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Development of an open-source carbon footprint calculator of the UK craft brewing value chain

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ABSTRACT

Craft breweries may fall behind large brewing companies in reducing the carbon footprints of their value chains due to limited resources, financial constraints, and a lack of technical knowledge to fully understand their emissions. However, by increasing their awareness of the impact of their entire value chains, craft breweries can accelerate the decarbonisation of the industry by creating competition among breweries to appeal to environmentally conscious consumers. This work developed a freely available carbon calculator (10.6084/m9.figshare.22758692) using transparent, open-source data which may be used for benchmarking and identifying opportunities for emission reductions in UK craft breweries as well as providing a reference point for future carbon footprint analyses of global brewing value chains. The carbon footprint for craft brewing was calculated for a wide range of packaging types across three realistic scenarios (low, medium, and high carbon footprints) based on collected data and addresses the discrepancies between values reported in previous literature. Overall, the calculated carbon footprints ranged between 205 (20 L steel kegs, low carbon footprint scenario) and 1483 (single-use, 0.33 L glass bottles, high carbon footprint scenario) gCO_2e per litre of beer. Novel hotspots (including wort boiling, the packaging process in a brewery, and the contribution of secondary and tertiary packaging) were identified. The overwhelming contribution of Scope 3 emissions (contributing between 57 and 95 % of the total carbon footprint) further emphasised the need to provide increased knowledge to craft breweries.

1. Introduction

The food and drink industry is the largest manufacturing sector in the UK within which the beverages category was the largest contributor to food's gross value added in 2020 (Defra, 2023). Beer is the oldest and most widely consumed alcoholic beverage in the world (Piron and Poelmans, 2016). In the United Kingdom, beer consumption per capita was 61 L in 2020, while beer production per capita was 48 L (The Brewers of Europe, 2021). Therefore, decarbonisation of the brewing industry can significantly contribute towards the UK's target of a net zero economy by 2050 (BEIS, 2021). Several large breweries have publicised their sustainability ambitions, including AB InBev, which aims to only purchase renewable electricity and to reduce the carbon footprint of their value chain by 25 % by 2025 (AB InBev, 2021), and Heineken, which aims to have carbon-neutral production sites and value chains by 2030 and 2040, respectively (Heineken, 2021). However, there are 2426 breweries operating in the UK, with most being independent craft beer companies (UHY Hacker Young, 2022). The Society of Independent Brewers in the UK had 702 member breweries, with an average annual production of approximately 3500 hL (hl) in 2022 where an annual production of less than 500,000 hl is considered a small brewery size (SIBA, 2022).

Craft breweries often lack the resources, finances, and technical knowledge to evaluate the carbon footprint of their entire value chain and typically focus their sustainability efforts on reducing their energy consumption, which is easier to monitor (Shin & Searcy, 2018). The

Abbreviations: LDPE, Low Density Polyethylene; PET, Polyethylene Terephthalate.

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Greenhouse Gas (GHG) Protocol divides carbon emissions from an organisation into three scopes (Patchell, 2018). Scope 1 covers direct emissions from owned sources, scope 2 includes indirect emissions from purchased energy, and scope 3 encompasses all other indirect emissions in the value chain, both upstream and downstream. Reducing the energy consumption of craft breweries only targets scope 1 and 2 emissions, whereas scope 3 includes all indirect emissions from upstream and downstream in the value chain. Scope 3 emissions often account for the largest proportion of a value chain's carbon footprint. For example, a recent analysis concluded that 88 % of emissions in the food and beverage sector originated from scope 3 sources (Hansen et al., 2022). Calculating scope 3 emissions is complex and demanding even for multi-national companies (Patchell, 2018). Therefore, there is a need to provide craft breweries with the data and methodology required so they are able to determine where to invest their time and resources to achieve a more sustainable value chain. This will enable the identification of hotspot areas for emissions and permit quantification and comparison of the impact of potential mitigation strategies.

In the near future, displaying the carbon footprint of food items on labels is anticipated to become universal, an idea that is supported by around two-thirds of consumers (Carbon Trust, 2020). Once implemented, this will influence consumer choice of products and provide an incentive for companies to reduce the carbon footprint of the full value chains, rather than only reducing energy consumption at their manufacturing sites. Until then, larger corporations, with the resources to understand the impact along the entire value chain, can prepare for this change and begin implementing emission reduction measures. Craft breweries, on the other hand, without this knowledge, will lag behind the larger manufacturers. This constitutes a missed opportunity as craft breweries are often considered more innovative than large beer manufacturers and more conscious of social and environmental issues (Baiano, 2021; Erhardt et al., 2022; Brewers Association, 2014). With greater knowledge of the carbon footprint along the value chain, craft breweries can accelerate the decarbonisation of the brewing industry by increasing competition for the perception of environmental awareness amongst consumers.

To address this need to provide understanding to craft breweries about the carbon footprints of brewing value chains, this work provides three contributions:

1.) The creation of a freely available carbon calculator (available as a downloadable Excel spreadsheet:10.6084/m9.figshare.22758692) using transparent, open-source data which may be used for benchmarking and identifying opportunities for emission reductions in UK craft breweries. Furthermore, this calculator and the accompanying data establish a reference point for future carbon footprint analyses of global brewing value chains. Discussion surrounding converting the calculator to alternative locations is provided in section 3 of the Supplementary Information. Previous works quantifying carbon footprints in the brewing value chain either did not disclose the emission factors utilised (Amienyo and Azapagic, 2016; Morgan et al., 2021), used emission factors from proprietary databases (Cimini and Moresi, 2016), or did not provide the underlying calculations (The Climate Conservancy, 2008; BIER, 2012a).
2.) The calculation of value chain carbon footprints for a wide range of packaging types including glass, reusable glass, and polyethylene terephthalate (PET) bottles; aluminium and steel cans; and steel and PET kegs. Furthermore, this was conducted across three scenarios (low, medium, and high carbon footprints) based on collected data to provide realistic estimation of the uncertainty. The study addresses the discrepancies between values reported in previous literature, vindicating the recalculation of the brewing carbon footprints.
3.) The analysis of carbon hotspots including the identification of novel hotspots not previously identified in the literature. Furthermore, the carbon footprints are analysed by scope to highlight the dominance of scope 3 emissions and emphasise the importance of providing craft breweries with the knowledge to facilitate informed sustainability decisions.

2. Methodology

The craft brewing value chain carbon footprint calculator was designed for the context of the UK in 2023. Guidance on how to convert the calculator to alternative locations in provided in section 3 of the Supplementary Information. Three scenarios are presented in the Results section: a low, medium, and high carbon footprint case to demonstrate the variability in calculator outputs by changing the input values. The values used in these scenarios are based on the collected data from previous literature and therefore provide realistic uncertainty in the quantified carbon footprints. Furthermore, these scenarios highlight the need to obtain as accurate data as possible and to evaluate uncertainty when using carbon footprint calculations for decision-making purposes. The values used for each of these cases are listed in sections 2.1 to 2.8. The functional unit used for this analysis is 1 L of beer produced. The GHG emissions are calculated based on the IPCC AR5 100-year global warming potential factors in terms of CO_2 equivalents (gCO_2e). Trading impacts are excluded from the analysis.

Fig. 1 shows the system boundary considered in this work, split into the different stages of the brewing value chain. The use of propylene glycol in the chiller system has been excluded due to the unavailability of data on quantity, replacement rate, and disposal methods. However, the energy consumption of the chiller system is included and previous carbon footprint studies have not included the material use of propylene glycol. No emissions were assigned to the production of spent grains and waste yeast as it is assumed that they are used for animal feed purposes, following the guidance of European Commission (2018). Only compression and transport emissions were attributed to the carbon dioxide used in the brewing process. Consistent with the guidance provided by BIER (2022) and other previous studies (The Climate Conservancy, 2008), it was assumed that the carbon dioxide was sourced from a waste stream, such as fertiliser production or energy production from fossil sources, and therefore no emissions are associated with its production.

2.1. Material emission factors

The emission factors of the materials utilised in multiple stages of the brewing value chain are presented in Table S1 in the Supplementary Information. The malting, brewing, and packaging cleaning processes use natural gas to raise temperatures and electricity to power machinery. Water is used in the malting and brewing procedures as well as for the packaging cleaning process where it is discharged as wastewater. Sodium hydroxide is used to clean the brewing equipment and packaging.

