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Integrating behavioural, material and environmental science to inform the design and evaluation of a reuse system for takeaway food

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ABSTRACT

Reuse packaging systems (both return and refill) are a key part of achieving a circular economy, however adoption and uptake are low. A reuse system must be environmentally beneficial, economically viable and acceptable to users such that they are willing to use, and reuse, the system. Here we focus on returnable takeaway food containers and develop a methodology that combines simulating wear associated with use, assessments of consumer willingness to reuse worn containers, and quantitative life cycle assessment (LCA). The findings suggest that environmental break-even points may be lower than the number of times people are willing to use a worn container. Factors such as the design of containers and washing can be improved through lightweighting and use of renewable energy, and behavioural interventions can be delivered to increase willingness. Such interdisciplinary research enables careful system design to ensure that reuse systems confer environmental benefit.

1. Introduction

The transition to a Circular Economy model is recognised as a route to a thriving economy within the Earth's planetary boundaries (Bening et al., 2021; Desing et al., 2020; Korhonen et al., 2018). Instead of the traditional linear model where finite materials are extracted, turned into products, and then disposed of ('take, make, waste'), a number of strategies can be employed, including sharing, repairing, reusing, remanufacturing and recycling to keep material in circulation for as long as possible, thus saving resources (Stahel, 2016). Despite multiple interpretations of the circular economy, a core consensus has emerged recognizing reuse and recycling as two fundamental principles (Kirchherr et al., 2017). Efforts in transitioning to a circular plastics economy have focused on recycling (Ghisellini et al., 2016) but there is now increasing interest in reuse (EUR-Lex, 2020).

The plastic packaging system is typically a linear material flow, from cradle to grave, often with a very short use-time. Once single-use plastic packaging has served its purpose of delivering the contents safely to the consumer in a convenient manner (Sherrington et al., 2017) it holds little value so is disposed of, or worse discarded as litter. As a result, 130 Mt of plastic packaging ends up in landfill, incineration or the natural environment worldwide per year (Geyer, 2020; Jambeck et al., 2015) and it has been estimated that 12 Mt per year of plastic waste is released to the environment (Hoseini and Bond, 2022) Plastic debris has even been found on the deep-sea floor of the Arctic (Bergmann et al., 2022). If packaging is designed to be reusable, then it can be given value, e.g. through a deposit or reward scheme, making it more likely to stay in the system for longer and reducing the risk of it ending up as litter.

Reusable packaging is defined as "packaging which has been conceived, designed and marketed to carry out multiple trips in its lifetime by being refilled or reused for the same purpose for which it was conceived" (Bradley and Corsini, 2023; EUR-Lex, 2020). A reuse scheme

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can either be return (where the business owns the packaging and is responsible for revers logistics including washing) or refill (where the consumer owns the packaging and is responsible for washing). Although there are a few successful schemes in existence (Beswick-Parsons et al., 2023), widespread implementation of returnable packaging systems is lacking (Bocken et al., 2022). New schemes require investment in additional infrastructure (e.g. transport for reverse-logistics, washing facilities) (Bocken et al., 2022; Coelho et al., 2020), there is a lack of ambition amongst brand owners, and government legislation may be needed for progress to be made (Ellen McArthur Foundation, 2016). Several studies have analysed the barriers with a focus on particular geographies, business types, or industry sectors (De Jesus and Mendonça, 2018; Hansen and Schmitt, 2021; Paletta et al., 2019). Barriers are often portrayed as though independent of each other, however, there are interdependencies between them, meaning that interdisciplinary research is key to finding solutions.

Previous studies on reusable packaging systems have shown that reuse systems can have environmental benefits (e.g. for Global Warming Potential (Accorsi et al., 2014; Gallego-Schmid et al., 2018; Zhou et al., 2020), but containers must be used a minimum number of times to show an improvement over single-use (this minimum number of times is termed the 'break-even point' (BEP)). However, it is likely that reusable containers will show signs of wear with repeated use, and research has shown that consumers will reject products in packaging that show even slight damage (White et al., 2016). For a reuse system to be viable, consumers must be willing to use the containers beyond the environmental BEP (Caspers et al., 2023; Greenwood et al., 2021). It is therefore necessary to take an interdisciplinary approach that quantifies both the environmental BEP and the number of times that consumers are willing to reuse containers to accurately assess whether a reusable packaging scheme will confer environmental benefit. While there are a number of studies that examine the LCA of a reusable packaging system (Błażejewski et al., 2021; Fry et al., 2010; Stefanini et al., 2021) and consumer willingness to engage with reusable packaging schemes (Baird et al., 2022; Soares et al., 2022; White et al., 2016) in isolation, no study to date has empirically demonstrated how such insights can be combined, despite previous work highlighting the importance of integrating these factors (Caspers et al., 2023; Greenwood et al., 2021; Wever and Vogtländer, 2013). It is also vital that the reuse scheme is economically viable, for both the consumer and the business.

A number of return schemes are being trialled or implemented in foodservice i.e. for takeaway food and drink (e.g. (caulibox, 2024; Vytal, 2024) One of the most successful is Vytal (Vytal, 2024), a reusable packaging system for takeaway food and drink that originated in Germany. Vytal quotes a total of 4.8 M rentals to date with a container return rate of 99 %. There is potential for large environmental savings in this sector – the global takeaway food market has been predicted to reach $144bn by 2025 (Statista, 2022). It has been estimated that China consumes 7.3bn plastic food tableware sets a year (Accorsi et al., 2014) and that 2.5bn takeaway containers are consumed in Europe (Chris Sherrington, 2017). The amount of takeaway packaging placed on the market in the UK was 1.2 Mt in 2019, of which 220 kT was plastic (Footprint Intelligence, 2022). Only a fraction of takeaway food packaging is recycled as often the food is consumed and the packaging disposed of on-the-go and food residue contaminates the recycling stream (Desing et al., 2020). Food containers and cutlery account for 9.4 % of all litter items found across aquatic ecosystems worldwide (Morales-Caselles et al., 2021).

