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Abstract

This study assesses the extent to which packaging and distribution impacts can be mitigated as environmental hotspots in the life cycle of micro-brewed beer. We conduct life cycle assessment (LCA) of seven breweries and compare their existing packaging and distribution practises with three mitigation options; use of aluminium cans or reusable glass bottles instead of single use glass bottles or use of polyethylene terephthalate (PET) kegs instead of steel kegs. Findings show that all participating breweries can achieve reductions across multiple impact categories if single use glass bottles are changed to aluminium cans or reusable glass, and further reductions are possible if mode of transport is changed from small delivery vans to lorries for distribution to retailers. The use of PET keg as an alternative to reusable steel keg is a less environmentally sustainable option when beer is delivered short distances, but some savings are possible in long distance scenarios using vans. Carbon footprints per litre beer range from 727 to 1336 g CO_2 eq. across the case study breweries, with reductions of 6-27% or 3-27% by changing to aluminium can or reusable glass bottle, respectively, when beer is delivered by van. The optimal combination of reusable glass bottle delivered by lorry reduces carbon footprints by between 45-55% but will require significant investment and coordination across the wider food and drink sector to implement. Identifying the best packaging material requires a holistic approach that considers interactions and burdens across packaging manufacturing, distribution, use and end-of-life stages.

Keywords: Life cycle analysis; recycling; local food; food miles; circular economy; climate change

1. Introduction

The Circular Economy has become established as an alternative, more sustainable model to aspire to, compared with the wasteful traditional approach taken in the manufacturing of goods involving a linear path of continuous extraction of finite raw materials and disposal to landfill or incineration following first use (Korhonen et al., 2018). Packaging plays a crucial role in protecting food and drink, extending the shelf life and ensuring food safety standards can be maintained from the post production stage through to consumption (Verghese et al., 2012). The negative effects of food packaging arise at the post-consumer stage. High consumption of fast moving consumer goods leads to unsustainable burdens from large volumes of waste packaging (Niero et al., 2017). In order to close the loop, there is a need for economic progression away from this reliance on finite natural resources (Kirchherr et al., 2017). Indeed, the effects of adopting a circular economic model are not confined to environmental metrics but also affect economic, technical and social domains (Iacovidou et al., 2017).

The most common packaging formats for beer are stainless steel kegs or casks, high density polyethylene casks, glass bottles, aluminium cans and polyethylene terephthalate (PET) kegs (Lorencová et al., 2019; Olajire, 2020). Several life cycle assessment (LCA) studies of beer production have identified packaging as the main hotspot and single use glass bottles incur larger environmental burdens than other packaging options (Amienyo et al., 2016; Cimini et al., 2016; Koroneos et al., 2005). The global warming potential (GWP) of beer packaged in glass bottles at a large scale multinational brewery was found to be 740 g CO_2 eq. per litre, 7% higher than for beer in aluminium cans and 196% higher than beer in a 30 L stainless steel keg (Cimini et al., 2016). Indeed numerous LCA studies have focused on packaging materials for food and drink (Amienyo et al., 2013; Ferrara et al., 2021; Hallström et al., 2018; Nessi et al., 2012; Von Falkenstein et al., 2010). A recent study of alternative wine packaging found single use glass bottle to have the highest GWP burden followed by PET, reusable glass, aseptic container (multilayer polymer-coated paperboards) and bag in box (Ferrara et al., 2020; Robertson, 2021). Kouloumpis (2020) found single use glass bottles to have higher GWP burdens than PET bottles because of impacts associated with production and transportation (Kouloumpis et al., 2020).

Contrary to previous LCA studies of large-scale drinks supply chains, a recent LCA study of beer produced in microbreweries with different packaging preferences, conducted by Morgan et al. (2020), found downstream distribution (rather than packaging) to be the main hotspot for many breweries and environmental impacts – because of reliance on small delivery vehicles with high emissions intensities per tonne-km of transport. Sensitivity analysis showed that an average 45% reduction in GWP could be achieved by changing mode of transport from light commercial vehicles to lorry (Morgan et al., 2020). There is growing interest among modern day consumers to "buy local" from small scale producers, and phenomena such farm-to-fork or paddock-to-plate driven by the perceived benefits of quality, traceability and sustainability (Selvey et al., 2013; Verger et al., 2018). This drive to shorten supply chains is no less relevant following geopolitical matters like Brexit and recovery from a global pandemic (Hendry et al., 2019; Hobbs, 2020). There is an urgent need to better understand the implications of supply chain downscaling in terms of interactions across production efficiency, packaging choice, distribution logistics and packaging end-of-life.

The beer sales market consists of two segments referred to as on-trade and off-trade. The former consists of venues such as pubs, clubs and restaurants, whilst the latter includes shops and supermarkets (Tomlinson et al., 2014). On-trade consumption has fallen 37% since 2000, and in 2018 the on-/off-trade drinking split was 46%/54% respectively (Brewers of Europe, 2019; British beer and pub association, 2017;). Beer for the on-trade sector is largely sold in keg and cask whilst bottled and canned beer can be for either the on- or off-trade (Morgan et al., 2020). The advantage of keg or cask is the ability to distribute a larger volume of beer in a single container, and a useful life of up to 30 years for a stainless steel keg makes this a lower impact packaging option compared to single use packaging such as aluminium can or single use glass bottle (Cimini et al., 2016; European Commission, 2018). An emerging alternative to the reusable keg is the single direction polyethylene terephthalate (PET) keg championed by manufacturers as a sustainable alternative that doesn't require a return journey back to the brewery, though little mention is made of transport for waste collection or recycling (Dolium, 2021; Keykeg, 2020). A thorough literature search found no academic peer review LCA studies have been conducted on PET kegs, but environmental product declarations (EPD) by the Carlsberg group have presented results for a 20 L modular PET keg with GWP results ranging between 502 to 562 g CO_2 eq. per 1 L of packaged beer (Reggiori, 2011c, 2011d, 2011a, 2011b). Pertinent to the off-trade, the use of aluminium cans by small and independent breweries in Britain has shown significant growth as an alternative to glass bottles, and is expected to continue in popularity (SIBA, 2020). A study of suitable packaging options for a Czech style lager concluded that aluminium can was the best option as a single-use packaging in terms of beer preservation, out-performing glass and PET bottles in tests of colour stability, beer foam stability and sensory analysis (Lorencová et al., 2019).

There is significant value to be gained from a circular business model by shifting the focus away from primary raw material use towards reuse or recycling (Zink et al., 2017), requiring product design with disassembly and reuse at the concept stage (Rathore et al., 2011). Revaluating the reverse logistics pathways for waste glass collection could improve the supply of cullet ultimately increasing the recycle content in glass packaging (Testa et al., 2017). As demand for plastic packaging increases the entire model needs revaluating to phase out petrochemical plastics and move towards developing a bio based value chain for plastic (Lamberti et al., 2020). The EU has an average recycle rate for container glass of 73%, and whilst recycling rates are improving, the UK figure is 68% (FEVE, 2015).

Several LCA studies conclude that glass packaging GWP footprint could be reduced by changing to a glass reuse system (Landi et al., 2019; Stefanini et al., 2021; Tua et al., 2020).

This work focuses on the unique challenges faced by small scale beer production to reduce packaging and distribution hotspots. Recent LCA evaluation has highlighted, somewhat counter-intuitively, that dependence on small vans to conduct local deliveries represents a major environmental hotspot for micro-brewed beer. For the first time, using a rich real-life dataset from multiple micro-breweries, we explore the interaction between packaging and distribution burdens in the context of environmental footprints for short drinks supply chains. Our work assesses the mitigation potential of reusable bottles, aluminium cans and PET kegs across seven breweries, each with a different approach to packaging and distribution, to explore context specificities when determining more sustainable and circular packaging and distribution options. The outcome from this work is expected to give new insight into the challenges and opportunities of implementing sustainable packaging and distribution across shorter supply chains.