2.2. Barley cultivation

The amount of malt used per litre of beer has been reported by various researchers and ranges between 0.095 and 0.382 kg per litre of beer produced. Malt use has been reported as 0.151–0.237 (Morgan et al., 2021), 0.382 (De Marco et al., 2016), 0.108–0.180 (UNEP, 1996), 0.177–0.333 (Cimini and Moresi, 2018), and 0.174 (Salazar et al., 2021) kg per litre of beer produced. Furthermore, the barley to malt ratio has been utilised as 1.22 (Kløverpris et al., 2009), 1.3 (MAGB, no date), and 1.33 (The Climate Conservancy, 2008), and the weight of barley used per litre of beer as 0.073 kg (Amienyo and Azapagic, 2016). Based on the median barley to malt ratio of 1.3, this would amount to 0.095 kg per litre of beer. In this work, three malt weights, representing the low, medium, and high carbon footprint scenarios have been selected: 0.152, 0.184, and 0.240 kg per litre of beer, respectively.

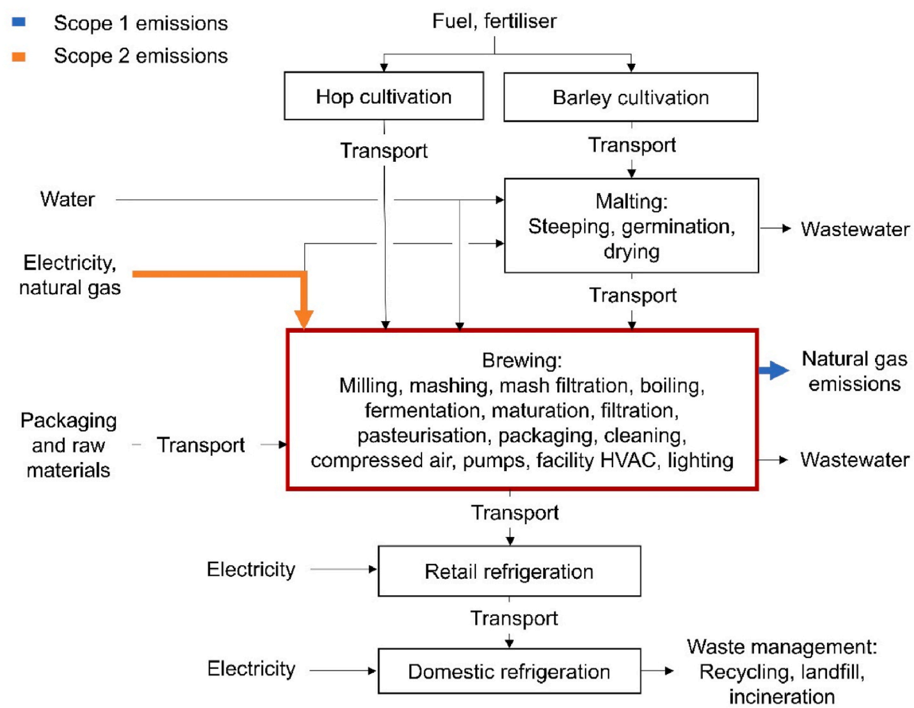

Fig. 1. The stages of the brewing value chain considered in this study. Scope 1 emissions for craft breweries caused by natural gas consumption are highlighted in blue. Scope 2 emissions from electricity and natural gas production are highlighted in orange. The dark red line displays the boundary for the brewery. The remaining stages comprise scope 3 emissions. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table S2 in the Supplementary Information presents the carbon footprint breakdown of barley cultivation reported in previous literature. The most significant emission contributors are fertiliser use, fertiliser production, agricultural field operations, and seed production, accounting for approximately 39.2%, 33.4%, 12.4%, and 5% of the carbon footprint from values reported in previous literature (Table S2), respectively. These four contributor categories have been calculated based on material usage for the scenarios presented in this work. The breakdown of these contributing factors can be found in Table S3 in the Supplementary Information.

2.3. Hop cultivation

The weight of hops used per litre of beer varies depending on the type of beer being produced. The weight of hops used per litre of beer has been reported as 1.3 (Amienyo, 2012), 0.7 (Cordella et al., 2008), 2.6 (Salazar et al., 2021), 3.2–24.3 (Morgan et al., 2021), 0.9–2.6 (Assobirra, 2014), and 2.6 (Cimini and Moresi, 2018) g per litre of beer. The hop content in craft beers can vary significantly, as different breweries use varying amounts of hops to achieve their desired flavour and aroma profiles. Therefore, values of 0.7, 2.18, and 24.3 g of hops per litre of beer are used for the low, medium, and high carbon footprint scenarios presented in this work, respectively. The carbon footprint breakdown of hop cultivation reported in previous literature is presented in Table S4 in the Supplementary Information. The highest contributing areas to the carbon footprint are drying (39.3 %), fertiliser production (19.7 %), agricultural machinery (14.7 %), and soil emissions (9.8 %) based on values from previous literature. The data and assumptions used to calculate these four categories (Drying, Fertiliser production, Agricultural machinery, and Soil emissions) are detailed in Table S5 in the Supplementary Information along with Pesticides and Other categories. Drying is used to preserve hops post-harvest, most commonly using propane-powered kilns (Bristol, 2022).

2.4. Malting process

The electricity usage during malting has been previously reported as 150 kWh per tonne of malt (MAGB, no date) and 129 kWh per tonne of malt (Carbon Trust, 2011). Similarly, natural gas usage has been estimated as 750 kWh per tonne of malt (MAGB, no date) and 702 kWh per tonne of malt (Carbon Trust, 2011). Water use has been reported as 4 m^3 per tonne by MAGB (no date) and 3.25 m^3 per tonne by Muller et al. (2021). The average of these values were used for the scenarios presented in this work. Table S6 in the Supplementary Information presents the energy breakdown used in this work for the malting process stages. Malting is composed of three primary stages: steeping, germination, and drying (kilning). Steeping is used to promote sprouting, germination is used to grow the barley grains, and kilning is used to stop the process and reduce the moisture content.

2.5. Brewing process

Table S7 in the Supplementary Information displays an overview of the material quantities utilised in both previous literature and the current study for the brewing process. In order to calculate a breakdown of the brewing process, Tables S8 and S9 in the Supplementary Information were compiled from previous literature which provide energy usage values and energy consumption percentages of each stage of the process, respectively. The median values for each process stage from Tables S8 and S9 were then calculated and the final breakdown used in the calculator. This breakdown may be altered through user-defined inputs. The electricity consumption of liquifying carbon dioxide has been estimated as 0.4 kWh per kg (The Climate Conservancy, 2008).

Adjunct grains, such as oats, wheat, and rye, are commonly used in craft brewing for their unique flavour and aroma contributions, as well as their ability to enhance mouthfeel and head retention (Morgan et al., 2022b). These may be used in malted or unmalted forms (along with unmalted barley). To account for these within the calculator, the relative emission factors compared to barley cultivation for oats (0.93), wheat

(1.21), and rye (1.18) cultivation determined in Rajaniemi et al. (2011) are used. The same malting energy and water consumption as for barley are used.

2.6. Packaging and waste management

In this work, 14 packaging types were considered. These were: 0.33 L glass bottles, 0.5 L glass bottles, 0.33 L reusable glass bottles, 0.5 L reusable glass bottles, 0.33 L aluminium cans, 0.5 L aluminium cans, 0.33 L steel cans, 0.5 L steel cans, 20 L steel kegs, 30 L steel kegs, 0.33 L PET bottles, 0.5 L PET bottles, 20 L PET kegs, and 30 L PET kegs. A 3.22 ratio of UK waste landfilled versus incinerated was used for all packaging types (Defra, 2018).

2.6.1. Glass

The carbon footprint of recycled glass production has been estimated as 0.823 kgCO_2e per kg glass compared with 1.403 kgCO_2e per kg glass for the virgin material (BEIS, 2022). In the UK, Zero Waste Europe (2022a) estimates the rate of glass recycling to be 71%, while the proportion of recycled material used in new glass production is been reported as 38%. The carbon footprint of filling beer bottles has been calculated to be 0.00198 kgCO_2e per litre of beer (Duotank, 2022). The carbon footprint of waste disposal options for glass are 0.0213 (recycling), 0.0213 (incineration), and 0.0089 (landfilling) kgCO_2e per kg glass (BEIS, 2022). The weight of a 0.33 L glass bottle has been reported as 230 (Amienyo and Azapagic, 2016), 230 (Cordella et al., 2008), 240 (Duotank, 2022), 300 (Simon et al., 2016), 190 (Carbon Trust, 2021), 240 (Boesen et al., 2019), 185 (Cimini and Moresi, 2016), and 190 (De Marco et al., 2016) g. Therefore, values of 190, 230, and 240 g have been used for the low, medium, and high carbon footprint scenarios in this study, respectively. The weight of a 0.5 L glass bottle has been reported to be 300 g by Morebeer (no date) and Brewpac (no date), while Simon et al. (2016) reported a weight of 360 g. Hence, the median value of 300 g is used in this study.

