (FU) being: "*The environmental impacts of packaging, when transporting 1000 T of fresh fish from Iceland to the UK, from cradle-to-grave, every year for eight years*". The following conclusions can be drawn from this study:

- Single-use EPS 41 L boxes had the overall highest environmental impacts for all assessed impact categories, compared to PE and PUR multi-use tubs of different volumes (460 L, 290 L, and 41 L), designs, and assessed recycled plastic ratios.
- Similar design as EPS boxes (41 L), a multi-tub made from PE resulted with the lowest environmental impact in Ozon layer depletion, Acidification, and after 7-year lifetime in Global warming, suggesting that stacking efficiency, during export, import and cleaning, is one of the key factors for lowering the environmental impacts.
- With extended lifetime of the multi-use tubs, the effect of polymer used in the raw materials decreases, including the recycled plastic ratios.
- Across all impact categories, the higher the recyclable ratio of plastics used in the container solutions, a decrease of environmental impacts can be detected. However, if the recyclable ratio is increased up to 30–50%, food grade plastic bags needs to be used for sealing of the fresh fish as legislation bans recycled plastics as food grade material. The environmental impacts from the plastic bags increased with the longer lifetime of the multi-use tubs as the plastic bags are single use.
- Incentives to increase recycling of plastics need to be implemented as our results show both benefits of increased recycling and increased use of recycled materials in packaging solutions for fresh fish. This would require standardizing commodity plastics with appropriate frameworks enabling industry to move forward with more environmentally friendly packaging solutions.
- When developing new packaging solutions or new materials, applying LCA is highly recommended in the design phase to investigate beforehand the potential environmental effect due to changes.

CRediT authorship contribution statement

Gudrun Svana Hilmarsdóttir: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis. **Bjorn Margeirsson:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization. **Sebastian Spierling:** Writing – review & editing, Validation. **Olafur Ögmundarson:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

Authors have no conflict of interest to declare.

Data availability

Data will be made available on request.

Acknowledgement

The authors gratefully acknowledge the support from the Icelandic Ministry of Food, Agriculture and Fisheries for funding the study (Umhverfisvænni matvælaumbúðir; UMMAT no. ANR21060110) and the University of Iceland Research Fund (no. 15647).

Furthermore, we thank Sæplast and Tempra for the primary data, collected from their processes and production sites.

Appendix

Table X1

Environmental impacts for a 44 kg 460 L PE tub, with 50% recyclable PE raw material and additional plastic bag.

Impact category	Unit	Total	Plastic bag	Plastic bag/ total
Abiotic depletion	kg Sb eq	6.5E-05	3.9E-06	6.1%
Abiotic depletion (fossil fuels)	MJ	4.4E+02	2.0E+01	4.5%
Global warming (GWP100a)	kg CO_2 eq	3.6E+01	6.6E-01	1.8%
Ozone layer depletion (ODP)	kg CFC-11 eq	1.3E-06	1.2E-08	0.9%
Human toxicity	kg 1,4-DB eq	1.8E+01	2.8E-01	1.5%
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	5.8E+01	2.0E-01	0.3%
Marine aquatic ecotoxicity	kg 1,4-DB eq	3.2E+05	5.0E+02	0.2%
Terrestrial ecotoxicity	kg 1,4-DB eq	1.5E-01	5.9E-04	0.4%
Photochemical oxidation	kg C_2H_4 eq	7.2E-03	3.8E-04	5.2%
Acidification	kg SO_2 eq	2.0E-01	2.4E-03	1.2%
Eutrophication	kg PO_4 eq	6.3E-02	6.8E-04	1.1%

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