In this research we take a novel, interdisciplinary approach to assessing the likely impact of a container return scheme by combining investigations of how containers wear with use and reuse (material science), whether consumers are willing to accept any resultant signs of wear (behavioural science), the levels of reuse required for environmental benefit (environmental science) and an analysis of the economic implications. A scheme for borrowing returnable containers for takeaway food (see Supporting Information 6.1) in cafés at the University of Sheffield (UK) was chosen as a Living Lab for this case study. There are four interwoven strands, each led by different disciplines, and brought together in an interdisciplinary approach: (i) A set of containers were subjected to simulated use cycles in the laboratory and photographed after each cycle, (ii) Images of the packaging after various use cycles were shown to participants to determine the point at which consumers become unwilling to use a container (termed their 'willingness threshold', WT) following a paradigm developed by Baird et al. (Baird et al., 2022), (iii) An LCA was conducted comparing the reusable containers to the existing single-use packaging (in accordance with ISO14040 [40]), and iv) the economics of the scheme were evaluated. A total of 70 use cycles were chosen for the LCA comparison as this is the theoretical lifetime of the container based on the return rate (98.6 %) observed in the living lab (See Supporting Information 6.2). The BEP was calculated for global warming potential and water usage. The LCA results highlight which product and process factors can be modified to reduce the BEP and move it to within the WT, thereby enabling reuse with a systemic environmental benefit.

Taken together, the present research seeks to provide both (i) the empirical evidence needed to evaluate the success of a company-owned reusable packaging system for takeaway food (on a university campus), and (ii) demonstrate how an interdisciplinary approach can integrate insights from the material and behavioural sciences into an LCA of reusable packaging systems.

2. Materials and methods

2.1. Durability testing

To simulate wear, the reusable containers (177 g) were worn in laboratory conditions through 28 cycles of scratching, staining and washing in an industrial dishwasher (Figure S1) and were photographed between each cycle.

2.1.1. Scratching

Two methods were employed to simulate protracted use with metal cutlery: manual and automated scratching using a specially constructed device. Manual scratching of the surface, using both a metal serrated knife and a brass wire brush, was carried out in a random pattern 20 times/cycle. Although labour intensive, this allows visual simulation of a more realistic wear pattern on the surface and on areas of the bowl untouched by the cup wire brush (Figure S1). For the automated scratching, containers were scratched with a rotary wire brush that was spun at 80 rpm for 30 s with an applied force of 1.9 N. This method results in a reproducible and visible circular wear pattern on the surface. While this is not specifically indicative of the wear expected in real-life, it gives a worst-case surface abrasion to reproducibly exemplify interactions between abrasion and staining. These processes result in small scratches and the creation of microplastics (small flakes from 0.1 mm to 1 mm, sized by eye).

2.1.2. Staining

A selection of commonly used foods and drinks were selected for staining: tomato pasta sauce, tomato puree, turmeric, chilli powder, baked beans, chopped tomatoes, tomato soup, tea and coffee. The chosen foods contain the oleophilic staining compounds lycopene (from tomatoes) and curcumin (from turmeric) that are insoluble in water, and tannins (from turmeric, tea and coffee) that are water soluble. Food combinations were prepared and placed into the containers for 1 h/cycle, a subset of the samples were also heated in a 900 W microwave until boiling. Plastics are more susceptible to staining if heated, scratched, oiled or pitted.

2.1.3. Washing

A Classeq D500 commercial 2 tank under counter dishwasher was used for washing, with Suma Nova L6 detergent and Suma Rinse A5

Rinse Aid at the recommended dose. The containers were washed on a 2-minute wash cycle at 55 °C and rinsed at 82 °C upside down on a wash rack with a retaining mesh to avoid movement during washing. After washing they were removed from the washer in the rack and allowed to dry at room temperature before being photographed.

2.2. Assessing willingness

To investigate whether and how changes in the appearance of containers over time influences participants' willingness to use the containers, we adapted a computer-based paradigm developed by Baird et. al., (Baird et al., 2022). Participants were asked to imagine that they were getting lunch "to go" in their local town, and that the restaurant that they had chosen had replaced their single-use container with a reusable container. Participants were told that they would be shown images of different reusable containers and asked to decide whether they would be willing to eat from the container displayed on the screen. Participants' responses were used to determine their 50 % thresholds (that is, the point at which participants became unwilling to eat from the container) using the interleaved, adaptive staircase procedure described by Baird et al. (Baird et al., 2022). An ascending and a descending staircase (i.e., starting with either the cleanest or dirtiest) were run concurrently to reduce any 'anchoring' effects of the initial starting point. The paradigm therefore identified two thresholds for each participant – one for each staircase.

Stimuli. Eight sets of 28 images showing the reusable containers following different numbers of (simulated) uses were used as input.

Design. An 8-between (contaminant: baked beans, chopped tomatoes, chopped tomatoes with turmeric and chilli, tomato pasta sauce, tomato puree with water, tomato soup, coffee, and tea) by 2-within (staircase: ascending vs. descending) design was used, with participants' threshold as the dependant variable.[2]

Procedure. Participants were recruited through Prolific (an online participant recruitment platform) and directed to Qualtrics (an online survey platform) to read more information about the study and complete a consent form. Participants were then asked to complete a pre-questionnaire consisting of demographics (e.g., age, gender, ethnicity) and questions relating to how hungry they were (on a scale from 1 to 10 where 1 indicated "Not hungry at all" and 10 indicated "Very hungry") and how long it had been since they had last eaten (in hours). Participants were then directed to Pavlovia (a platform used to run behavioural experiments online) to complete the paradigm designed to measure their willingness to reuse. On completion of the task, participants were redirected back to Qualtrics where they were provided with a written debrief. Participants were reimbursed £2 for their time.