2.6.1.1. Reusable glass bottles. The weight of 0.33 L reusable glass bottles has been reported as 30 % heavier than non-reusable bottles (Vetropack, 2021). This would equate to a weight of 299 g using the median weight of a 0.33 L non-reusable bottle (230 g, Section 2.6.1 Glass). However, Carbon Trust (2021) used a weight of 380 g for a 0.33 L reusable beer bottle and Boesen et al. (2019) used a weight of 301 g. Therefore, in this study, a weight of 301 g is used. The weight of 0.5 L reusable glass bottles has been reported as 22 % heavier than non-reusable bottles (Vetropack, 2021). Therefore, a weight of 366 g is used in this study. The reuse rate of reusable glass bottles has been estimated as 9.2 (Melon et al., 2012), 30 (European Commission, 2018), 8–21 (Carbon Trust, 2021), 25–30 (Zero Waste Europe, 2022b), and 30 (Tua et al., 2020) times. For this study, values of 30, 28, and 15 have been used for the low, medium, and high carbon footprint scenarios, respectively. Ferrara and De Feo (2020) stated that to clean refillable wine bottles 0.008 kWh electricity, 0.15 MJ natural gas, 0.82 L of water, and 15.2 g of sodium hydroxide were required per 3 L of wine. Tua et al. (2020) used 0.459 MJ natural gas, 0.24 g sodium hydroxide, and 0.67 L of water to clean 1 L glass reusable water bottles. In this study, the median values of 0.0013 kWh electricity, 0.071 kWh natural gas, 2.65 g sodium hydroxide, and 0.47 L of water per clean per litre of beer are used.

2.6.2. Aluminium

The carbon footprint of recycled aluminium production has been estimated as 0.999 (BEIS, 2022) kgCO_2e per kg compared with 9.123 (BEIS, 2022) kgCO_2e per kg for virgin aluminium. The recycling rate of aluminium beverage cans in the UK has been reported as 82 % (Alupro, 2021) whilst the proportion of recycled content in European aluminium can sheet production is 47 % (Carbon Trust, 2021). The carbon footprint of filling beer cans has been calculated as 0.009 kgCO_2e per litre of beer (Duotank, 2022). The carbon footprint of waste disposal options for aluminium are 0.0213 (recycling), 0.0213 (incineration), and 0.0089 (landfilling) kgCO_2e per kg (BEIS, 2022). The weight of a 0.33 L aluminium can has been reported as 14.5 (Simon et al., 2016), 12 (Carbon Trust, 2021), 12.3 (Cimini and Moresi, 2016), and 12.2 (Metal Packaging Europe, 2019) g. Therefore, values of 12.2, 12.3, and 12.9 g are used for the low, medium, and high carbon footprint scenarios in this study, respectively. The weight of a 0.5 L aluminium can has been reported as 18.5 (Simon et al., 2016), 17 (Duotank, 2022), 15.6 (Boesen et al., 2019), and 15.1 (Metal Packaging Europe, 2019) g. In this study, the weights of 15.5, 16.3, and 17.4 g have been used for 0.5 L aluminium cans in the low, medium, and high carbon footprint scenarios, respectively.

2.6.3. Steel

BEIS (2022) reports the carbon footprint of virgin steel as 3.101 kgCO_2e per kg and that of recycled steel as 1.741 kgCO_2e per kg. A recycled content of 50 % is used in this study (Duotank, 2022). The steel packaging recycling rate in Europe is 84 % (APEAL, 2022) The carbon footprint of filling beer cans has been calculated as 0.009 kgCO_2e per litre of beer (Duotank, 2022). The carbon footprint of waste disposal options for steel are 0.0213 (recycling), 0.0213 (incineration), and 0.0089 (landfilling) kgCO_2e per kg (BEIS, 2022).

2.6.3.1. Steel cans. It was assumed that steel cans weigh 2.1 times the weight of aluminium cans, as used in Amienyo and Azapagic (2016).

2.6.3.2. Steel kegs. The weight of a 20 L steel keg has been estimated as 6 (Wyss and Rolf, 2013), 8.8 (Cordella et al., 2008), and 5.8 (Thielmann, 2018) kg. Therefore, a weight of 6 kg has been used in this study. The reuse rate of a steel keg has been reported as 72 (Cimini and Moresi, 2016), 85 (Cordella et al., 2008) and 120 (Thielmann, 2018) times. Therefore, reuse rates of 103, 85, and 79 have been used in this study for the low, medium, and high carbon footprint scenarios, respectively. Martin et al. (2022) reported that 11.4 kJ of electricity, 3 L of water, and 9 g of sodium hydroxide are used to clean and fill a keg. This amounts to 0.485 gCO_2e per reuse per litre of beer. Thielmann (2018) stated that a single steel keg wash contributed 24.5 gCO_2e per litre of beer. Duotank (2022) estimated 0.68 gCO_2e per reuse per litre of beer to clean, fill, and dispense steel kegs. Therefore, the median value of 0.68 gCO_2e per reuse per litre of beer has been used in this study to account for cleaning, filling, and dispensing the kegs. Regarding the transportation of sodium hydroxide to the brewery for keg cleaning, this is assumed to be 9 g as used in Martin et al. (2022). Martin et al. (2022) also reported that it required 47.5 kWh to crush a 30 L steel keg during the recycling process. In this work, it is assumed this value is the same for the 20 L steel kegs. It is assumed all steel kegs are recycled. The weight of a 30 L steel keg has been estimated as 9.6 kg by Martin et al. (2022) and Cimini and Moresi (2016).

2.6.4. PET

The carbon footprint of recycled PET production has been estimated as 3.13 (BEIS, 2022) kgCO_2e per kg. The carbon footprint to produce virgin PET is estimated as 4.03 (BEIS, 2022) kgCO_2e per kg. The proportion of recycled material used in the production of PET has been estimated as 5 (Chilton et al., 2010), 11 (Carbon Trust, 2021), and 3 (BIER, 2012b) %. Therefore, 5 % has been used in this study. The recycling rate of plastic drink bottles in the UK is 74 % (RECOUP, 2023). The carbon footprint of waste disposal options for PET are 0.0213 (recycling), 0.0213 (incineration), and 0.0089 (landfilling) kgCO_2e per kg (BEIS, 2022).

2.6.4.1. PET bottles. The weight of a 0.33 L PET bottle has been reported as 21.5 (Carbon Trust, 2021) and 38 g (Boesen et al., 2019), and the weight of a 0.5 L PET bottle has been reported as 55 g (Simon et al., 2016). Therefore, a value of 30 g has been used for 0.33 L PET bottles in this study along with the value of 55 g for 0.5 L PET bottles. The carbon footprint of filling beer bottles has been calculated as 0.00198 $kgCO_2e$ per litre of beer (Duotank, 2022).

2.6.4.2. PET kegs. The weight of a 20 L PET keg has been reported as 1–1.05 (Wyss and Rolf, 2013) and 1.2 (Thielmann, 2018) kg. Therefore, 1.05 kg is used in this study. Duotank (2022) estimated 0.68 gCO_2e per litre of beer to clean, fill, and dispense kegs. It is assumed all PET kegs are recycled. It is assumed that a 30 L PET keg weighs 1.6 kg.

2.6.5. Secondary and tertiary packaging

The mass of labels for bottled beer has been estimated as 0.69–1.11 g per bottle of beer (Cimini and Moresi, 2016). Furthermore, the mass of adhesive for labels has been reported as 0.154–0.293 g per bottle (Cimini and Moresi, 2016). Therefore, values of 0.9 g and 0.224 were used in this study for the mass of labels and adhesive, respectively, for glass and PET bottles. The recycled content of paper manufactured in the UK is approximately 73 % (WRAP, 2020). The carbon footprint of virgin paper production is 919.4 gCO_2e per kg and for recycled paper production it is 739.4 gCO_2e per kg (BEIS, 2022). The emission factor for adhesive has been reported as 2.35 $kgCO_2e$ per kg (The Climate Conservancy, 2008). It is assumed that labels are not recycled. A landfill emission factor of 1041.8 gCO_2e per kg and an incineration emission factor of 21.28 gCO_2e per kg have been applied (BEIS, 2022).

