Sustainable Production and Consumption 34 (2022) 330–341

Contents lists available at ScienceDirect

Sustainable Production and Consumption

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

Environmental impacts of Scottish faba bean-based beer in an integrated beer and animal feed value chain

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ARTICLE INFO

Article history:
Received 15 June 2022
Received in revised form 20 September 2022
Accepted 21 September 2022
Available online 24 September 2022

Editor: Prof. Shabbir Gheewala

Keywords:
Life cycle assessment
Grain legume
Pulses
Beer
Agricultural rotations
Feed substitution

ABSTRACT

Beer is one of the most popular drinks globally and production methods clearly need to become more sustainable. The brewing of legume grains could contribute to improved sustainability through encouraging the diversification of cropped systems and by providing more nutritious local co-products as animal feed. The aim of this study was to assess the potential environmental effect of partially substituting malted barley with grain legumes as an option to mitigate the environmental impact of beer. A Life Cycle Assessment (LCA) was performed to compare a novel Scottish beer produced with malted barley and UK-grown faba beans with a traditional malted barley beer. We considered beer production as part of a multi-functional beer and animal feed value chain, where co-products are used as a high-protein UK-grown animal feed. The environmental performances of the different beers were highly dependent on the system boundaries adopted. The simple attributional LCA indicated that a barley-bean beer could offer environmental savings when alcohol yields are optimised, with environmental burdens that were significantly smaller than those of the barley beer across 6 categories. When boundaries were expanded to include both feed substitution and agricultural rotations, the barley-bean beer with current alcohol yields outperformed the barley beer across 8 impact categories, with a 15 %–17 % smaller climate change burden, mainly due to higher feed substitution achieved from a larger volume of brewing co-products with higher protein concentrations. Therefore, brewers should consider the use of legumes in their brewing recipes to lower their environmental footprint, increasing the availability of more nutritious beer co-products as a local source of animal feed, and diversifying cropping systems while adding novelty to their product range. Different boundaries settings and scenarios should be assessed in a beer LCA, and entire cropping rotations should be integrated to capture a more accurate picture of the agricultural stage.

1. Introduction

Beer is the world's third favourite beverage (Nelson, 2005). It is a staple drink for many, and its popularity can be traced back to the times in which it was safer to drink than water, due to the boiling required in its production, and use of hops. Recently, in addition to traditional cereal-based beer, brewing using legume grains has been spreading globally with differences across the globe depending on which crop grows locally, such as lentils (*Lens culinaris* L.) in the United States (Company, 2022), peas (*Pisum sativum* L.) in Lithuania (Biržų alus, 2022), faba beans (*Vicia faba* L.) in the United Kingdom (Barney's Beer, 2022), and edamame (immature green soybean, *Glycine* max L.) in Japan (The Mainichi, 2019).

Precisely because of its popularity, the environmental impact of beer is considerably high, requiring large inputs of energy, water, and natural raw materials. Life Cycle Assessment (LCA) is a method used to calculate the potential environmental impact of a product or process throughout its life cycle, from the extraction of raw materials through to farm cultivation, factory processing, consumption, or disposal and recycling stages, considering inputs and emissions involved. Numerous LCAs of beer from various countries have been performed. Most of them, however, have been published 10 or more years ago, and they all have a

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https://doi.org/10.1016/j.spc.2022.09.019
2352-5509/

common finding that bottle production is an environmental hotspot. The most recent studies include Amienyo and Azapagic (2016), Morgan et al. (2022), and Salazar et al. (2021). Amienyo and Azapagic (2016) and Morgan et al. (2022) provided detailed assessments and identified improvement options at the packaging and distribution stages, while Salazar et al. (2021) investigated the instantaneous water heating system for micro-breweries. Their inventory data on the cultivation stage, however, were extracted from a secondary, aggregated process for barley cultivation from the Ecoinvent database (Wernet et al., 2016), and therefore the authors could not quantify any environmental improvement opportunities for this stage of the life cycle, although it was one of the major hotspots (Amienyo and Azapagic, 2016; Morgan et al., 2022; Salazar et al., 2021). This was also the case in previous studies, such as in Cordella et al. (2008). All these studies recognised that it was of key relevance to identify opportunities to reduce the environmental impact of barley cultivation in the beer value chain. Moreover, as in most LCA publications, these studies draw the boundaries around one cultivation year only, ignoring the environmental effects of crop rotations and nutrient cycling effects.