Participants. We sought to recruit 100 participants per condition and therefore aimed to recruit $N = 800$ participants in total. Due to some technical challenges, we obtained data from 656 participants. Furthermore, since a relatively large number of trials may indicate that the participants were responding randomly on the task making it difficult for the paradigm to converge on participants 50 % threshold, the thresholds of 35 participants (5 %) whose number of trials exceeded 3 standard deviations from the mean were removed. The final sample for analysis therefore contained $N = 621$ participants.

Participants were aged between 18 and 83 years old ($M_{age} = 36.64$; $SD_{age} = 12.52$) and 34 % identified as male, 65 % female and 1 % other. With respect to ethnicity, 86 % were white, 7 % were Asian or Asian British, 4 % were Black/Black British, 3 % mixed/multiple ethnic groups, 1 %, other ethnic group or Latino/Hispanic. Most of the participants (81 %) selected the UK as their country of origin, were employed full time (53 %) and had completed an undergraduate degree (41 %). Participants reported being relatively hungry ($M = 5.05$, 95 % CI = [4.88, 5.23]) and had typically eaten over two hours ago ($M = 2.42$, 95 % CI = [2.17, 2.68].

2.3. Environmental impacts: Life cycle assessment (LCA) methodology

LCA was carried out in accordance with ISO14040 and ISO14044 guidelines (ISO-14044, 2006; ISO 14040, 2006). The analysis was conducted using SimaPro 9.3 and the Ecoinvent V.3.8 database.

2.3.1. Goal and scope definition

The aim of the LCA was to assess the cradle-to-grave environmental impact of reusable and single-use containers and evaluate the BEP, i.e., the minimum number of times a reusable container needs to be used to be considered preferable to a single-use container. The reusable container is made from polypropylene (with pigment added to make it an opaque off-white colour), with a lid made from thermoplastic elastomer (black pigmented) and polypropylene (unpigmented to provide a semi-opaque window). The single-use container used in the cafes at the University of Sheffield is a corrugated paper box with a PET lining and a PET window in the lid (Table S1). This is chosen as a comparator to the reuse system due to its low global warming potential (GWP) (~25 gCO_2e/container) compared to other single use containers, rendering it a 'best-case scenario' for single-use (Greenwood et al., 2021). For comparison, an EPS clamshell and a polypropylene microwave container have GWPs of ~50 gCO_2e/container and >120 gCO_2e/container respectively (Gallego-Schmid et al., 2018; Greenwood et al., 2021). The window accounts for just under 10 % of the GWP; a windowless corrugated paper box would have a higher GWP than the one considered here.

The functional unit was the use of a container that can hold 650 ml of takeaway food from a restaurant at the University of Sheffield. Transport between the restaurant and the consumer location is assumed to be on foot, and to have no energy consumption or environmental impacts attached to it. This is a reasonable assumption if the restaurant and office/home are close to each other. Additional packaging for ordering takeaway food is not included in this study (e.g., cutlery and bags), since it is assumed that such packaging would be required regardless of the container used.

Figure S3 depicts a generic system boundary diagram for the reuse and single-use containers. The system consists of four stages: production and manufacturing, consumption (use phase), waste collection and waste treatment (end-of-life). Washing of reusable containers takes place on site. After the lifespan of containers, the waste is collected, with the end-of-life being either recycling or incineration with energy recovery as determined by the material type. As polypropylene has a low recycling rate, incineration is chosen as the default end-of-life, however the reusable containers can be recycled so this is considered in sensitivity analysis.

2.3.2. Life cycle inventory

The life cycle inventory (LCI) is given in Table S3 and S4. Inventory data was taken from a range of sources. For each container, the main manufacturing processes were applied using representative processes from the Ecoinvent 3.8 database. These processes were modified if necessary to represent the correct country of manufacture, as shown in Table S3. For the washing stage, the required water and energy are included in the analysis, however the treatment of wastewater produced during the washing is not considered. For washing, a small commercial dishwasher was chosen which required 1.4–3.6 litres of cold water and

[2] An 8-between by 2-within participant design is a type of experimental design commonly used in behavioural research to investigate the effects of two independent variables (in this case (i) the eight types of contaminants and (ii) the two staircases used in the task) on the dependent variable (in this case, participants' willingness thresholds). A between factor means that participants were only presented with one of the conditions (e.g., participants either saw bowls that had been stained with baked beans or pasta sauce). A within factor means that participants were presented with both conditions (i.e., all participants completed both the ascending and descending staircase).

0.232 kWh electricity per cycle holding 9 containers.

The default allocation system is the avoided burden approach, meaning that production and recycling of primary plastic is included in the analysis. The end-of-life is modelled so that the products of recycling (material) and/or incineration (heat and electricity) are credited to the system.

2.3.3. Life cycle impact assessment

The environmental impacts are calculated using ReCiPe 2016 Midpoint (Hierarchical). The method contains 13 out of 14 impact categories recommended for the Product Environmental Footprint (PEF). Sensitivity analysis is carried out to investigate the impact of container weight and source of electricity for washing. The lowest container weight investigated is 40 g, equivalent to the single-use PP containers used in takeaways (that could be reused but most often are not).

2.3.4. Break-even point (BEP) assessment

The BEP was calculated based on an approach outlined by Cottafava et.al (Cottafava et al., 2021) (Supporting Information 6.5.3).

2.4. Economic assessment

The economic model for Vytal includes a standing monthly charge per venue (£20/ month), plus a charge per container used (£0.30 including VAT). The LCI data were used to calculate a cost of washing per bowl of £0.011 (Supporting Information 6.6). The cost of the single-use box used here is £0.25 (including VAT and a bulk buy discount); other comparable single-use containers range from £0.35 - £0.45, therefore this is at the cheaper end of the spectrum.