The weight of a steel bottle cap has been estimated as 0.95 (The Climate Conservancy, 2008), 1.99 (Cimini and Moresi, 2016) and 6.3 g (Amienyo and Azapagic, 2016). The median weight, 1.99 g per bottle cap, is used in this study for all bottles. Furthermore, the can closure for aluminium cans has been estimated as 3.8 g per can (Cimini and Moresi, 2016). For steel cans, it is assumed that the can closure also weighs 2.1 times as much as aluminium cans (Amienyo and Azapagic, 2016).

The cardboard mass for glass bottled beer has been estimated as 1.84–12.2 (Morgan et al., 2021), 28.6–32.1 (Cimini and Moresi, 2016), 44.7 (The Climate Conservancy, 2008) and 48.5 g per litre of beer (Amienyo and Azapagic, 2016). Furthermore, the cardboard weight for secondary packaging of aluminium cans has been estimated as 11.5 g per litre of beer (Cimini and Moresi, 2016). Therefore, a value of 37.5 g is used in this study for glass and PET bottles and 11.5 g is used for aluminium and steel cans. The carbon footprint of virgin and recycled paperboard production is 828.87 and 719.56 gCO_2e per kg, respectively (BEIS, 2022).

The pallet mass for transporting bottles, cans, and kegs has been estimated as 27.5–31.6, 19.4, and 122 g per litre of beer, respectively (Cimini and Moresi, 2016). Furthermore, the mass of LDPE film for bottles and cans has been reported as 0.68–0.74 and 0.6 g per litre of beer, respectively (Cimini and Moresi, 2016). It is assumed that LDPE contains a recycled content of 30 % (Xtext, 2019). It is assumed that wooden pallets have a reuse rate of 25 times as recommended by European Commission (2018). It is assumed that wooden pallets are made from virgin wood and are recycled at the end of their life. The virgin wood production carbon footprint is 312.61 gCO_2e per kg (BEIS, 2022). The virgin and recycled LDPE production carbon footprints are 2600.64 and 1797.22 gCO_2e per kg, respectively (BEIS, 2022). The wood recycling carbon footprint has been reported as 21.28 gCO_2e per kg (BEIS, 2022). The LDPE recycling and incineration carbon footprints are also 21.28 gCO_2e per kg whereas it is 8.883 gCO_2e per kg for landfill (BEIS, 2022).

2.7. Transport

The transportation distances and methods for each material used in previous studies is presented in Table S10 in the Supplementary Information. In this work, it is assumed that all materials are transported in >17 tonne trucks, except for container ship transportation required for hop sourcing. Table S11 in the Supplementary Information presents the transportation distances and methods for hops from previous literature. The emission factor for a rigid, >17 tonne, average laden HGV is 185.97 gCO_2e per tonne km and the average emission factor for a container ship is 16.14 gCO_2e per tonne km (BEIS, 2022).

2.8. Refrigeration

BIER (2012a) suggested that 0–5 % of the products were cooled at retail. Therefore, a value of 2.5 % was used in this study. The Climate Conservancy (2008) assumed a retail display unit power demand of 6.96 W per litre of beer, Cimini and Moresi (2018) used a demand of 0.339 W per litre, and Brewery Vivant (2013) used a range of 1.58–2 W per litre of beer. Amienyo (2012) used values of 5.4 and 8.2 W per litre for canned and bottled beer, respectively. Therefore, in this study, values of 1.43, 4.3, and 6.84 W per litre have been used for the low, medium, and high carbon footprint scenarios, respectively. The retail time cooled before sale has been estimated as 1 (Amienyo and Azapagic, 2016), 7 (The Climate Conservancy, 2008), and 2–13 (BIER, 2012a) days. Therefore, a value of 5 days was used in this study. BIER (2012b) assumed 1–5 days of domestic refrigeration. Therefore, it was assumed that the product was cooled for 3 days in a 200 W 100 L capacity domestic refrigerator. The proportion of the refrigeration carbon footprint from refrigerant leakage has been estimated as 7 (Defra, 2014), 2–5 (Maykot et al., 2004), and 1 (The Climate Conservancy, 2008) %. Therefore, a value of 4 % was used in this study.

3. Results

The following section presents the total carbon footprint for the 14 packaging types separated into the stages of the brewing value chain for three realistic scenarios (low, medium, and high carbon footprints), the total carbon footprint for the 14 packaging types separated into Scope 1, 2, and 3 emissions for three realistic scenarios (low, medium, and high carbon footprints), a breakdown of the carbon footprint for each stage in the brewing value chain, hotspot identification for each packaging type and comparison to those identified in previous literature, and comparison with values reported in previous literature for each brewing value chain stage as well as the total carbon footprints for each packaging type.

3.1. Total carbon footprint breakdown

The results regarding the brewing value chain carbon footprint for the 14 packaging types (Fig. 2) are in accordance with existing literature. Specifically, previous works indicate that glass bottles have a larger carbon footprint compared to other options such as aluminium cans, steel cans, PET bottles, and PET kegs (Morgan et al., 2022a; Amienyo and Azapagic, 2016; BIER, 2012a; Boesen et al., 2019). Additionally, previous literature has found PET kegs to have a higher carbon footprint than steel kegs (Martin et al., 2022), and that PET bottles and steel cans have higher associated emissions than reusable glass bottles (BIER, 2012a; Boesen et al., 2019). However, there are some contradictions in the findings of this work in comparison to previous literature. In this study, it was found that aluminium cans have a similar carbon footprint to steel cans and PET kegs, whereas other studies have suggested that emissions from aluminium cans are higher (Morgan et al., 2022a; Amienyo and Azapagic, 2016; BIER, 2012a). The reason for this discrepancy is likely due to the different emission factors used in each assessment. For example, BIER (2012a) used an emission factor for aluminium that was four times higher compared with steel (9.9 gCO_2e per g aluminium, compared to 2.5 gCO_2e per g steel). Whereas in this study, it was only two times higher (5.3 gCO_2e per g aluminium, compared to 2.4 gCO_2e per g steel). Recalculating the results of this study using the emission factors from BIER (2012a) the carbon footprint

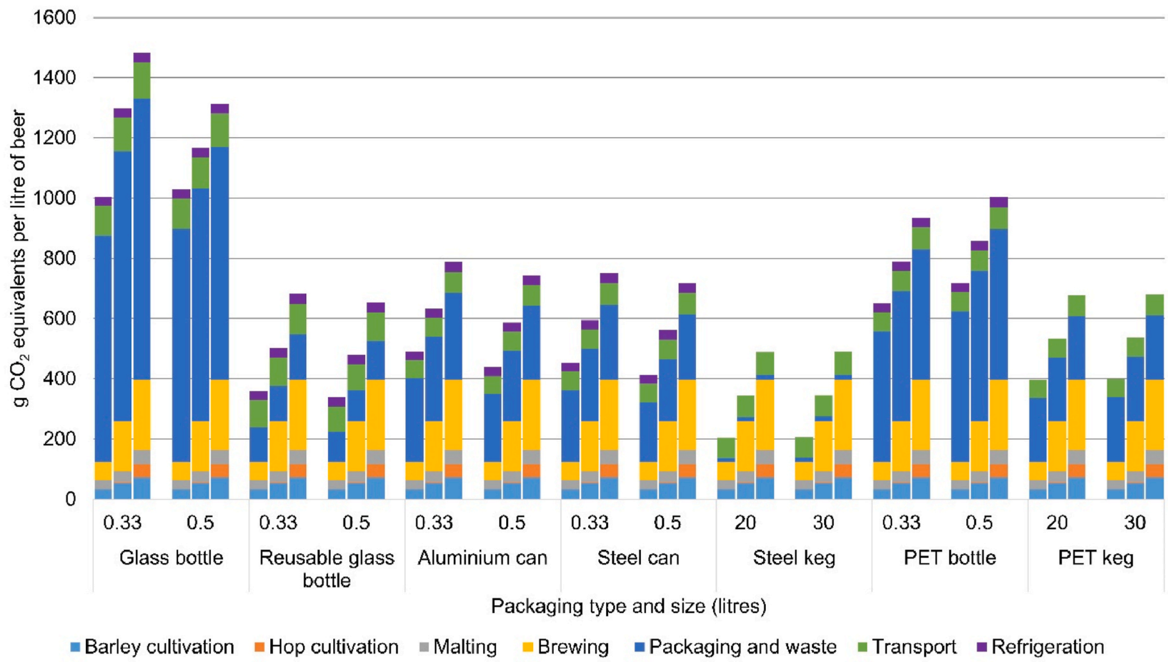

Fig. 2. The total and breakdown by value chain area of the carbon footprint for the 14 packaging types investigated for the low, medium, and high carbon footprint scenarios.

of 0.33 L aluminium cans becomes twice that of 0.33 L steel cans (506 compared with 248 gCO2e per litre of beer), bringing the results in line with previous studies. However, the BIER (2012a) emission factor was produced for the US in 2010 (PE Americas, 2010) compared with an emission factor for the UK in 2022 used in this study (BEIS, 2022). As such, despite this discrepancy, the similar emissions for aluminium cans, steel cans, and PET kegs in this study are in accordance with material emission factors in the UK. Primary aluminium production is electricity intensive, so the GHG emission factors are largely dependent on the electricity mix of the location (Claisse, 2016).