Partially substituting traditionally used cereals with legumes for brewing holds potential to reduce the environmental impact of beer. In addition to their capacity to fix atmospheric nitrogen (di-N, N_2) into biologically useful forms due to their symbiotic relationship with N_2-fixing bacteria, thus allow yield and offsetting the environmental impacts associated with production, application, and use of synthetic N fertilizer (Multari et al., 2015; Peoples et al., 2009), legumes improve soil structure, increase biodiversity, and reduce weed invasion (Sturludóttir et al., 2014). Legume co-products from alcohol production also hold more value than cereal-based co-products due to higher protein concentration (Lienhardt et al., 2019). In view of reducing the environmental impact of beer, Barney's Beer (2022), a brewery located in Edinburgh, Scotland, created *CoolBeans®* Faba Bean IPA beer made with 46 % UK-grown faba beans and 54 % barley.

This article aims to assess the potential environmental effect of partially substituting malted barley with grain legumes as an option to mitigate the environmental impact of beer. Thus, the relative environmental sustainability of integrating faba beans into beer as part of a multi-functional beer and animal feed value chain is investigated, where co-products obtained during the dehulling, malting, and mashing stages are used as a high-protein home-grown animal feed source in Europe, instead of using imported soy. This study also aims to provide more precise, disaggregated agricultural data for beer production in the United Kingdom (UK) and investigate the effect of integrating entire rotations in the system boundaries, instead of partially accounting for the agricultural stage. As recommended by Costa et al. (2020), we evaluated here the entire crop rotation by using a rotation generator for the crops of interest (Reckling et al., 2016b). The rotation generator produced crop rotations going from 3 to 6 years with minimum breaks between the same crops as well as a maximum crop frequency of the same crop types (Reckling et al., 2016b). By integrating the entire rotations in the assessment, barley cultivation and assessing the effects of partially replacing it with faba beans, our study aims to fill the gap of identifying environmental impact improvement opportunities at the cultivation stage. Therefore, this paper aims to answer the following questions: How is the environmental impact of beer affected by (i) the partial substitution of malted barley with faba beans? (ii) the expansion of system boundaries to account for entire crop rotations? (iii) the expansion of system boundaries to account for soybean and barley feed substitution with beer co-products?

2. Methods

2.1. Goal and scope

This study is a comparative attributional LCA (aLCA) aiming to validate the following hypotheses: (i) The environmental impact of the barley-bean beer is significantly lower than that of a conventional malted barley beer, potentially providing a more sustainable alternative to traditional beers; (ii) The expansion of system boundaries to account for entire crop rotations lowers the environmental impact of bean-barley beer (iii) The expansion of system boundaries to account for soybean and barley feed substitution with beer co-products lowers the environmental impact of all beers. The intended audience consists of brewers and stakeholders willing to decrease the environmental impact of beer production and make more informed choices, as well as LCA practitioners who are working on alcoholic products and who are willing to investigate further the different effects of boundary expansion and inclusion of entire crop rotations.

Several scenarios were assessed, using milled whole or dehulled beans (bean kernels) as raw materials to produce the bean beers, as these two forms are currently being used by the brewery. In addition to these existing scenarios, and reflecting a yet under-optimised bean brewing process, a scenario with the theoretical alcohol yield of bean beer was assessed. This scenario represents a future case where the maximum alcohol yield can be obtained from the faba beans when appropriate equipment for legume processing is used. The reason for this was that the brewery where the actual data came from did not have equipment for optimum processing of beans, and therefore alcohol obtained from the faba beans was below its potential. A barley beer with theoretical alcohol yield was not assessed, as centuries of barley beer production was assumed to result in optimised alcohol yields. The products assessed were recorded below:

1) *Bly*, for conventional malted barley beer;
2) *Bn(ac)*, for barley-whole bean beer with actual alcohol yields;
3) *dBn(ac)*, for barley-dehulled bean beer with actual alcohol yields;
4) *Bn(th)*, for barley-whole bean beer with theoretical alcohol yields;
5) *dBn(th)*, for barley-dehulled bean beer with theoretical alcohol yields.

2.2. Functional unit and system boundaries

The functional unit was defined as one 330 mL filled beer bottle at the brewery in Edinburgh. Two system boundary modelling approaches with differing complexities were investigated (Fig. 1). The first approach represents a simple aLCA with no rotation modelled nor allocation performed for malting co-products by allocating all of the impact on the beer, as recommended by the PEFCR (Product Environmental Footprint Category Rules), of beer (European Commission, 2018a) as, "*this could bias the choice in feed ingredients in compound feeds (which is out of scope of this PEFCR)*". The second approach represents an aLCA with expanded system boundaries that include feed substitution savings from co-products obtained during the beer making process, namely faba bean hulls, malt residuals, and spent grains, as well as environmental savings or burdens resulting from the additional crops (wheat and surplus barley) produced from the agricultural rotations. The wheat in the second scenario was modelled to substitute for winter wheat production. A sensitivity analysis was performed with a substitution for winter wheat production from a process proper to Ecoinvent v.3.7.1 (market process for France (Wheat FR)). The crop-related elements of the aLCA with expanded system boundaries are recorded in Fig. 2.