3. Results and discussion

3.1. Durability: How does the appearance of reusable containers change with use?

Unused polypropylene bowls appeared glossy after repeated (up to 75) washes. Use with plastic or wooden cutlery made no discernible marks, however, metal cutlery led to multiple scratches and the release of small amounts of friable material. Microwave heating was seen to greatly accelerate the staining process (Figure S2). This was due to increased absorption of the oleophilic staining compounds into the polypropylene as permeation is a function of diffusivity and solubility, both of which depend on temperature. The stains caused by foods containing tomatoes and turmeric were not particularly reduced by washing, due to their hydrophobic nature, in contrast to stains induced by the more water-soluble tannins from tea and coffee. These simulations showed that repeated exposure to foods (sometimes alongside heat), cutlery, and washing cycles had a range of effects on the containers, from significant staining and scratching after only around 10 cycles when they were treated harshly (e.g., when tomato-based food was repeatedly heated in the bowls), through to almost no visual change even after 75 wash cycles when exposed to other foods (e.g., soy sauce, see Figure S2).

3.2. Willingness: At what point are people unwilling to use a container?

To ascertain whether staining would undermine people's willingness to use the bowls, we showed participants images of the bowls repeatedly exposed to various cycles of the 8 contaminants that our durability testing suggested would stain the bowls the most. Average willingness thresholds ranged from 7 to 16 uses and, on average, participants were willing to reuse the bowls around 10 times ($M = 9.73$, 95 % CI = [9.27, 10.18] (Fig. 1 and Table S2). Participants were more willing to reuse containers that had been repeatedly exposed to tea and coffee ($M = 15.79$, 95 % CI = [14.90, 16.68]) (i.e. lighter staining) than containers exposed to highly staining foods ($M = 7.58$, 95 % CI = [7.01, 8.11]. Note that these thresholds represent the worst-case scenario; participants were only shown images of bowls that were repeatedly exposed to the contaminants that our durability testing suggested would lead to the greatest level of staining. Whilst possible, in practice it is unlikely that a bowl would be harshly scratched and used to microwave baked beans every time it is used.

3.3. Environmental impacts: What are the environmental impacts of reusable and single-use containers?

Fig. 2 shows the global warming (GW) impact and water consumption for single-use and reusable containers used 70 times. Results of other impact categories assessed are shown in the Supporting Information (Figure S4). The reusable container showed 13 % lower GW impact

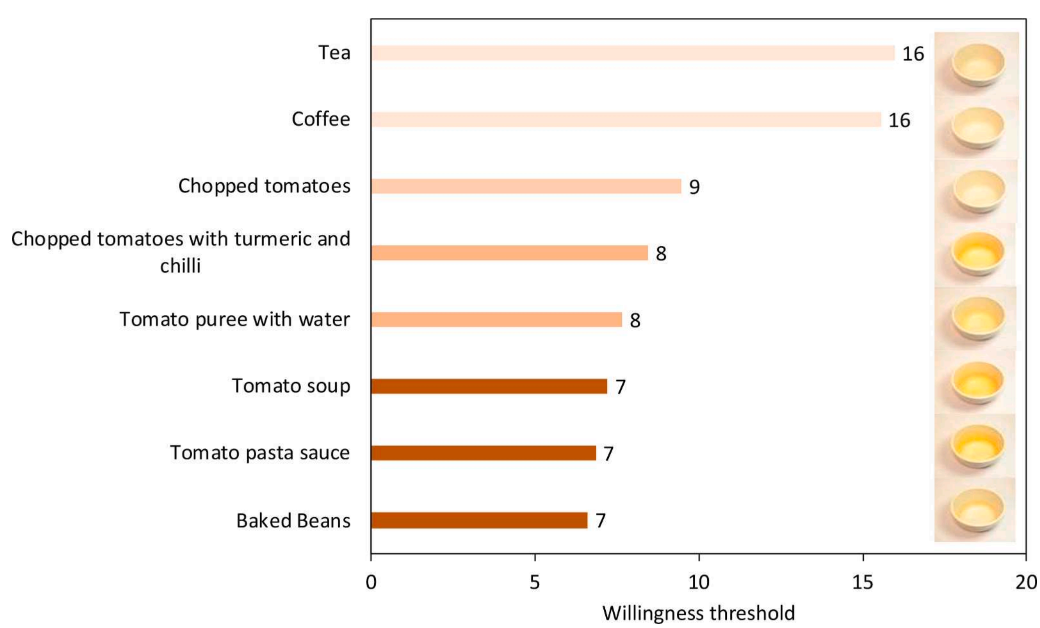

Fig. 1. Willingness thresholds across six types of food and two types of drink. These represent worst-case scenarios for willingness thresholds due to the harsh wear cycles (scratching, staining, washing) the containers are exposed to. Images of the bowls shown on the right correspond to the willingness threshold.

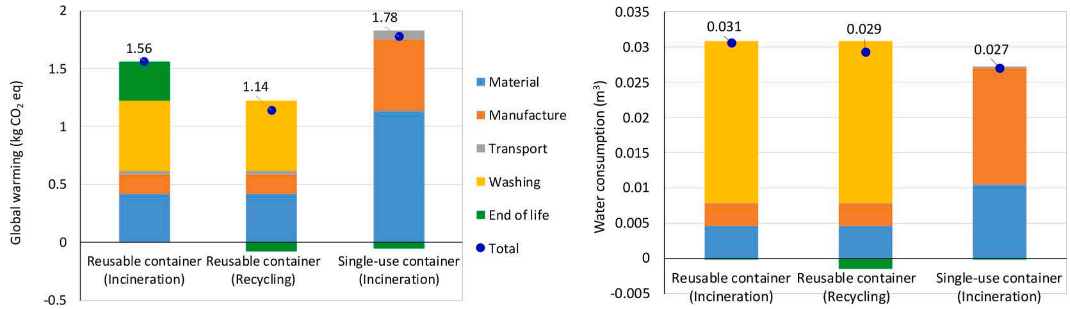

Fig. 2. Global warming (left) and water consumption (right) of use of 70 single-use containers (assuming reusable containers are used for 70 cycles) with different end-of-life (EoL) scenarios.

than the single-use container with incineration as the end-of-life scenario. The negative end-of-life GW impact associated with the single-use container is ascribed to the type of carbon (biogenic carbon) embedded in the single-use container and the avoided emissions associated with energy recovery from incineration. If the reusable container is recycled at end-of-life, the GW impact is reduced by 36 % compared to the single-use counterpart due to the avoided burden of producing new plastic. The reusable container shows approximately 13 % higher water consumption than the single-use counterpart assuming incineration at end-of-life (EoL). A move to recycling the reusable container reduces water consumption by 4 %, but is still 9 % higher than for a single-use container.