Fig. 3 shows that scope 3 emissions dominate all scenarios and packaging types, contributing between 57 % (20 L steel kegs) and 95 % (0.5 L non-reusable glass bottles) of the total carbon footprint. This emphasises the need to provide carbon footprint tools to craft breweries so that they can identify value chain emission hot spots outside their immediate operations (scope 1 and 2 emissions). However, the importance of acquiring accurate data is highlighted by the variability observed between the low, medium, and high carbon footprint scenarios presented in Figs. 2 and 3. For example, the carbon footprint of packaging into 20 L steel kegs varies between 205 and 489 gCO_2e per litre of

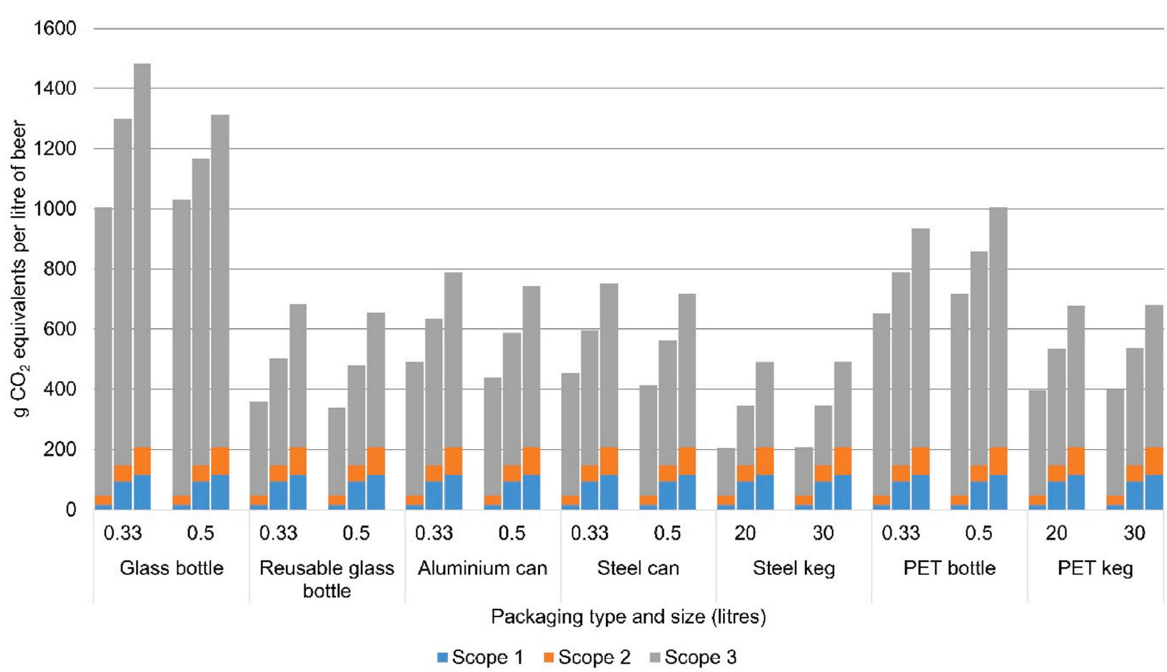

Fig. 3. The total and breakdown by emission scope of the carbon footprint for the 14 packaging types investigated for the low, medium, and high carbon footprint scenarios.

beer. It should also be noted that despite the dominance of scope 3 emissions, this does not diminish the efforts of craft breweries to reduce their scope 1 and 2 emissions (which are within their direct control). The calculation of scope 3 emissions provides information on further areas of the value chain not included in brewery energy consumption, such as the procurement of materials, transportation, or packaging choice.

3.2. Carbon footprint breakdown of each brewing value chain stage

Breakdowns of the carbon footprint for the barley cultivation, hop cultivation, malting process, and refrigeration stages are presented in Fig. 4a–d for the medium carbon footprint scenario considered. Emissions for the barley cultivation, hop cultivation, and malting process stages were consistent for all packaging types considered whilst refrigeration was not required for steel and PET kegs. Overall, the contribution from hop cultivation is approximately 13 times lower than for barley cultivation owing to the lower weights used in beer production (2.18 g versus 184 g per litre of beer). Drying is the largest contributor to the carbon footprint of malt production, accounting for 88 % of greenhouse gas emissions. Domestic refrigeration dominates retail refrigeration owing to the assumption that 100 % of domestic beer is refrigerated before consumption compared with 2.5 % at the retail stage.

Fig. 5 presents the breakdown of the carbon footprint for the brewing stage for the medium carbon footprint scenario. Emissions for the brewing process stage were consistent for all packaging types. Wort boiling and the packaging process were the two largest contributors to the brewing process carbon footprint. Wort boiling is energy intensive, using 20–40 % of natural gas consumption in a brewery (Andrews et al., 2011) or 34 % of total energy consumption (Scheller et al., 2008). The packaging process has been estimated to use 20 % of electricity consumption in the brewing process (Scheller et al., 2008), 25 % of both

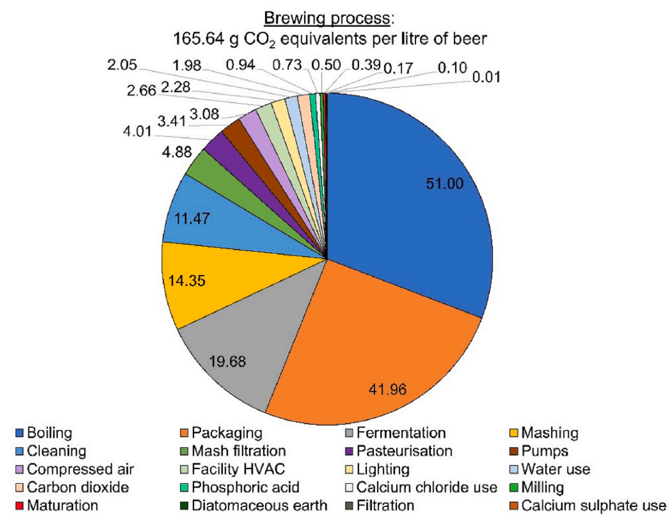

Fig. 5. The breakdown of the carbon footprint for the brewing process stage in the brewing value chain using the medium carbon footprint scenario. Not all the brewing process stages included in the calculator may be applicable to every brewery. The calculator has been designed to be flexible in this regard where brewing process stages can be omitted from the calculation.