2.3. Life cycle inventory

The Ecoinvent database version 3.7.1 (Wernet et al., 2016) was used in the open-source LCA software OpenLCA version 1.10.3 (GreenDelta, 2022).

Multi-pack crates for transporting the bottles and the container in which the beer is held to be transported to the packaging facility were excluded from the system boundaries, as well as yeast production and water used for cleaning the equipment. Ingredients that represented <1 % of the total ingredients by mass were excluded, such as diatomaceous earth,

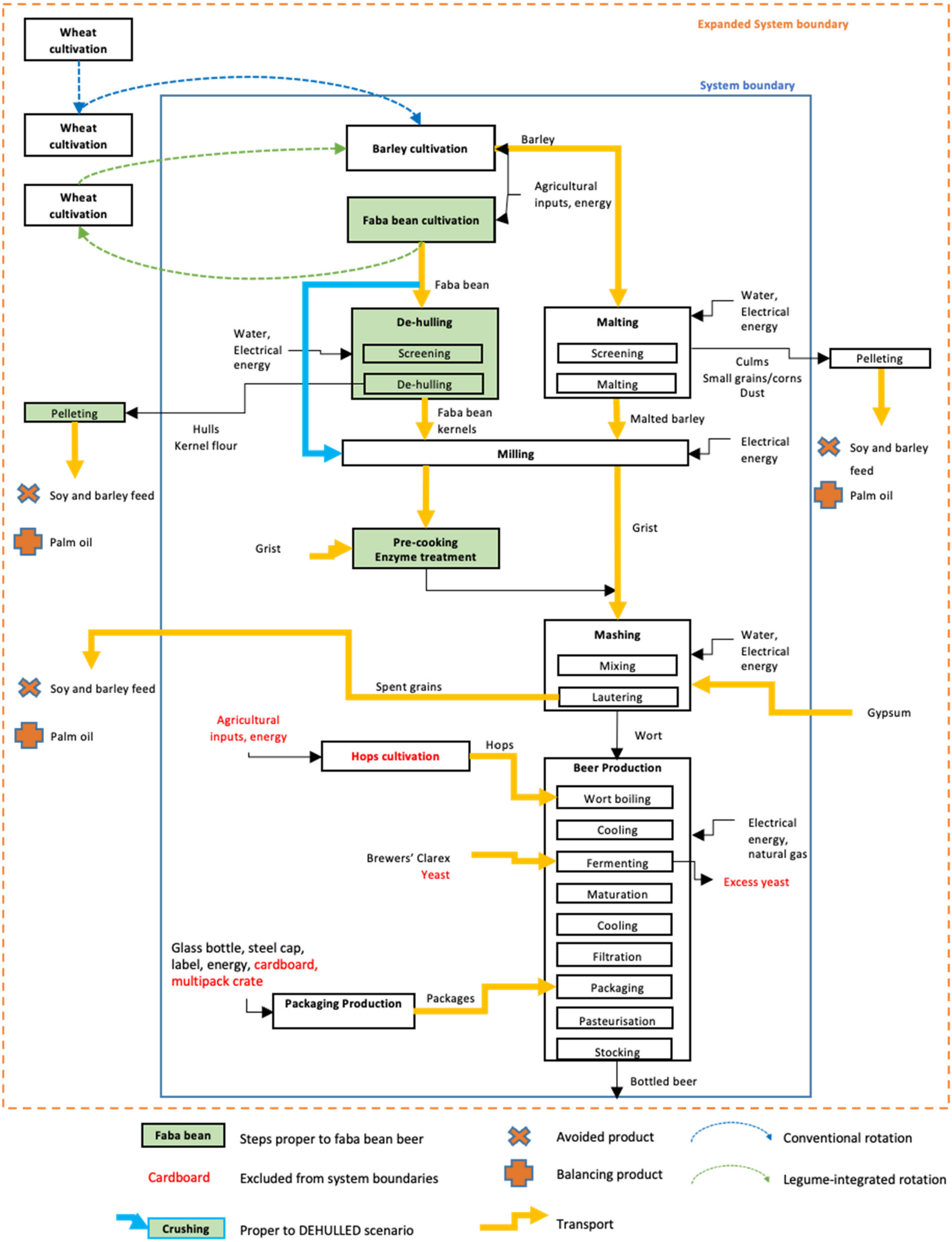


Fig. 1. System boundaries of the beers assessed in this study.

sodium hydroxide, phosphoric acid, and sulphuric acid, due to the lack of data. This was not a significant issue in our study, as these values don't differ between the products compared, and the novel aspect of the study is the integration of faba beans into the beer.