2. Methodology

2.1. Goal and scope definition

The overall objective of this study is to evaluate the influence of different packaging and distribution options on the environmental footprint of beer produced by seven small-scale breweries, often referred to as "micro-breweries". In table S 1 (supplementary material) the annual production for the breweries range from 13,336 L to 191,000 L. The target audience is small-scale food and drinks manufacturers, sustainability analysts and policy makers wishing to identify more sustainable (circular) packaging and distribution options. Each of the seven case studies have unique characteristics in terms of raw materials, packaging preference and delivery distance. Here we attempt to identify the best packaging option to reduce the environmental footprint by focusing on two key stages of the beer life cycle, production of packaging material and transportation. The default packaging for each brewery is compared against three alternative packaging options applied to equivalent formats. In option one, all beer distributed in single use small packaging (single use glass bottle or aluminium can of various sizes) is instead packaged in 0.44 L aluminium cans. In option two, all beer distributed in single use small packaging is packaged into reusable bottles that undergo 30 bottle collection, washing and (re)use cycles. In option three, all beer distributed in reusable kegs or casks is instead packaged in single-use PET keg, representing an increasingly popular packaging and distribution option for small-scale breweries owing to simplified linear logistics (Tsallagov, 2021). The functional unit is defined as one litre of packaged beer at the point of retail to the consumer. The objective here is to identify the best packaging and distribution option(s) to reduce the overall environmental footprint of beer for each of the seven case study micro-breweries.

The life cycle impact assessment is carried out according to the guidance provided by the European Product Environmental Footprint (PEF) method (Fazio et al., 2018), excluding more methodologically uncertain toxicity and water scarcity impacts. Thus, 10 impact categories were analysed: GWP, fossil resource depletion potential (FRDP), acidification potential, freshwater eutrophication potential, ionizing radiation potential, marine eutrophication potential, ozone depletion potential, photochemical ozone formation potential, terrestrial eutrophication potential and abiotic resource depletion potential. Of these, additional emphasis was placed on three impact categories with high normalised scores (Fig. 3): GWP, FRDP and acidification potential. Open LCA v.1.10.2 is used for some calculations taken from Ecoinvent v 3.5 data base (Wernet et al., 2016). Data are collated in MS Excel to generate the final footprint results. The complete list of default findings for all case studies are shown in Table S 2 (supplementary material). In order to compare impact categories, the results have been normalised based on global per capita factors (Fazio et al., 2018).

2.2. Single packaging material footprint

The case studies have quotas of beer allocated to packaging options based on the personal preference for each brewery. Table S 1 (supplementary material) shows the unique combinations of reusable keg and cask and single use small packaging like bottles and cans across the breweries. To understand how each packaging material influences brewery footprints in isolation, a generic case study was created based on brewery G, with all beer distributed in single packaging options across scenarios.

2.3. System boundaries

An attributional LCA is implemented in this study (Finkbeiner et al., 2006). Cultivation, processing, upstream distribution, brewing, packaging, downstream distribution, and waste management are included in the scope of the analysis (Figure 1). An expanded boundary approach is applied to account for by-products from brewery processing used as cattle feed, with "credits" from avoided barley and soy meal production (Morgan et al., 2020).

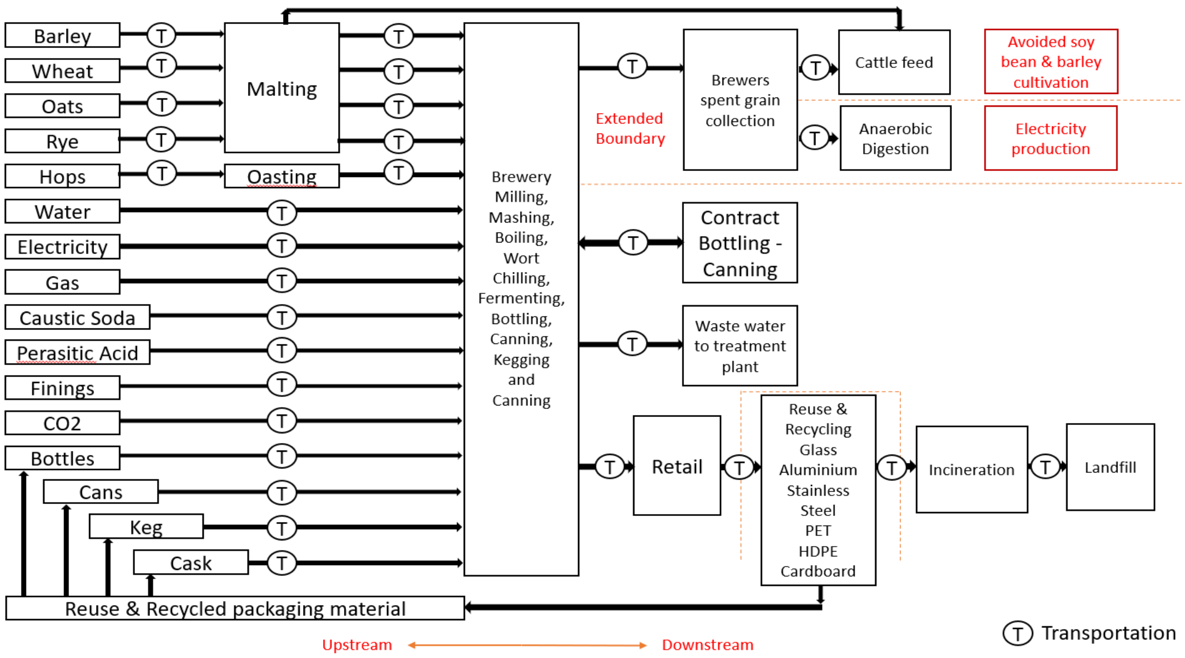


Figure 1: Scope of product life cycle included in this study with system boundary consisting of production of raw ingredients, processing, upstream transportation, brewery production, downstream distribution and waste with an extended boundary to account for substitution of barley and soy meal by brewers spent grain and malting by-products used as animal feed (Morgan et al., 2020).

2.4. Ingredients and production

The primary ingredients used across all case study breweries are shown is Table S 3 (supplementary material), the volume of combined grains refers to a mixture of wheat, oats and rye but barley is the primary ingredient. Average batch volume varies between 469 and 1990 L for participating breweries Water is used in beer production and to clean the equipment, sometimes in large quantities (Edmonds, 2016). A brewery with relatively good efficiency can achieve a ratio ranging between 4 and 7 litres of water per litre of beer (Olajire, 2020). The participating breweries consumption is between 3 and 5.3 of water per litre of beer (Table S 1).

2.5. Packaging

All participating breweries have differing packaging profiles, involving different packaging materials, container capacities and the volume of beer allocated to each packaging type. Table S 1 shows a summary of batch average packaging profiles for each participating brewery with between 9% and 32% of beer packaged into single use packaging, apart from brewery E where 60% of beer is packaged in single use glass bottles.

2.6. Transport

Transport activities arise primarily in to two stages, upstream transport of ingredients and packaging to the brewery and downstream distribution of beer from the brewery to the retailer. In previous work, upstream transport made little contribution to the overall results regardless of long transport distances, and the critical point was identified as downstream distribution because of the use of light commercial vehicles to distribute beer to customers (Morgan et al., 2020). Table 1 shows transport activity factors for beer across different packaging options for each brewery, expressed as kg-km per litre of beer.

Table 1: Transport activity factors for distribution of packaged beer from each of the case study breweries, with default results representing current packaging preferences for comparison with alternative options. Option 1 represents all beer packaged in single use glass bottles replaced with 0.44 L aluminium cans. Option 2 represents all beer packaged in single use glass bottles replaced with reusable glass bottles. Option 3 represents all beer packaged in reusable kegs and casks replaced with 30 L single use polyethylene terephthalate kegs.

		{Single packaging transport factors}									
Packaging	Unit	All Can	All Bottle	All PET	BrewA	BrewB	BrewC	BrewD	BrewE	BrewF	BrewG
Bottle	kg-km/L				12	85	47	27	135	53	51
Can	kg-km/L										20
Stainless steel keg	kg-km/L				75		5			14	323
Stainless steel cask	kg-km/L				87	94				65	
HDPE cask	kg-km/L					78	74	218	40		
PET keg	kg-km/L										11
Total (default)	kg-km/L				174	257	126	245	175	132	405
Aluminium can	kg-km/L	268			8	55	30	18	87	34	53
Stainless steel keg	kg-km/L				75		5			14	323
Stainless steel cask	kg-km/L				87	94				65	
HDPE cask	kg-km/L					78	74	218	40		
PET keg	kg-km/L										11
Total Option 1	kg-km/L	268			170	227	109	236	127	113	387
Reusable bottle	kg-km/L		432		13	92	51	29	146	57	85
Stainless steel keg	kg-km/L				75		5			14	323
Stainless steel cask	kg-km/L				87	94				65	
HDPE cask	kg-km/L					78	74	218	40		
PET keg	kg-km/L										11
Total Option 2	kg-km/L		432		175	264	130	247	186	136	419
Bottle	kg-km/L				12	85	47	27	135	53	51
Can	kg-km/L										20
PET keg	kg-km/L			269	134	130	65	181	33	56	216
Total Option 3	kg-km/L			269	146	215	112	208	168	109	287

Packaging and distribution: single use bottle 0.3 kg, reusable bottle 0.365 kg, aluminium can 0.015 kg, 50 L stainless steel keg 12.3 kg, 30 L stainless steel keg 9.5 kg, stainless steel cask 10.1 kg, HDPE cask 5.05 kg & 30 L PET keg 1.07 kg.