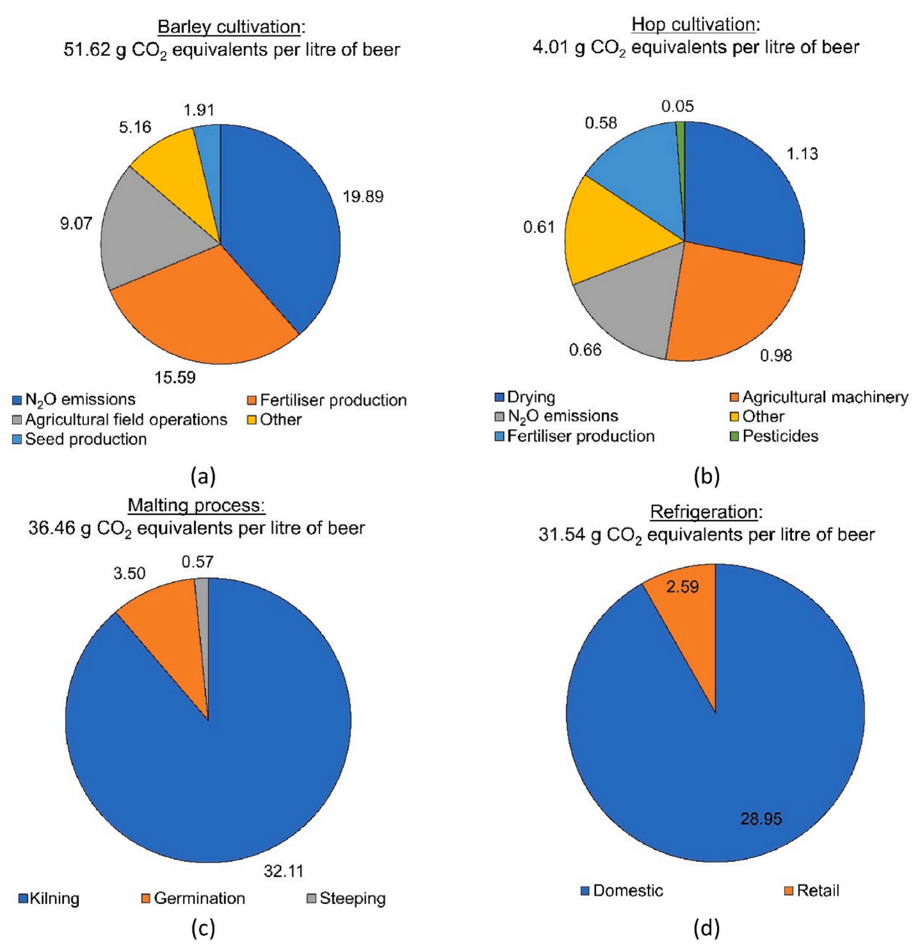

Fig. 4. The breakdown of the carbon footprint of individual brewing value chain stages using the medium carbon footprint scenarios. The carbon footprints for the barley cultivation, hop cultivation, and malting process are consistent across all packaging types whilst refrigeration is not required for steel and PET kegs.

electricity and natural gas consumption (Brewers Association, 2014), or 10 % of electricity and up to 60 % of natural gas consumption (Cimini and Moresi, 2016). Importantly, the areas included in the brewing process carbon quantification are within the breweries' control and therefore mitigation measures can be implemented. However, it is possible that not all the brewing process stages included in the calculator are applicable to every brewery. The calculator has been designed to be flexible in this regard where brewing process stages can be omitted from the calculation if desired.

Fig. 6a and b presents the breakdown of the carbon footprint for the packaging and transportation stages of the brewing value chain for the medium carbon footprint scenario, respectively. The carbon footprint associated with packaging and transportation differs for each packaging type. Therefore, two packaging types are presented for the packaging and transportation breakdown: the highest emission packaging (0.33 L glass bottles) and the lowest emission packaging (20 L steel kegs). For both the 0.33 L glass bottles and 20 L steel kegs the material production is the greatest contributor to the carbon footprint. However, glass bottle material production is approximately 100 times larger than steel kegs. The carbon footprint to transport the packaged beer is similar for both

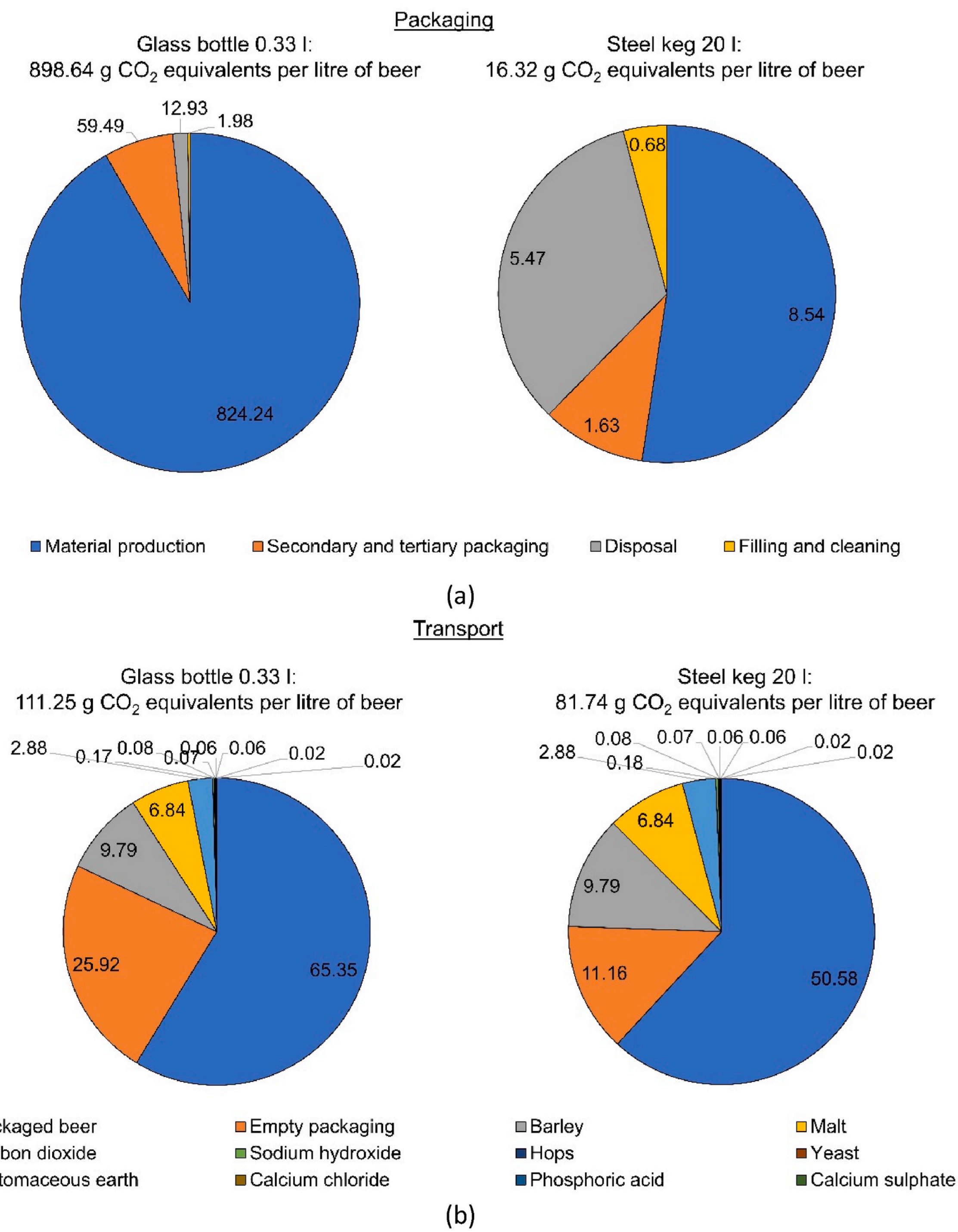

Fig. 6. The breakdown of the carbon footprint for the packaging and transportation stages of the brewing value chain for the medium carbon footprint scenario. The carbon footprint associated with packaging and transportation differ for each packaging type. Two packaging types are presented for the packaging and transportation breakdown: the highest emission packaging (0.33 L glass bottles) and the lowest emission packaging (20 L steel kegs).

packaging types, owing to the weight of the beer dominating the total transportation weight.

3.3. Hotspot identification

Fig. 7 displays the hotspots identified in this study for each packaging type. The carbon footprint percentage contribution of the top five contributing value chain hotspots identified in this study for each packaging type is presented in Table S12 in the Supplementary Information. Wort boiling was ranked as the most significant contributor to beer packaged in steel kegs. Moreover, secondary and tertiary packaging were within the top five contributors for five out of seven packaging types. Malt kilning also appears in the top five contributors for both steel and PET kegs, and N_2O emissions from soil during barley cultivation appear for steel kegs only. For all but two packaging types (reusable glass bottles and steel kegs) packaging production was found to be the primary contributor to the final carbon footprint.

Table 1 lists the brewing value chain hotspots identified in previous literature. Notably, wort boiling, the packaging process in a brewery, malt kilning, and N_2O emissions from soil during barley cultivation, identified as hotspots in this study, have not been previously identified as brewing value chain hotspots. The identification of these new hotspots, the increased granularity of the value chain breakdown, and the consideration of a wide range of packaging types highlight the contribution of the calculator presented in this work. Furthermore, whilst the top five contributing factors from each packaging type are presented in Fig. 7, the freely available calculator consists of 66 individual contributing areas which provides greater granularity for the end user if required.