39 % and 27 % of the GW impact for the reusable container were attributed to the washing and material phase, respectively. Ensuring the design of the bowls maximises the number of bowls washed per cycle would improve the environmental footprint.

The GW impact of the reusable container showed significant sensitivity to the weight (Fig. 3), with a 47 % reduction in impact if the container weight is reduced from 177 g to 40 g, using the worst-case

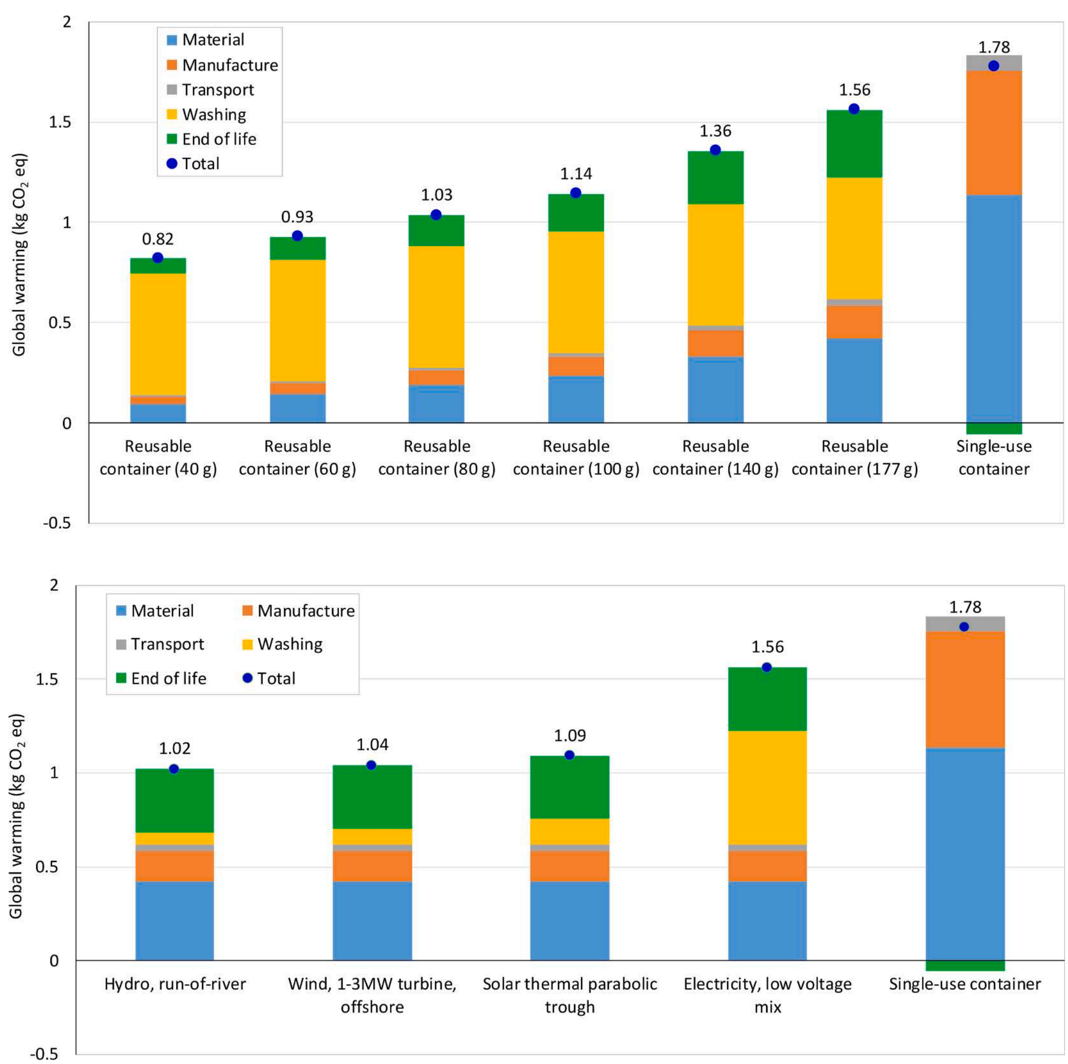

Fig. 3. Sensitivity analysis on: (top) the weight of reusable container and (bottom) the energy source used in the washing phase (assuming constant volume and incineration scenarios for end-of-life). Reusable containers are assumed to be used 70 times.

scenario of incineration with energy recovery as the EoL scenario. Moreover, the contribution of material to the total GW impact decreased from 27 % to 11 % (i.e. 60 % reduction). The GW impact of the manufacturing phase and EoL together decreased by 77 % as the weight of the container decreased from 177 g to 40 g (Fig. 2). The weight of the container is therefore one of the key parameters in designing a sustainable reusable container.

It was assumed that UK grid electricity is used for washing (83 % of the energy comes from non-renewable energy sources). The GW impact of the washing phase can be reduced by between 68 % and 89 % by moving to a higher proportion of renewable energy e.g., hydro run of river, wind and solar (Fig. 3). This equates to an overall GW reduction of up to 34 %. To achieve this decrease, the renewable energy must be in addition to the current electricity grid, not from it. If the renewable electricity is from the existing grid, whilst this might reduce the carbon footprint of the washing, it increases the carbon footprint of the remaining grid electricity giving a net result of no change. Ideally not only the cleaning phase but also the entire system, i.e., production, transport and waste management, should be powered by renewable energy.

For the base-case container, the break-even point for Global Warming Potential was 60 uses, whereas for water consumption the break-even point was 136 uses.