2.7. Option one: replacing single use bottle with aluminium can

This option involves directly exchanging the volume of beer each brewery packages in glass bottles to aluminium cans to understand how the lighter material affects packaging and distribution burdens. The capacity of aluminium cans varies, as it does for bottles, but for this scenario a 0.44 L can is used to represent the most popular size option among breweries (Wavegrip, 2019). This means that regardless of a brewery's preference for 0.33 L or 0.5 L glass bottle, the scenario focuses on a single can size.

2.8. Option two: Taking single use glass bottles and replacing them with reusable bottles.

The value chain stages that are affected from this change are packaging, upstream distribution, downstream distribution and end-of-life. A reusable bottle scheme requires the bottle to be thicker and more robust, resulting in the 0.33 L bottle being 30% heavier and the 500 ml bottle 22% heavier than the lighter single use version (Vetropack, 2021). A reuse rate of 30 cycles is assumed based on PEF recommendations, and the total weight of glass bottles used is divided by the reuse rate (European Commission, 2018). It is assumed that post-consumer stage for distribution of single use and reusable glass would be similar on the basis that both packaging options are processed domestically and not exported. There is no change to the downstream distribution delivery distances but transporting heavier bottles does increase kg-km transport factors (Table 1). Primary and secondary data were used to account for the bottle washing process based on machinery with a capacity of 60,000 bottles per hour consuming 0.010 kWh of electricity, 0.44 L of water, 0.008 kg of caustic and 0.088 MJ of natural gas, per litre of beer packaged (IC Filling Systems, 2021; Jade Trading, 2021; Ponstein et al., 2019).

2.9. Option three: replacing conventional kegs and casks with single use PET alternative.

Similar, to the aluminium can scenario, the volume of beer packaged into reusable kegs and casks according to each brewery's packaging and distribution strategy is replicated with a single use one way PET keg. The participating breweries have individual preferences for using kegs and casks, and in order to understand the effects of using PET on the environmental footprint, beer that would be packaged in to the reusable kegs and casks is modelled with the 30 L size PET keg options (Keykeg, 2020). The purpose of this exercise is to understand how the reduction in weight affects both up and downstream distribution when using the lighter PET keg, and to compare the manufacturing and end-of-life burdens of different volumes of different packaging materials. The majority of reusable keg and cask are owned by the breweries and are made of stainless steel or high density polyethylene (HDPE) in a constant cycle of filling, distribution, dispensing at the place of retail, empty containers collected by the brewery, cleaning and then reuse. The PET keg is promoted as a more sustainable option because of its light weight construction, it does not require a return journey to the brewery and is recyclable (Keykeg, 2021). The majority of the UK post-consumer plastics are exported often to countries with low environmental standards raising some uncertainties around the true fate of used PET kegs (Bishop et al., 2020; Wrap, 2019).

3. Results

The default environmental footprint per 1 L of beer varies greatly amongst all case studies (Table S 2), reflecting different scales, batch capacity, packaging preferences and downstream distribution distances. The carbon footprint results range from 727 g CO_2 eq. per L (Brewery A) to 1336 g CO_2 eq. per L of beer (Brewery G), with a median value of 837 g CO_2 eq. per L for brewery C. Brewery E has the largest GWP burden for packaging, at 406 g CO_2 eq. per L owing to the heavy reliance on glass bottles. Brewery G has the largest GWP burden for combined packaging and distribution, at 893 g CO_2 eq. per L, owing to a long average transport distance of 522 km.

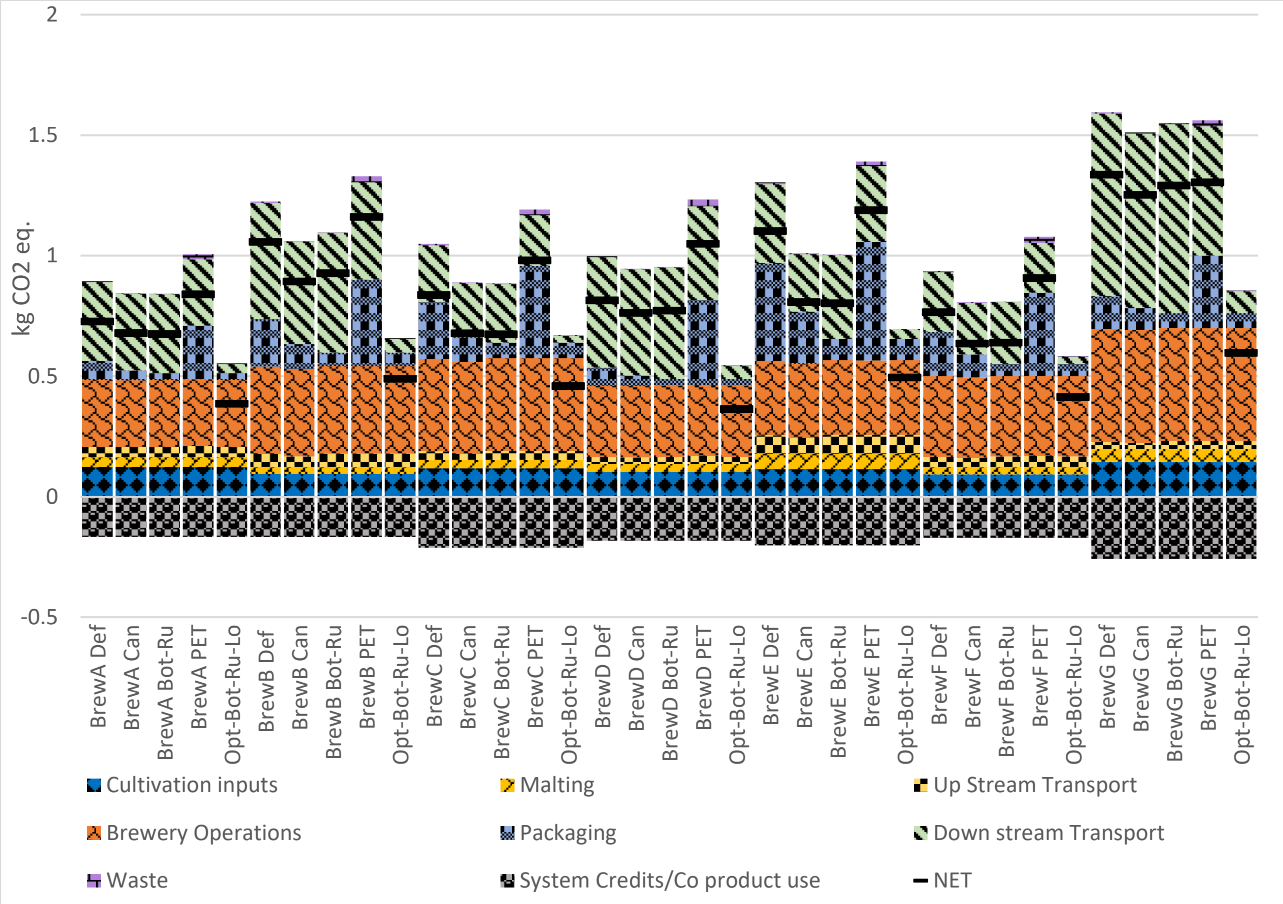
3.1. Switching packaging options across micro breweries

Changing single use small packaging to either aluminium can or reusable glass bottle is effective in reducing GWP burdens. The packaging material that resulted in the biggest reduction for each brewery is shown in Figure 2. Reusable glass bottle is the best option for breweries A, C and E whilst aluminium can is the best option for breweries B, D, F and G. Brewery E shows the biggest beer footprint reduction of 27% from changing to reusable glass bottle (1102 g CO_2 eq. down to 803 g CO_2 eq. per L beer) and a reduction of 27% from switching to aluminium can (1102 g CO_2 eq. down to 807 g CO_2 eq. per L beer). The mean average reductions (across all breweries) for each relevant stage of the beer life cycle for aluminium cans vs single use bottles are: 15% for upstream transport, 45% for packaging production, 11% for downstream transport, and 30% for waste management (S 4 supplementary material). Aluminium cans reduced the average overall beer footprint by 14% (across all breweries). The small increase in weight of reusable glass bottle results in an average 4% increase (across all breweries) to upstream transport burdens and an average 3% increase (across all breweries) to downstream transport burdens. However, switching to reusable bottle achieves a 68% reduction in packaging production burden, and a 40% reduction in waste management burden, resulting in an overall beer footprint reduction of 13% (S 4 supplementary material). Overall, changing from stainless steel to PET keg increases beer footprints by an average 14% (across all breweries), and up to 29% for Brewery D (815 kg CO_2 eq. up to 1050 kg CO_2 eq. per L beer) (S 4 supplementary material). Brewery G was the only case study to show a small (2%) reduction in beer footprint from using PET keg, owing to having the longest downstream distribution distance of 522 km (S 1 supplementary material).