3.4. Comparison of value chain stage carbon footprints to previous literature

Fig. 8 compares the carbon footprints calculated for different stages of the brewing value chain in this study to values reported in previous literature. Table S13 in the Supplementary Information details the values and corresponding references from previous literature. The results from the medium carbon footprint scenario are used for all comparisons. The results showed that the carbon footprint of barley cultivation, which was calculated to be 51.62 gCO_2e per litre of beer, is on the lower end of the range of values reported in previous literature. However, it closely agrees with a recent study conducted by Muntons (2022), a UK-based malt manufacturer, which reported a value of 52 gCO_2e per litre of beer. The carbon footprint for hop cultivation determined in this study (4.01 gCO_2e per litre of beer) is also towards the lower end of the values reported in previous literature. However, it is consistent with The Climate Conservancy (2008) which is the most transparent study in the previous literature and reports a value equivalent of 5.1 gCO_2e per litre of beer. The carbon footprint for malting determined in this work (36.46 gCO_2e per litre of beer) is also similar to Muntons (2022) (22 gCO_2e per litre of beer). The lower carbon footprint determined by Muntons (2022) is likely due to their use of renewable natural gas (20.3 % of natural gas usage) and electricity sources (11.2 %

Table 1
The brewing value chain hotspots identified in previous literature.

Previous study	Hotspots identified
The Climate Conservancy (2008)	Retail refrigeration Glass production Barley production Downstream distribution
Amienyo (2012)	Packaging production Raw materials (including barley, carbon dioxide, fuel for steam production)
BIER (2012a)	Malt production Packaging production Brewing
Vivant (2013)	Brewing natural gas Aluminium production Barley agriculture Retail utilities and refrigeration Brewing electricity
Sipperly et al. (2014)	Aluminium can production Barley and rice cultivation Glass bottle production
Cimini and Moresi (2016)	Glass bottle production Barley cultivation
Morgan et al. (2021)	Downstream distribution

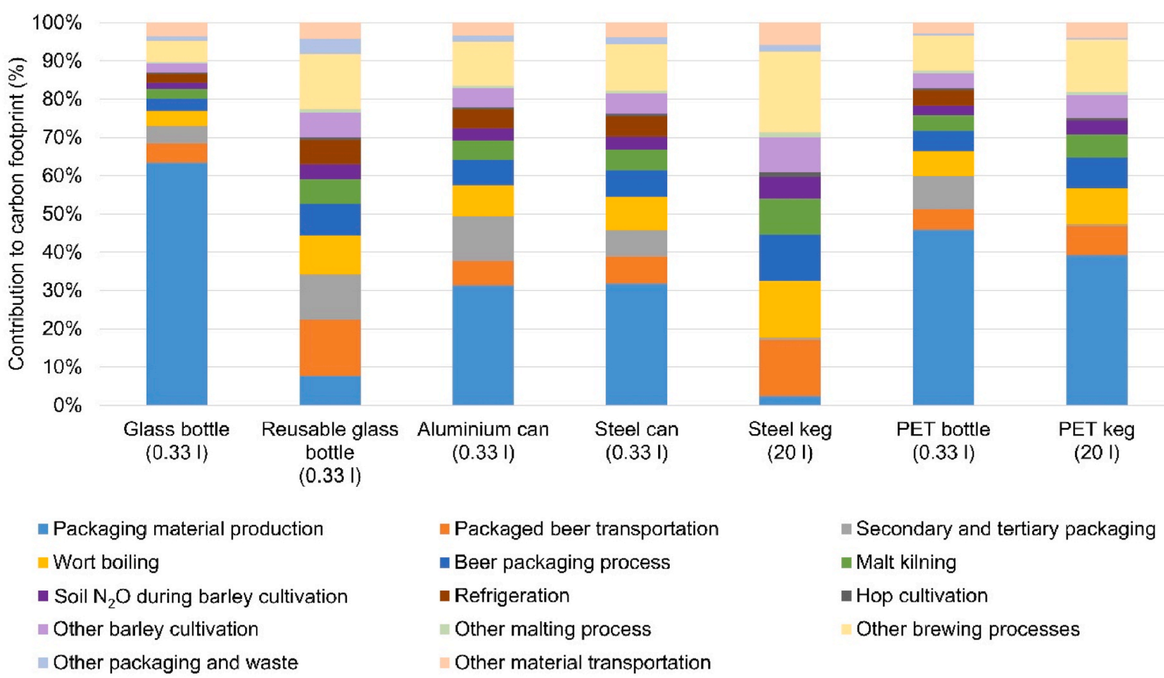

Fig. 7. The brewing value chain hotspots identified in this study for each packaging type along with their percentage contribution to the total value chain carbon footprint.

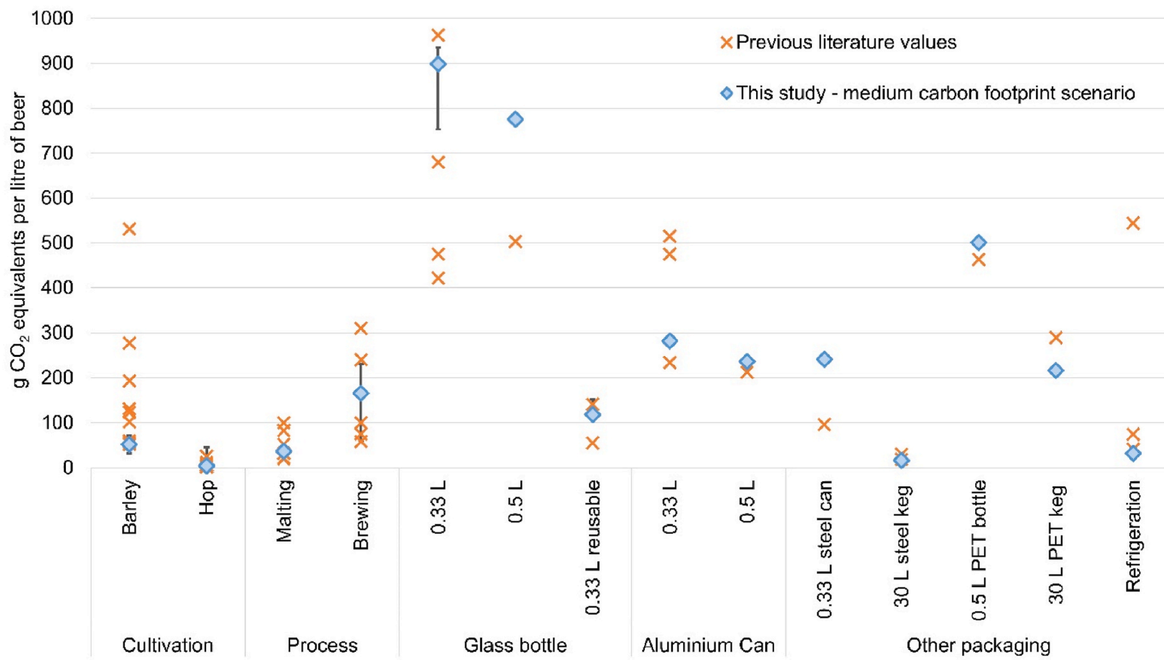

Fig. 8. The carbon footprint values calculated for stages of the brewing value chains in this study compared with results reported in previous literature. The black bars represent the range of the low to high carbon footprint scenarios determined in this work.

of electricity usage). Notably, the carbon footprint of the brewing process, which was determined to be 165.6 gCO_2e per litre of beer in this study, aligns with the mean (156 gCO_2e per litre of beer) of the values reported in previous literature. The carbon footprint of the brewing process was determined to be greater than the most recent previous studies. For example, The Climate Conservancy (2008) reported emissions of 58 gCO_2e per litre of beer whereas Amienyo and Azapagic (2016) reported 73–76 gCO_2e per litre of beer. This is likely due to The Climate Conservancy (2008) assuming the use of renewable electricity, thereby assigning no emissions, and Amienyo and Azapagic (2016) assuming that no natural gas was used in the brewing process, contradicting other studies (Morgan et al., 2021; Cimini and Moresi, 2018).

The carbon footprint results from packaging in this study were generally consistent with values from previous literature. However, some discrepancies were observed, which might be due to differences in the emission factors used between studies. Few studies reported the emission factors utilised, but, for example, Cimini and Moresi (2016) used a glass manufacturing emission factor of 0.57 gCO_2e per g compared with 1.18 gCO_2e per g used in this study. Furthermore, Cimini and Moresi (2016) used an aluminium emission factor of 8.96 gCO_2e per g compared with 5.3 gCO_2e per g used in this work. Using the emission factors from Cimini and Moresi (2016) the carbon footprint of 0.33 L glass bottles decreases from 899 to 472 gCO2e per litre of beer in line with the value of 422 gCO2e per litre of beer determined in Cimini and Moresi (2016). Undertaking the same emission factor substitution for 0.33 L aluminium cans, the carbon footprint increases from 282 to 460 gCO2e per litre of beer consistent with 475 calculated by Cimini and Moresi (2016). This highlights that emission factors must be representative of the time and geographical location for an accurate analysis. The emission factors for packaging used in this study were produced for the UK in 2022 (BEIS, 2022) making them relevant to the geographical location and time period for the use of the calculator. The location of these emission factors used in Cimini and Moresi (2016) was not disclosed. Finally, the carbon footprint of retail and domestic refrigeration in this study was found to be relatively low, with a value of 31.54 gCO_2e per litre of beer. This value falls within the range calculated by BIER (2012a) but is lower than The Climate Conservancy (2008) (544 gCO_2e per litre of beer) and Brewery Vivant (2013) (74 gCO_2e per litre of beer). This is because Brewery Vivant (2013) assumed that 100 % of the product was cooled for 1 day at retail and The Climate Conservancy (2008) assumed that 100 % of the product was cooled for 1 week at retail. In comparison, in this work, it was assumed that 2.5 % of the product was cooled at retail for five days (Section 2.8 Refrigeration).