3.4. Economic assessment

Not including the standing monthly charge, the reusable container costs the café £0.06 more per container than the single-use container. The cafés in this study charge a £0.30 surcharge on all single-use containers to reduce waste; this is used to cover the difference in cost. This model works whilst consumers continue to use single-use as well as reusable containers. When including the standing monthly charge, the viability depends on the total number of takeaway meals bought and the ratio of single-use to reusable (see Figure S5). The surcharge on single-use containers is designed to reduce waste, therefore the aim should not be to make a profit on the containers, rather to not make a loss. For 1000 takeaways per month, this allows for a reuse rate of up to 78 %. If this is exceeded, then either the surcharge would need to increase or the cost of the food would need to increase to account for the cost.

The reusable containers do not cost anything for the consumer (assuming they are returned), whereas the single-use containers cost the consumer an additional £0.30. Using a reusable container is therefore beneficial to the consumer in all circumstances.

3.5. Integrating insights across disciplines: Strategies for aligning the break-even point with consumer willingness

For a reuse scheme to benefit the environment, the number of times that people are willing to reuse a container must exceed the environmental break-even point. Integrating the insights across the three components of this research suggests that people may become unwilling to reuse containers before they have been used enough times to confer benefit over the single-use alternative (e.g., when the bowls are exposed to highly staining foods). That is, willingness thresholds ranged from 7 to 16 uses (mean 10), while the BEP was 60 uses. Although these thresholds represent a ‘worst case’ scenario (our simulated wear testing showed that many foods did not significantly stain the containers and so we would expect that people would be willing to use and reuse them many times), they do indicate that reuse systems need to consider whether typical use cases (e.g., reheating tomato-based products in the reusable bowls) could undermine peoples willingness to use the system. To be a sustainable system, either the BEP must decrease, and/or the number of times that people are willing to use a container must increase.

Starting with strategies to reduce the BEP, for GW Impact, the weight of the container had a significant impact on the BEP with a significant reduction from 60 to 13 uses when the weight of the reusable container decreased from 177 to 40 g (Fig. 4a). The BEP for GW impact also changes dramatically depending on the EoL scenario (Fig. 4b) and the BEP shifted from 60 to 33 uses using recycling rather than incineration as EoL of the reusable container. Moving to renewable electricity for washing reduces the GW BEP from 60 to 40 uses (Fig. 4c). Reducing the weight of reusable containers (Fig. 5a) and the carbon intensity of the energy (Fig. 5b) brings the water consumption BEP closer to the willingness threshold. Taking the reusable container from 177 to 40 g, reduces the BEP for water consumption by 78 % (from 136 to 30 uses).

Combining the best of the above proposed changes (i.e., a 40 g container, electricity from wind and recycling at EoL) gives a BEP of 5 uses for GW impact (Fig. 6). This is less than the worst-case scenario of willingness threshold (i.e. a willingness threshold of 7 uses for a container repeatedly exposed to tomato sauce), indicating the potential

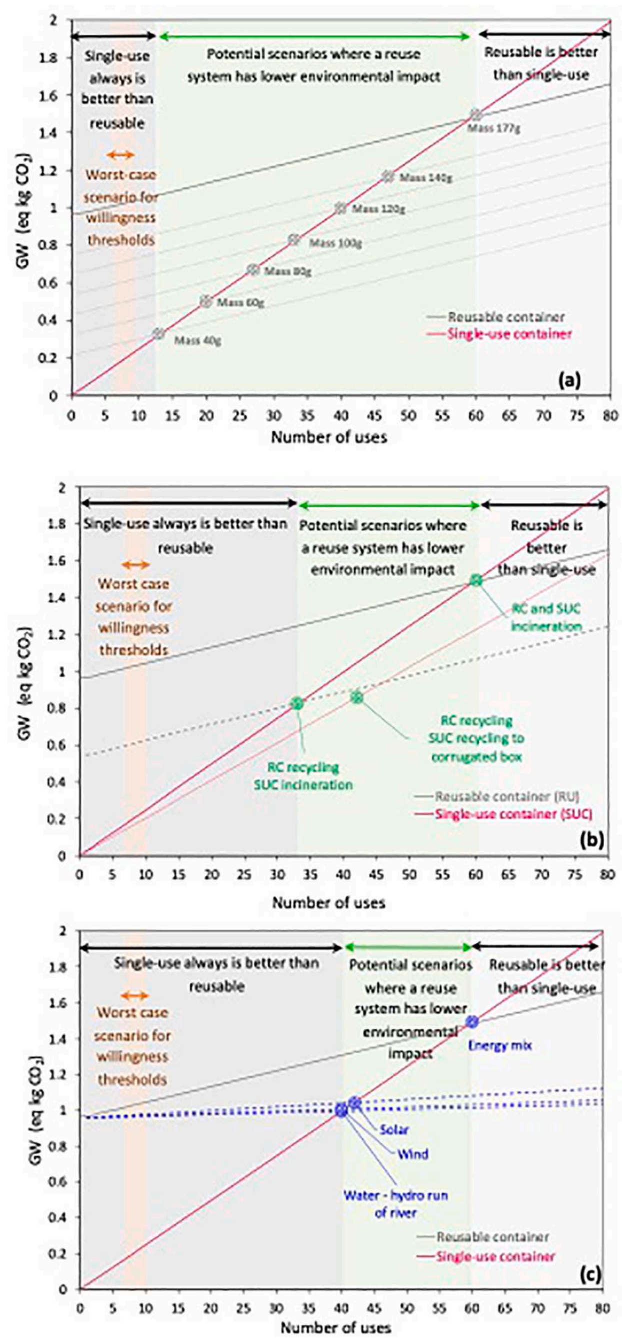

Fig. 4. Effect of (a) weight of reusable container (RC), (b) end-of-life and (c) energy type on global warming (GW) break-even point (BEP).