FRDP burdens are reduced when packaging material is changed to aluminium can or reusable glass bottle across all breweries. Aluminium can is the best option for reducing FRDP burdens for breweries B, D, E, F and G, whilst breweries A and C see bigger reductions in FRDP burdens from switching to reusable glass bottles. Changing default packaging to aluminium can results in an average reduction (across all breweries) of 15% to upstream distribution, 41% to packaging, 11% to downstream distribution, 57% to waste management, and an overall average reduction (across all breweries) of 12% in beer footprints. As for GWP, reusable glass bottles result in an average 4 & 3% increase (across all breweries) of upstream and downstream FRDP burdens respectively, but packaging and waste management burdens are reduced on average by 64% and 64%, respectively, resulting in an average overall beer footprint reduction of 11% across all breweries (S 4 supplementary material). Brewery E sees the biggest reduction in beer FRDP footprints of 24% for aluminium cans, reducing the burden from 17.65 MJ down to 13.48 MJ per L beer. Brewery E also sees the biggest FRDP reduction, of 23% for glass bottle, from 17.65MJ down to 13.55MJ per L beer. The PET keg option increases FRDP footprints across all case studies by an average of 21%, increasing the footprint for Brewery D from 14.04 MJ up to 19.66MJ per L beer.

Acidification burdens are reduced when single use glass packaging is changed to aluminium can or reusable glass bottle. The aluminium can was best option for reducing acidification burdens for breweries B, D and G whilst the reusable bottle system was best for breweries A, C, E and F. With aluminium can we find average reductions (across all breweries) of 14% for upstream distribution, 57% for packaging, 11% for downstream distribution, 37% for waste stage and an overall average reduction of 15% (S 4 supplementary material). Reusable glass bottles incur an average 4 & 3% increase (across all breweries) to up and downstream distribution respectively, but reductions of 78% for packaging, 46% for waste management and overall average reduction of 15% across all breweries (S 4 supplementary material). Brewery E sees the biggest overall reduction in beer footprint of 29% with a switch to aluminium cans, with acidification footprints reducing from 0.00952 molc H+ eq. to 0.00679 molc H+ eq per L beer. Brewery E see the biggest reduction in beer footprint of 31% for reusable glass bottle, with footprint reducing from 0.00952 molc H+ eq. to 0.00657 molc H+ eq. per L beer. Switching from steel to PET kegs resulted in an average acidification increase (across all breweries) of 6%, with brewery D showing the biggest change of 14% to increase beer footprint from 0.0066 molc H+ eq. to 0.0076 molc H+ eq. Brewery G is the only case study to show a (4%) reduction in beer footprint following a shift to PET keg, from 0.0103 molc H+ eq. to 0.0099 molc H+ eq. per L beer.