3.5. *Comparison of total carbon footprints to previous literature*

Fig. 9 presents the total carbon footprints determined in this study for different packaging types, comparing them with values reported in previous literature. Table S14 in the Supplementary Information details the previous values and corresponding references. These results illustrate that the carbon footprint values of beer production using different packaging types reported in previous literature vary widely (Fig. 9). For example, the carbon footprint of producing beer in 0.33 l glass bottles was found to range by ± 38.1%, while 0.33 l reusable glass bottles varied by ± 73.9%. The carbon footprint of 0.33 l aluminium cans also varied significantly, ranging by ± 31.2%, while 0.5 l aluminium cans varied by ± 25.1%. Notably, for 30 l steel kegs, 0.5 l steel cans, and 30 l PET kegs the medium carbon footprint scenario results from this study were found to be outside the range of previously reported literature being, 38.4% higher, 15.3% higher, and, 42.4% lower, than the previously reported ranges, respectively. These discrepancies and the range of values from previous literature are attributed to the emission factor and material use differences used for the different brewing stages which cascade through to the final brewing value chain carbon footprint. This vindicates the recalculation of beer production carbon footprints for the use of craft breweries in the UK. To aid in translating the created calculator to other geographic locations, section S3 ‘Conversion to other locations’ has been added to the Supplementary Information.

4. Future work

This work focused on the characterisation of GHG emissions from the brewing value chain, quantified based on 100-year global warming potential. This is because GHG emission reduction is today a top priority for businesses to increase profitability by reducing resource use and to win more new customers over competitors by reducing the carbon

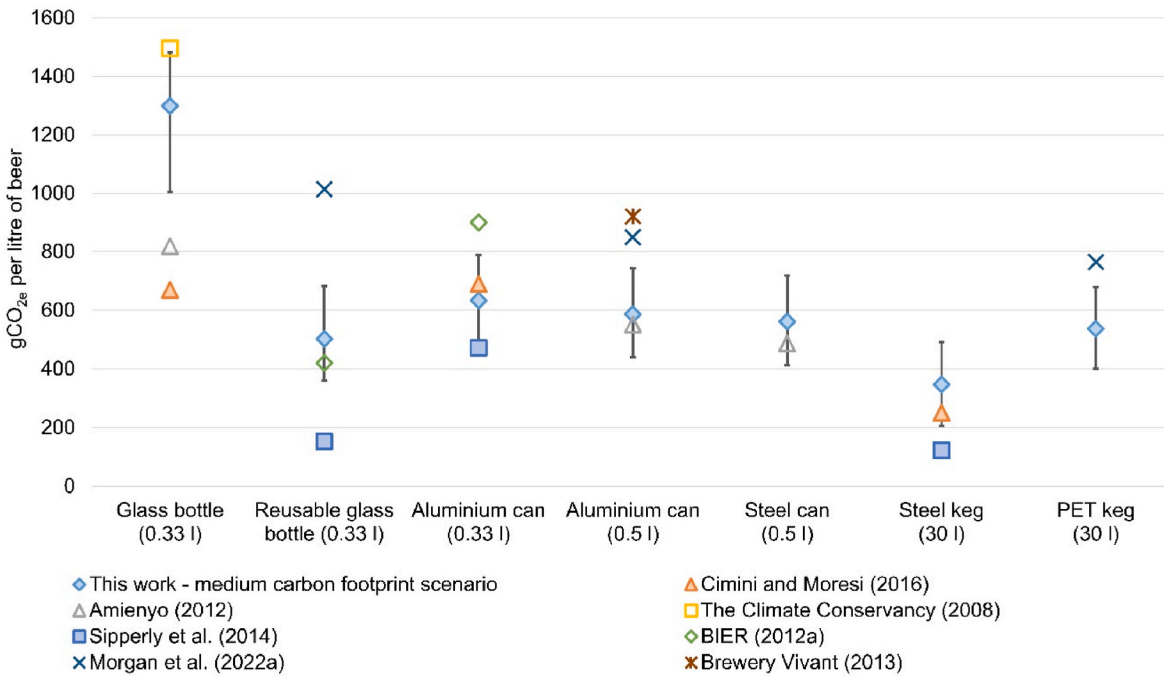

Fig. 9. A comparison of the total carbon footprints of beer production determined in this study for different packaging types compared to values reported in previous literature. The black bars represent the range of the low to high carbon footprint scenarios determined in this work.

footprint of their value chains. However, craft breweries have limited time and budget resources to enhance sustainability practices, so the decision was taken to focus on carbon footprint quantification to maximise the impact of the research. Other environmental impact categories are important to consider (such as water usage, primary energy demand, acidification, toxicity, eutrophication, ozone depletion, and fossil resource depletion (Amienyo, 2012; Morgan et al., 2021)), but are outside of the scope of this work. Future LCAs aiming to quantify the impact of the brewing value chain, as opposed to providing quick and actionable knowledge to brewers, can quantify additional environmental impacts whilst using the current study's assessment of global warming potential as a reference point.

5. Conclusion

Craft breweries often lack the resources, finances, and technical knowledge to fully understand the emissions of their value chains, leading them to only focus on reducing energy consumption. With greater knowledge of carbon footprints along the value chain, craft breweries can accelerate the decarbonisation of the brewing industry by competing to appeal to consumers who are increasingly conscious of environmental issues. To address this, this study provides three contributions:

1. This study developed a freely available, open-source carbon calculator for benchmarking and identifying opportunities for emission reductions in the UK craft brewing sector (available as a downloadable Excel spreadsheet: 10.6084/m9.figshare.22758692). The calculator uses transparent data sources and can be a reference point for future carbon footprint analyses of global brewing value chains. Overall, 279 out of 360 (80.3 %) of collected data values are worldwide applicable. Furthermore, 126 out of 207 (60.9 %) of values used in the calculator are worldwide applicable. A list of the location-specific values required to convert the calculator to another location other than the UK is provided in section S.3 in the Supplementary Information.
2. Emissions were quantified for a wide range of packaging types including glass, reusable glass, and polyethylene terephthalate (PET) bottles; aluminium and steel cans; and steel and PET kegs. Furthermore, this was conducted across three scenarios (low, medium, and high carbon footprints) based on collected data to provide realistic estimation of the uncertainty. Overall, the carbon footprint for craft brewing was calculated to range between 205 (20 L steel kegs, low carbon footprint scenario) and 1483 (single-use, 0.33 L glass bottles, high carbon footprint scenario) gCO_2e per litre of beer. Discrepancies between values reported in previous literature are addressed, vindicating the calculation of the brewing carbon footprints.
3. This study reported novel hotspots not previously identified in the literature including wort boiling and the packaging process within a brewery as well as the contribution of secondary and tertiary packaging. Scope 3 emissions were found to dominate all considered carbon footprint scenarios and packaging types compared with scope 1 and 2 emissions, contributing between 57 and 95 % of the total carbon footprint. This underscores the need to provide knowledge to craft breweries to enable the making of informed and effective sustainability decisions. While scope 3 emissions are dominant, this does not diminish efforts by craft breweries to reduce their scope 1 and 2 emissions which are within their direct control. Instead, calculation of scope 3 emissions provides information about additional areas of the value chain not included within brewery energy consumption such as the procurement of materials, transportation, or packaging choice.

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CRediT authorship contribution statement

Alexander L. Bowler: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Sarah Rodgers:** Methodology, Software, Validation, Data curation, Writing – review & editing, Visualization. **Fanran Meng:** Methodology, Validation, Writing – review & editing. **Jon McKechnie:** Methodology, Validation, Writing – review & editing.

David J. Cook: Writing – review & editing, Supervision, Project administration, Funding acquisition. **Nicholas J. Watson:** Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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

Link to data shared in manuscript and cover letter.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.140181.

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