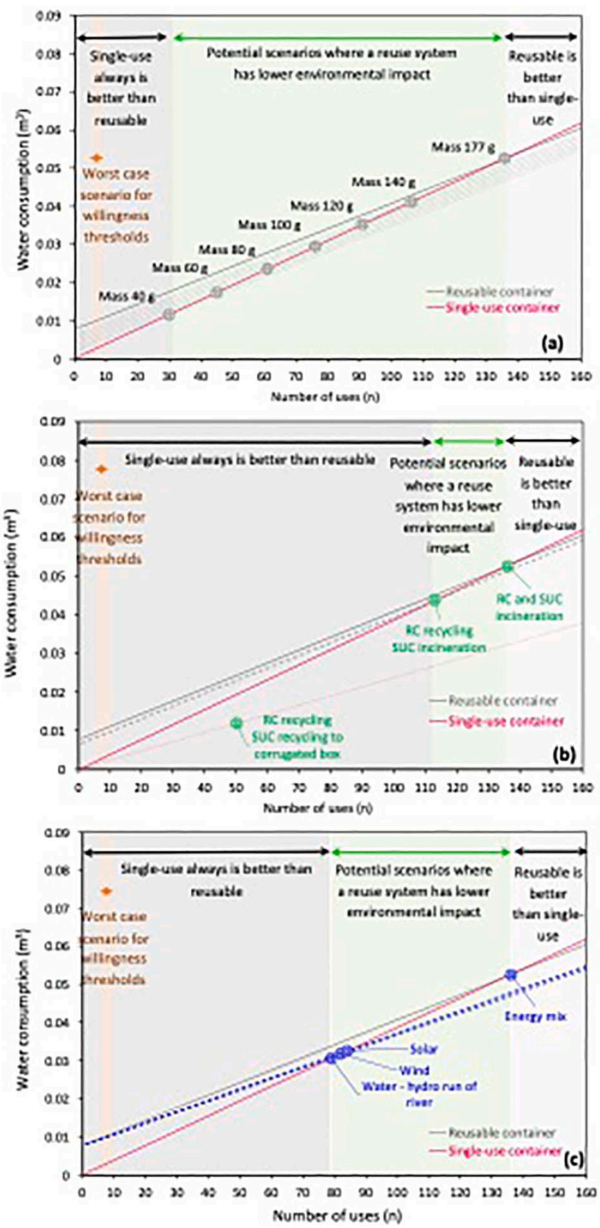

Fig. 5. Effect of (a) weight of reusable container (RC), (b) end-of-life and, (c) energy type on water consumption break-even point (BEP).

for a system that is both environmentally beneficial and that people will be willing to use. The viability of these scenarios needs to be assessed to evaluate if such a reuse system is better in practice than the single-use alternative. Whilst electricity from wind is feasible now (although a dedicated renewable electricity supply would be needed) and recycling of polypropylene is possible but not widespread, the integral durability of lightweighting to 40 g (similar to commonly used single-use PP take away containers that weigh 36 g) would need to be ascertained. This is particularly important when considering water consumption, which relies on container lightweighting to reach equivalence. The lowest BEP evaluated for water consumption is 15 uses, which is greater than most people are willing to reuse a container that has been repeatedly exposed to staining ingredients. It is, however, well within the expected lifetime of the container and the willingness to use an unstained container. A summary of the BEP values for all scenarios is presented in Table S5.

As well as reducing the BEP for reusable containers, strategies could also be employed to increase people's willingness to reuse containers. The lack of willingness to use clean-yet-stained containers suggests that discoloration leads to feelings of disgust, fear of bacteria/viruses or fear of consuming chemicals leaked into the food(Schaller, 2011) . However, an increase in willingness to reuse might be achieved through advances in materials (e.g., developing containers that are less likely to show signs of previous use). We also advocate the use of established frameworks for developing interventions (e.g., the Behaviour Change Wheel (Michie et al., 2013, 2011) that link behaviour change techniques to the putative determinants of behaviour (for a review, see (Allison et al., 2022)). For example, if research identified that people are concerned about potential contamination then an intervention might try to alter how users think about signs of wear (e.g., view them as 'battle scars' earned from fighting the battle against plastic waste, or to convey positive feelings of value and use [48]). Alternatively, interventions might penalise single-use (as for carrier bags (Poortinga et al., 2013)) and/or incentive reuse, either financially or via a reward scheme or positive feedback to motivate people to be more tolerant of signs of previous use.

The willingness of people to engage with the reuse system, to ensure they will both use the packaging in the first place and return it after use, is key. To achieve 50 uses per item of reusable packaging, the container must have a 98 % return rate. This depends on the integral durability of the container (i.e. it must last long enough to be used 50 times) and the return rate from consumers (i.e. consumers must return the container for reuse). The business model used for the packaging considered in this study involves customers providing payment details to an app before they can borrow a container. There is no charge so long as the container is returned within two weeks; if the container is kept for longer, then a charge is applied. This model has shown $a > 98.5$ % customer return rate over a period of a year.

Return can be encouraged by using incentives such as rewards and deposits. Design parameters, such as the weight of the product and its durability and colour, and system design factors, such as ease of collection, have an impact on return rate and acceptability, and therefore the likelihood of the willingness threshold being greater than the BEP. Clearly there will be trade-offs; light-weighting means reduced wall thickness which can compromise durability, so the system optimisation involves maximising the number of reuses between the BEP and the willingness threshold whilst maintaining sufficient durability.

Whilst use of the reuse system does not impact the consumer economically (as long as the container is returned), economics is an incentive to consumers. To try to increase uptake of the reuse scheme, an intervention of a £1 hot drink offer was put in place for a week if the consumer used a reusable cup (normally hot drinks are £2-£3.50). The number of checkouts went from 30 per week to 485 during the intervention and then stabilised at 120 per week. This shows that consumers were motivated by price and, once part of the scheme, continued to use it despite the drinks returning to normal price.

3.6. Strengths and limitations

The approach taken to evaluate a centralised reusable packaging scheme for takeaway food is novel and ambitious in that it combines empirical insights from the material, behavioural, and environmental sciences. Although the value of interdisciplinary research in the current context is well recognised (e.g., (Greenwood et al., 2021)), this is the first study to demonstrate how disciplines and methodologies can, and need to, be combined to produce new insights. Although the context for our work is specific to a company-owned reusable packaging system (operating on a university campus), the method can be applied to other types of reusable packaging schemes.