Switching to reusable bottles is the best option to reduce freshwater eutrophication, abiotic resource depletion potential and ionizing radiation burdens, whereas switching to aluminium can is the best option to reduce marine eutrophication, ozone depletion, photochemical ozone formation and terrestrial eutrophication burdens.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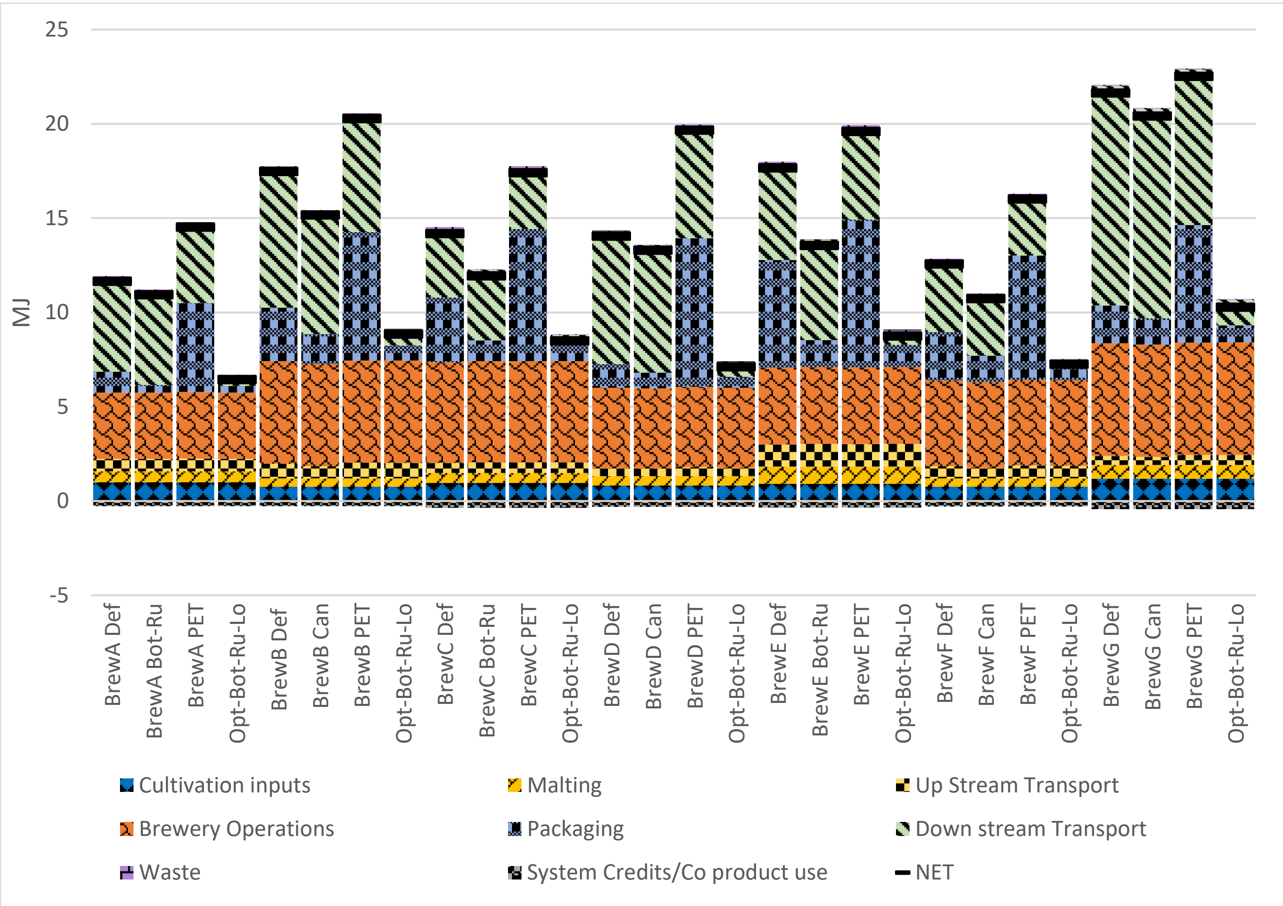
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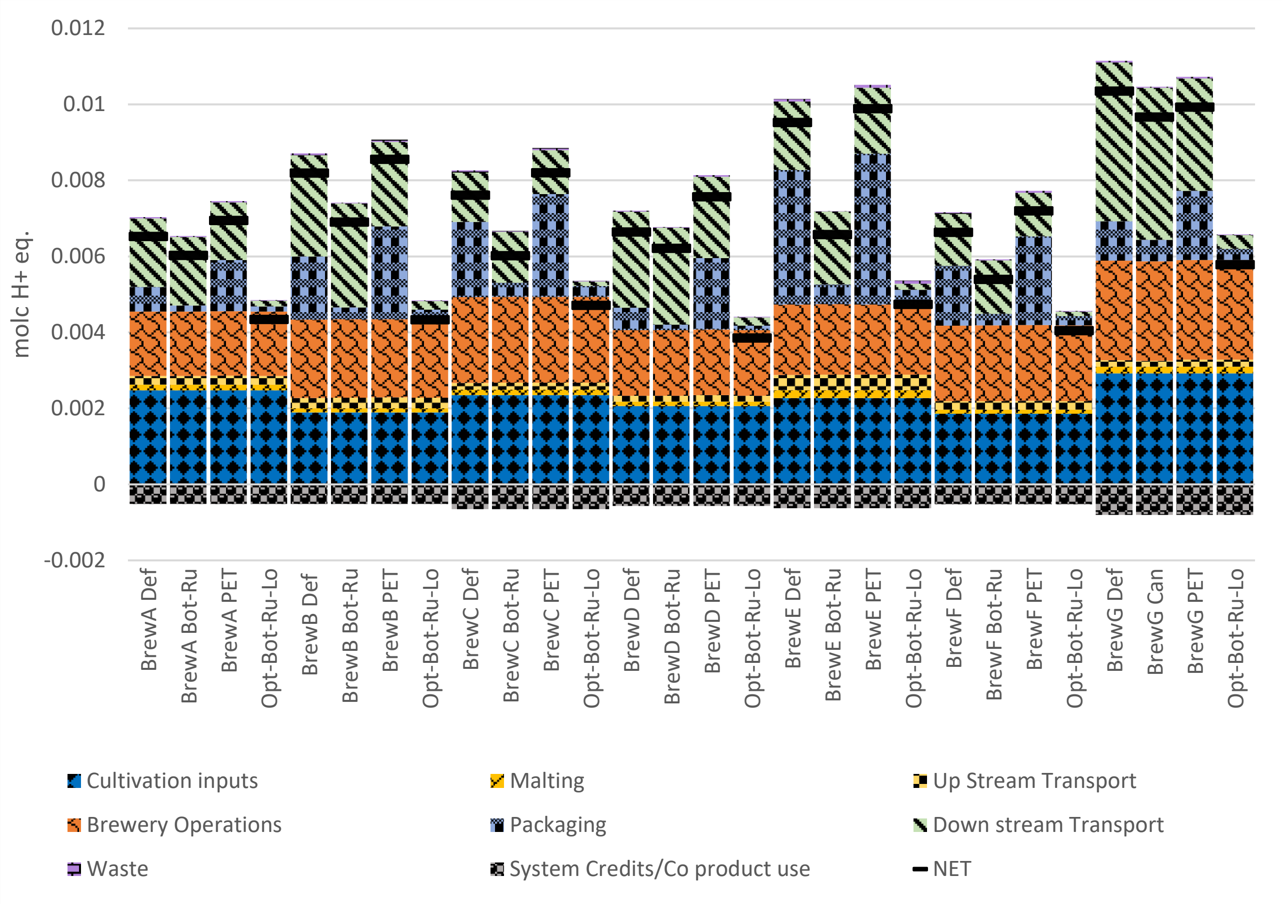
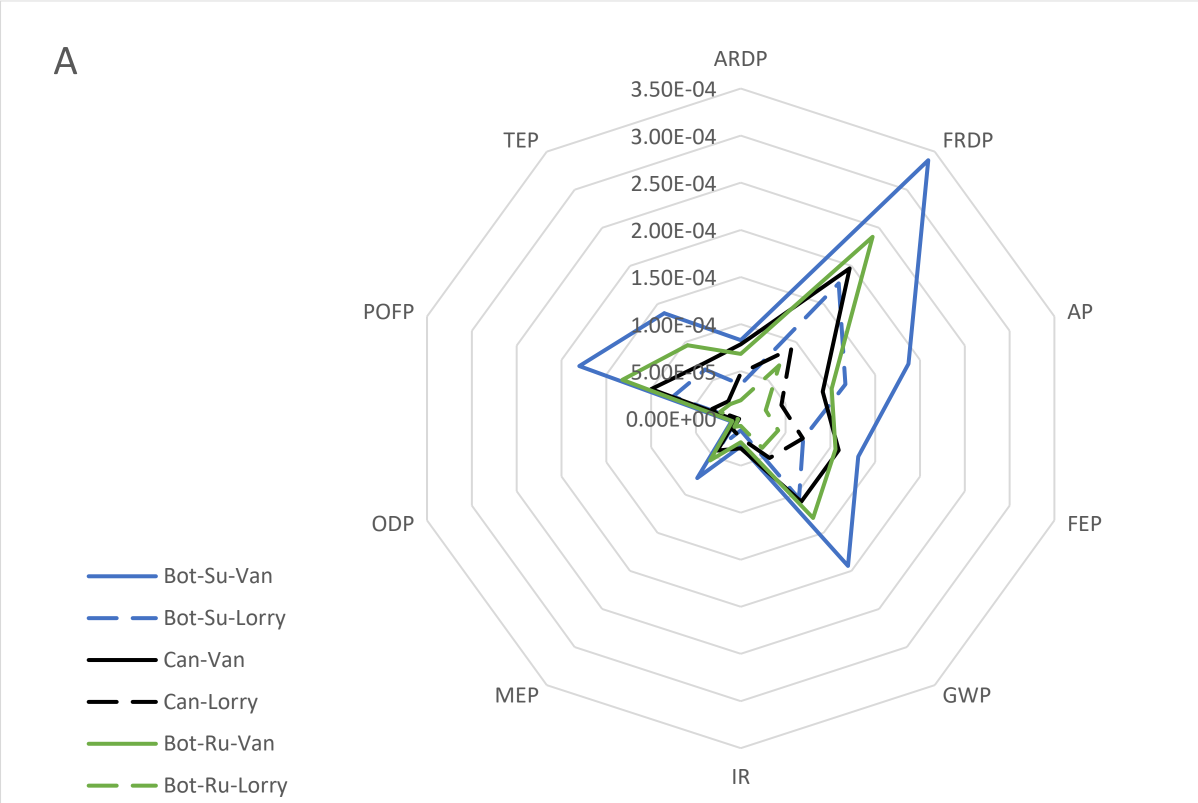


Figure 2: GWP, FRDP and Acidification footprints for beer produced across seven case study breweries. Results show default values (Def), best performing single use packaging for each brewery showing either reusable glass (Bot-Ru) or aluminium can (Can), reusable keg and cask changed to PET keg (PET) and optimised method combining reusable bottle with a shift from van to 7 – 16 tonne lorry for distribution (Opt-Bot-Ru-Lo).

3.2. Comparative performance of combined packaging and distribution options

Distribution from brewery to retailer has been identified as a particular hotspot for micro-brewed beer because it is typically carried out using small vehicles that are inefficient at transporting cargo (Morgan et al., 2020). Figure 3 A shows generic footprints with all beer in a single packaging material, for transport with van or lorry over 522 km (adapted from Brewery G data). Single use bottle delivered with van (Bot-Su-Van) results in the largest burdens across all impact categories, with the highest normalised scores for FRDP, GWP, photochemical ozone formation and terrestrial eutrophication (S 5 supplementary material). Scores for aluminium can delivered by van (Can-Van) and reusable glass bottle delivered by van (Bot-Ru-Van) are very similar. Both options have lower scores (smaller burdens) compared to single use bottle, with the biggest differences for FRDP and acidification (Fig. 3 A). When the mode of transport is changed to lorry, the footprints for all packaging options are reduced (Fig. 2), and the comparative performance of reusable glass bottle (Bot-Ru-Lorry) improves the most to achieve lowest normalised scores across all impact categories (Fig. 3 A).

Figure 3 B shows that PET keg delivered with van (PET-Keg-Van) has the highest normalised scores for FRDP and freshwater eutrophication, whilst stainless steel keg delivered with van (SS-Keg-Van) has the highest scores for abiotic depletion potential, acidification, GWP, marine eutrophication, ozone depletion potential, photochemical ozone formation and terrestrial eutrophication. When mode of transport is changed to lorry, the footprints for all packaging options are reduced, HDPE cask and stainless steel keg and cask show biggest improvements to normalised scores across all impact categories (Fig 3 B).



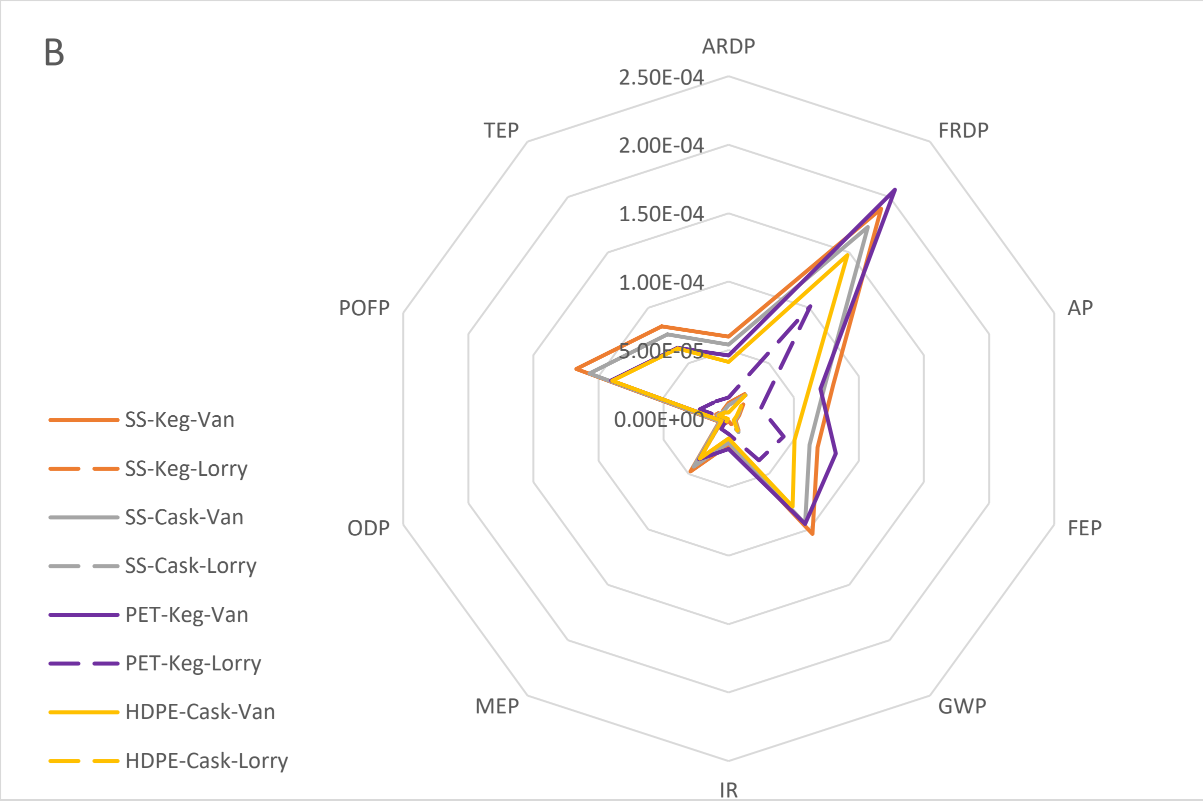
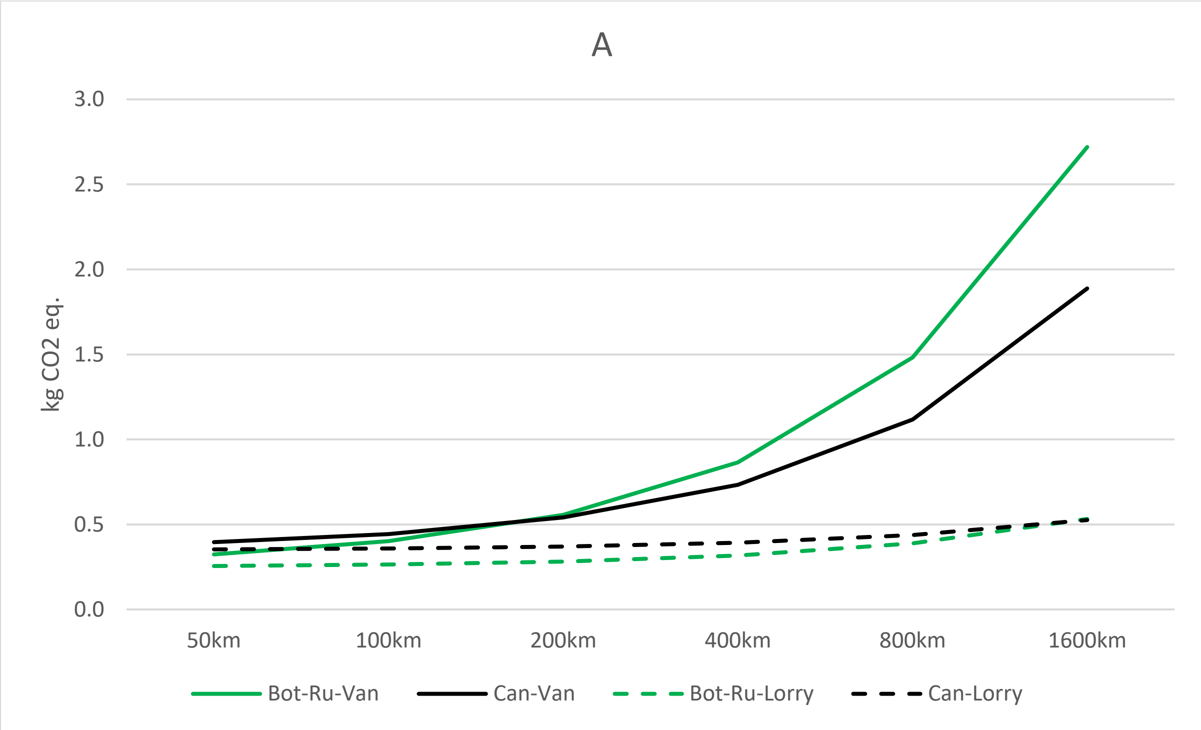


Figure 3: Part A shows a radar plot of normalised scores across ten impact categories for single use glass bottle and delivery with van (Bot-Su-Van), single use glass bottle delivered with lorry (Bot-Su-Lorry), aluminium can delivered with van (Can-Van), aluminium can delivered with lorry (Can-Lorry), reusable glass bottle delivered with van (Bot-Ru-Van) and reusable glass bottle delivered with lorry (Bot-Ru-Lorry). Part B shows normalised scores for stainless steel keg delivered with van (SS-Keg-Van) stainless steel keg delivered with lorry (SS-Keg-Lorry), stainless steel cask delivered with van (SS-Cask-Van), stainless steel cask delivered with lorry (SS-Cask-Lorry), PET keg delivered with van (PET-Keg-Van), PET keg delivered with lorry (PET-Keg-Lorry), HDPE cask delivered with van (HDPE-Cask-Van) and HDPE cask delivered with lorry (HDPE-Cask-Lorry). The impact categories include Abiotic resource depletion potential (ARDP), Fossil resource depletion potential (FRDP), Acidification potential (AP), Freshwater eutrophication potential (FEP), Global warming potential (GWP), Ionizing radiation (IR), Marine eutrophication potential (MEP), Ozone depletion potential (ODP), Photochemical ozone formation potential (POFP) and Terrestrial eutrophication potential (TEP).

3.3. Lowest burden packaging choice across distribution options

In Figure 4 the combined GWP burden of packaging and distribution stages are taken from the generic single packaging footprints. The solid lines in Fig. 4 A show aluminium can delivered by van and reusable bottle delivered by van, showing that reusable bottles have a lower GWP burden up to approximately 200 km, but that aluminium cans have a lower burden at greater distances. Aluminium cans have a larger packaging production burden than bottles, but heavier weight of glass bottles compared with aluminium cans increases distribution burdens. If mode of transport is changed to lorry, reusable bottles retain an environmental advantage over aluminium cans up to 1600 km distribution distance (Fig. 4 A).

Fig. 4 B compares the combined production and distribution burden of stainless steel keg and PET keg. The GWP burden for stainless steel kegs remains below that of PET kegs up to approximately 400 km distribution distance with vans. Stainless steel kegs have a lower packaging production footprint across 120 use cycles compared to single use PET containers but are heavier and therefore incur greater transport burdens (S 5 supplementary material: stainless steel kegs weigh 316 g/L of beer whilst PET kegs weigh 36 g/L of beer). If mode of transport is changed to lorry, stainless steel kegs maintain an environmental advantage well beyond 1600 km (Fig. 4 B).