There are, however, some limitations that should be acknowledged. First, due to the infancy of centrally owned reuse systems in the UK, it was not possible to obtain bowls that had completed a sufficient number of use cycles in a real setting. Therefore, a number of strategies were designed to simulate wear to the bowls. The images that were used to assess whether people were willing to use bowls that show signs of prior use represent "worse-case scenarios" (e.g., heating tomato-based foods

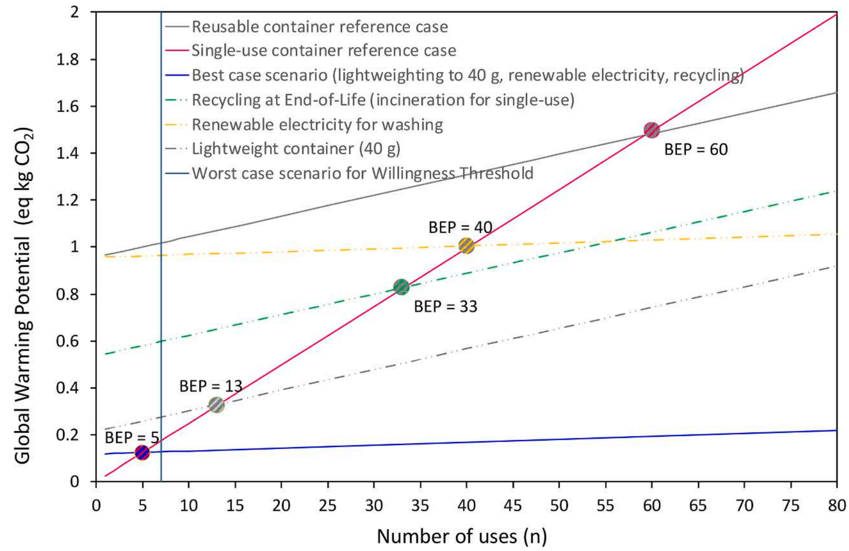

Fig. 6. "Best-case scenario" for recycling and energy, with a container weight of 40 g, showing the break-even point (BEP) for each scenario. The practical viability of these scenarios would need to be ascertained.

in the bowls) and people may be willing to use and reuse bowls exposed to other foods or heated or washed in different ways a greater number of times. We therefore suggest that the present findings are used as a template for considering how particular exposures of interest may effect consumers' willingness relative to the point at which reuse confers benefit to determine if specific reuse systems are likely to be sustainable in practice.

A second limitation of the research is that participants who indicated their willingness to use and reuse bowls were a self-selected sample, who responded to an online survey. Although participants were paid (and so were perhaps not motivated to take part because they are more environmentally conscious), the sample was relatively homogeneous (e.g., 81 % were from the UK, 40 % had an undergraduate degree) and participants were not able to physically inspect the bowls as they would in real life. However, previous research has found that people are relatively unwilling to use bowls that showed signs of wear, even when given the opportunity to hold and inspect the bowls in real life (Collis et al., 2023). Further, we improved upon the ecological validity of the original paradigm developed by Baird et al. (Baird et al., 2022), which used computer-generated images, by using images of real bowls that had gone through cycles of exposure to food and washing.

A third limitation is that durability of a reusable takeaway container can be considered as a function of the surface durability (i.e. wear and staining) and integral durability (i.e., cracking of the main body of the container and distortion). The containers used in the scheme were extremely robust, meaning their integral durability would far outlast their number of uses, and so we concentrated solely on the surface durability. However, when looking at lighter weight containers it is possible that physical integrity would become more important. Further work should explore the integral durability of light weighting to understand how little material can be used whilst retaining integral durability.

Finally, although the present research focused on consumers likely responses to reusing containers, the introduction of reusable packaging is a change not only for consumers but also for the producer and retailer. Innovation in business models is needed to ensure such a system is accepted by both consumers and businesses. Further interdisciplinary research is needed to study the applicability of reuse systems for different markets, not only packaging systems. The deployment of reuse systems also requires government intervention to generate policies that enable infrastructure development and require businesses to have a responsibility beyond the prevalent linear, single-use system. Such policies would enable the design of packaging systems that include collection, cleaning and reuse that deliver the potential environmental benefits whilst continuing to return shareholder value.

4. Conclusions

Packaging design can reduce the environmental impacts across the whole life cycle of reusable products (i.e. material production, energy consumption and end-of-life). However, consumers' behaviour - particularly their willingness to reuse containers that show signs of prior use - is critical to determining whether a reuse system will confer environmental benefit over a single-use system. It would be counterproductive to introduce reuse schemes that have greater global warming potential than the single-use scheme they might replace if the energy and materials investment in the reusable packaging could not be recovered because the willingness to reuse was too low. To avoid superficially attractive "green" practices that are actually worse for the environment, an analytical methodology combining quantitative assessment of human behaviour and quantitative assessment of environmental impact is essential.

Using an interdisciplinary, integrated approach this work has shown that lightweighting of takeaway containers and use of renewable energy for washing is necessary to reduce the global warming potential break-even point to below even the worst-case willingness threshold. An understanding of container integral durability is necessary to understand the balance between lightweighting and lifetime of containers.

CRediT authorship contribution statement

Maryam Hoseini: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sarah C. Greenwood:** Writing – review & editing, Writing – original draft, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization. **Saima Eman:** Writing – original draft, Formal analysis, Data curation. **Paul Mattinson:** Writing – original draft, Formal analysis, Data curation. **Harriet M. Baird:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Rorie Beswick-Parsons:** Writing – review & editing, Funding acquisition, Conceptualization. **J. Patrick A. Fairclough:** Writing – review & editing, Methodology, Conceptualization, Supervision. **Thomas L. Webb:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Anthony J. Ryan:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Formal analysis, Conceptualization. **Rachael H. Rothman:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Formal analysis, 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.

Data availability

Data is included in the supporting information

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Supplementary materials

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