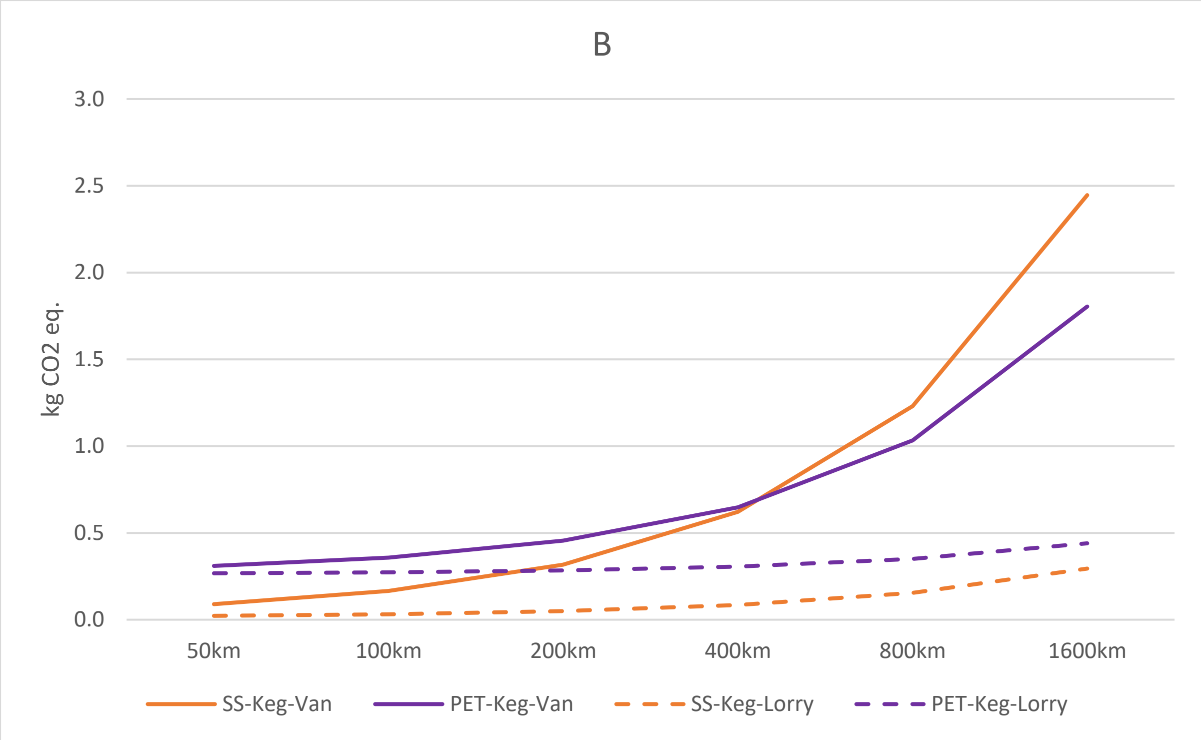


Figure 4: Chart A shows the combined GWP results for packaging and distribution for reusable bottle delivered by van (Bot-Ru-Van) and aluminium can delivered by van (Can-Van). The dotted lines show reusable bottle delivered by lorry (Bot-Ru-Lorry) and aluminium can delivered by lorry (Can-Lorry). In Chart B combined GWP results for packaging and distribution for stainless steel keg delivered by van (SS-Keg-Van) and PET keg delivered by van (PET-Keg-Van). The dotted lines show stainless steel keg delivered by lorry (SS-Keg-Lorry) and PET keg delivered by lorry (PET-Keg-Lorry).

3.4. Sensitivity analysis

In order to understand uncertainties, a sensitivity analysis was carried out focusing on the recycled content of packaging material. Table 2 shows generic single-packaging beer footprints alongside the mixed packaging portfolio beer footprints from the seven case study breweries, for GWP and abiotic resource depletion potential. The single packaging material footprint is a generic footprint with all beer packaged into can, reusable bottle or PET keg. Three sensitivity analysis were carried out, including having aluminium produced with 80% recycled material, glass bottle made with 69% recycled cullet using Ecoinvent 3.5 process for (DE) packaging glass, and PET made with 100% recycled material using Ecoinvent 3.5 process for (CH) bottle grade recycled PET (Wernet et al., 2016). The percentage change discussed in sensitivity analysis is benchmarked against default findings not the results in mitigation options.

Aluminium can with 80% recycled material reduces generic beer GWP footprint by 13%, to 737 kg CO_2 eq. and the case study brewery footprints by between 8% (BrewA, D & G) and 33% (BrewE). The abiotic resource depletion potential footprint of generic beer (100% aluminium can baseline) is reduced by 15%, to 0.0044 g Sb eq., with BrewG showing the largest reduction in beer footprints for the case study breweries, a 3% reduction – reflecting small share of aluminium cans in the breweries.

Reusable glass bottle with 69% recycled material reduces generic beer GWP footprint by 1%, to 1004 g CO_2 eq. and case study footprints between 4 (BrewG) and 29% (BrewE). Abiotic resource depletion potential result for generic beer footprint shows 0.3% change, case study breweries footprints are reduced between 3% (BrewD) and 18% (BrewE).

PET keg made with 100% recycled material reduces generic beer GWP footprint by 14%, to 655 g CO_2 eq., and case study brewery G footprint is reduced by 6% to 1254 g CO_2 eq. Abiotic resource depletion potential footprint for generic beer is reduced by 19%, to 0.0022 g Sb eq., with a maximum reduction of 18% seen for Brewery G.

Table 2: Sensitivity analysis results for GWP and ARDP results associated with increase share of recycled materials across different packaging options. Generic beer footprints relate to all beer being packaged in single format. Percentage change in results relate back to default results for each brewery, which are based on brewery – specific packaging mixes.

		{Single packaging material footprint}									
Process	Unit	All Can	All Bottle	All PET	BrewA	BrewB	BrewC	BrewD	BrewE	BrewF	BrewG
Default GWP	**g CO_2 eq.**	**850**	**1014**	**765**	**727**	**1057**	**837**	**815**	**1102**	**766**	**1336**
Default ARDP	**g Sb eq.**	**0.0052**	**0.0040**	**0.0027**	**0.0023**	**0.0049**	**0.0032**	**0.0036**	**0.0033**	**0.0029**	**0.0045**
Scenario one											
440 ml can, 80% recycled aluminium											
GWP	g CO_2 eq.	737			667	863	641	753	739	607	1230
		(-13%)			(-8%)	(-18%)	(-23%)	(-8%)	(-33%)	(-21%)	(-8%)
ARDP		0.0044			0.0023	0.0048	0.0033	0.0036	0.0034	0.0029	0.0044
		(-15%)			(+1%)	(-1%)	(+2%)	(-0.3%)	(+4%)	(+1%)	(-3%)
Scenario two											
Reusable bottle, 69% recycled cullet											
GWP	g CO_2 eq.		1004		674	917	662	768	780	630	1289
			(-1%)		(-7%)	(-13%)	(-21%)	(-6%)	(-29%)	(-18%)	(-4%)
ARDP	g Sb eq.		0.0039		0.0022	0.0046	0.0028	0.0035	0.0027	0.0026	0.0043
			(-0.3%)		(-4%)	(-6%)	(-13%)	(-3%)	(-18%)	(-10%)	(-4%)
Scenario three											
PET keg, 100% recycled PET											
GWP	g CO_2 eq.			655	769	1082	906	853	1145	830	1254
				(-14%)	(+6%)	(+2%)	(+8%)	(+5%)	(+4%)	(+8%)	(-6%)
ARDP	g Sb eq.			0.0022	0.0020	0.0046	0.0032	0.0035	0.0033	0.0027	0.0037
				(-19%)	(-11%)	(-6%)		(-3%)		(-7%)	(-18%)

Rounding may show the same results when percentage difference are small

4. Discussion

4.1. Short-term packaging options for mitigation

Packaging and distribution are two critical stages of the beer life cycle. When changes are made to the packaging stage these can affect distribution because of packaging weight. When beer has a short delivery distance the critical factor to consider is the burden associated with producing the packaging. As delivery distance increases the burden of distributing the beer increases and will eventually exceed the burden for manufacturing the packaging. At this point the mass of the packaging option becomes the critical factor. Single use glass bottle was the most popular option among case studies and the environmental footprint of beer can be significantly reduced if breweries are willing to change packaging material. All case studies demonstrated reductions in overall global warming potential, fossil resource depletion, acidification, terrestrial eutrophication, photochemical ozone formation and marine eutrophication burdens per L of beer when aluminium cans or reusable glass bottles replace single use glass bottles. Neither mitigation option was an outright best solution across all impact categories because of the variations in delivery distance and volume of beer allocated to single use packaging in each case study. The only packaging mitigation option immediately available to small breweries in the UK is the aluminium can, as there is no established bottle return scheme in place in the UK (Błażejewski et al., 2021; Butler et al., 2005; Mühle et al., 2010).

Recently, distribution was identified as an unexpected environmental hotspot for beer produced by micro-breweries (Morgan et al., 2020). The logic of replacing heavy reusable kegs and casks with lighter, single-use PET kegs focuses on reducing transport loads, and may reduce handling costs (Keykeg, 2021). However, the burden of producing single use PET keg increases the footprint beyond the savings achieved from distribution. Switching to larger delivery vehicles would mean that distribution burden savings from PET kegs become trivial. The results show that changing from reusable keg and cask to single use PET keg increases burdens for six out of seven of the case studies. In some circumstances switching to PET keg can reduce carbon footprint, notably with van delivery beyond 400 km (Fig. 4 B). The convenience of PET Keg is appealing and can reduce footprints when long distance delivery is needed, but findings also show reusable steel kegs have a lower footprint when beer is distributed by lorry, up to the 1600 km maximum distance modelled here (Fig. 4 B). Whilst some LCA studies have focused on PET bottles (Cappiello et al., 2021; Cottafava et al., 2021; Ferrara et al., 2021; Nessi et al., 2012; Stefanini et al., 2021), no previous studies could be found assessing the environmental footprint of PET kegs. The advantage of PET has been marketed as a “one way” container aimed at producers who send beer further than their normal delivery area with no need to collect (Keykeg, 2021). Waste polyethylene from the UK is exported to countries like China, Indonesia, Malaysia and Vietnam for recycling, associated with significant littering of the environment (Bishop et al., 2020), raising questions around current marketing of PET kegs as a sustainable option with lower transport burdens owing to “no return trip” (Dolium, 2021; Keykeg, 2021). New advances in keg tracking technology will allow hire companies to know the location of their kegs at every stage of the beer life cycle, enhancing the security and sustainability of reusable kegs (Smart container company, 2021). Reusable steel kegs have a life expectancy of up to 30 years and represent a more circular packaging option, especially when combined with more efficient (lorry) transport (Thielmann, 2020).

4.2. Bottle return schemes

This study has shown that a reusable glass bottle system is an effective way of reducing the environmental footprint of beer compared to the current model of single use glass and recycling, and that reusable glass bottles are the best option on a local basis. Similar assessments for mineral water (Tua et al., 2020) and milk (Błażejewski et al., 2021) also considered a reuse rate of 30 cycles to show reusable glass bottle to be the best option. A reusable glass bottle scheme would require a new pathway for collection, cleaning and distribution and the success of this kind of system would rely on industry or government financial support and coordination (Cottafava et al., 2021). Since 2019, the UK government has been reviewing a deposit return scheme for packaging designed to incentivise consumers to return empty packaging for reuse (DEFRA, 2019). Deposit return schemes are already in place in several European countries operated through reverse vending machines that repay consumers for returned packaging (Oke et al., 2020; Oltermann, 2018). An interesting example of collaboration among businesses to manage packaging waste was of the Soju producers in South Korea. Soju is one of the most consumed alcoholic drinks in south Korea (Kim et al., 2021). Several prominent producers agreed to standardise the colour and size of bottle used in order to streamline collection, handling, and redistribution. The agreement among all Soju producers is not enforced by law and in 2019 a new brand was launched in a different bottle causing logistical difficulties as the bottles were not of the standardised shape and colour, resulting in criticism from other members of the scheme having to sort the bottles when received back from the consumer (Dong-hwan, 2019). Such a system is an efficient way of inventory pooling that can reduce cost and improve logistic performance, but the lack of government regulation leaves the system vulnerable (Ko et al., 2012; Moon-kyu, 2019). Collaboration among Welsh micro-breweries (and/or other drinks manufacturers) could facilitate an efficient bottle reuse scheme.

4.3. Mode of distribution

In the context of global supply chains, “last mile delivery” is often regarded as the shortest leg of the journey (Arroyo et al., 2020; Bergmann et al., 2020). The majority of case studies source some raw ingredients from overseas, but the “last mile” in the value chain incurs a significant burden owing to the weight of beer (mostly water) and packaging, and the inefficient mode of transport used by micro breweries for product distribution (Morgan et al., 2020). There is a potentially significant reduction to footprints if breweries are able to change the mode of transport from van to lorry. This is an effective measure to significantly reduce the overall environmental footprint of beer, but implementing it would require dramatic increases in the size of delivery batches to realise the potential savings – which only accrue when lorries operate at high payloads (Galos et al., 2015; Hazen, 2014). Lessons of how small businesses work together may be learnt from other divisions of the food sector in Wales, such as mixed food boxes, by drawing in collaboration from different local producers to coordinate local deliveries (Moragues-Faus et al., 2020). Collaboration among local producers already arises in several regions of Wales, and these networks are believed to have strengthened as a direct result of the Covid-19 pandemic (Prosser et al., 2021). There has been a revival in the UK of small dairy companies providing home delivery services popular with environmentally conscious consumers able to shop locally in order to avoid the complex supply chains established for the supermarkets (Hayes, 2018). A similar trend has occurred as small breweries adapted to Covid 19 restrictions by providing home delivery services to customers, showing that a direct home delivery and collection system is feasible (Wild Horse Brewing co, 2021). However, no studies could be found of businesses actively sharing delivery loads to reduce the environmental footprint of distribution. This must be a priority to reduce a hotspot for increasingly popular local and artesian food and drink products often perceived to have a smaller environmental footprint because of factors such as shorter supply chains (Smith et al., 2008).

4.4. Limitations

Some assumptions were made on delivery distance when beer was distributed by courier. Most case studies ship a small fraction of beer by courier outside of normal delivery routes and in all cases a 200 km distance is applied to courier delivered beer. In most cases, courier was used for shipping beer packaged in glass bottle or aluminium can, apart from Brewery A who use currier to deliver hired steel keg and cask. There are also some limitations on data used for raw ingredients. The cultivation of barley is based on an Ecoinvent process for French barley as no process existed for UK barley (Wernet et al., 2016), though yields and inputs are similar. It was not possible to get specific data on the consumption of energy, water and electricity for malting and estimates are based on data sourced from maltsters association of Great Britain website (MAGB, 2011). The results also relied on transport burdens expressed per tkm from Ecoinvent (Wernet et al., 2016), which in turn embed assumptions regarding average load factors and return distances.

5. Conclusion

This study has shown that micro-breweries face particular challenges in terms of efficient and sustainable packaging and distribution. Solutions require an individual approach to determine appropriate measures that can reduce environmental footprints, demonstrated here based on packaging weight and distribution distances. Results from this study may be applicable to larger scales of brewing, but also to other small-scale food and drink producers facing similar challenges in terms of packaging and distribution.

Changing from single use bottle to aluminium can is an effective measure to reduce environmental footprints across the study breweries, confirming that the findings of previous studies also apply to small scale beer value chains (Amienyo et al., 2016; Cimini et al., 2016). This is believed to be the most convenient option for the breweries, but some traditional consumers may prefer glass to aluminium can. The advantages of reusable glass bottles over single use are widely known (Ferrara et al., 2020; Ponstein et al., 2019; Solano et al., 2021; Tua et al., 2020). Here it is also found to be a viable mitigation option for small scale breweries distributing beer on a local basis. The success of such a system would require new post-consumer pathways to be created to process reusable bottles, and the greatest savings involve combining this with more efficient transport mode. A (standardised) reusable bottle system could be expanded to other food and drink producers, but would probably require government support in the form of financial assistance, coordination and regulation to instigate. New insight provided here has shown single use PET kegs incur a greater environmental cost than steel kegs, unless beer is transported long distance by inefficient delivery vans. Plastic end-of-life is also associated with considerable environmental impact via littering that is not captured in current LCA methodology, so that reusable steel kegs are likely to be a superior environmental option overall.

Small business networks in Wales could present an opportunity to consolidate freight into larger loads and justify the use of larger transport vehicles (lorries) to distribute produce. The considerable coordination required could be achieved through informal agreements across businesses, and/or could be led by third party distributors. Further research could focus on cross-sectoral models to achieve optimised logistics, and the impact of emerging technologies such as keg tracking and delivery vehicle electrification to better understand long-term prospects of environmental mitigation from packaging and distribution.

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