Theoretical alcohol yields were calculated with the following approach. The litre degrees (L°) per kilogram of faba beans was calculated for a bean starch content of 61 % and used to determine the actual brewhouse extract efficiency for processing beans (37 %). The theoretical bean requirements (kg) to obtain this same level of extract were then calculated using the actual brewhouse efficiency for malted barley (82 %).

2.3.1. Malt barley beer inventory

The life cycle inventory of the different types of beers assessed is recorded in Table 1. Faba bean and barley ingredients used to produce one bottle of beer for all scenarios assessed in this study are recorded in Fig. 3. Varying quantities of faba beans and barley grains were needed to produce a same volume of beer, yielding different amounts of co-products.

Agricultural rotations used in this study were adapted from rotations in (Reckling et al., 2016a), which were modelled through a rotation generator (Reckling et al., 2016b). The conventional rotation consisted of winter wheat followed by winter wheat, which in turn was followed by winter barley. Nitrogen, Phosphorus, and Potassium (NPK) fertilizer applications are recorded in Table A1 of the Appendix. The distribution of fertilizer types specific to the UK were extracted from the (International Fertilizer Association, 2020), and two applications of fertilizer were assumed. The N_2O and CO_2 emission factors were extracted from the IPCC 2019 guidelines (Liang and Noble, 2019). Soil tillage operations were modelled using the existing Ecoinvent 3.8 process “tillage, ploughing”, representing a four-furrow plough (Wernet et al., 2016) for each crop in the rotation.

The conventional barley-only beer assessed in this study is produced as follows. Barley grown in the UK, and East Anglia mainly, was supplied by Bairds Malt (Malt, 2022). Following harvest, the drying step of barley grain was adapted from the Agri-footprint 3.0 process “Barley grain, dried, at farm, Economic” (Durlinger et al., 2017), adjusting Dry Matter (DM) contents from 0.84 to 0.89 (De Klein et al., 2006). The dried barley is then transported for an average of 50 km between the field and the maltsters by lorry. The grains are stored in silos and dried to a 14 % moisture content in forced heating. Grains are cleaned, partly with a cleaning drum, and organized by size. Malt is then obtained from the grains by soaking them in water, leaving them to germinate, and then drying them (kilning). The average yield is of 1.3 t of barley for 1 t of malt, requires 1140 gal, uses 750 kWh of gas and 150 kWh of electricity (UK Malt, 2019). The obtained malt contains amylases, proteases and beta-glucanases that have a key role in the next processes. Malting co-products include malt residual pellets and barley screenings, which are used in the feed industry (UK Malt, 2011). These are transported to a feed company 113 km away and were assumed to be transformed into pig feed. The next step is milling, during which the malt is crushed and turned into grist. Water is then added to the grist during mashing. In this step, fermentable sugar is obtained from starch conversion by amylases. Proteins and gums are broken down by the proteases and beta-glucanases. The mash is then filtered and spent grains are obtained as an animal feed alongside the wort, a sugary liquid. The spent grains were assumed to be transported a further 113 km to a farm, as for the malt residual pellets, and used as cattle feed. Wort is then boiled and hops imported from the United States by ship over a distance of 15,976 km (SeaRates, 2022) and by truck for 1000 km (European Commission, 2018b) and are added to the wort for flavouring. Residues are then extracted via a whirlpool. Next comes the fermentation step, in which yeast is added to the cooled wort. This step lasts 6 days at a temperature of 20 °C. The obtained green beer is left to mature, and then bottled and pasteurized. The average ale temperatures for fermentation range from 20 to 22 °C (Mosher and Trantham, 2017).

2.3.2. Faba bean beer inventory

The innovative beer type made of barley with whole or dehulled faba beans is produced as follows. Once harvested, the beans are transported 92 km from the farms to Askew and Barrett (Barrett, 2022), where they are sorted for the *Bn* beer and sorted and dehulled for the *dBn* beer. Whole faba beans are made of 82 % kernels and 18 % hulls (Walker et al., 2014). To produce a *dBn* beer, 0.0377 kg whole beans are dehulled and 0.0034 kg of hulls are mixed and processed with 0.0079 kg kernel flour into pellets, which are then used for animal feed. The remaining 0.026 kg of kernel flour is transported for 643 km to Dundee, where it is milled. To produce a *Bn* beer, 0.026 kg whole beans are directly transported to Dundee for milling. After milling, the beans are transported 95 km to the Summerhall Brewery in Edinburgh (Barney's Beer, 2022).

The hull co-product obtained when producing a *dBn* beer is mixed with faba bean flour after the dehulling step and is processed into pellets. They are then transported for 170 km by truck to a facility where they serve as cattle (70 %) and sheep (30 %) feed. These pellets were modelled to replace soybean and barley feed based on a total protein content of 0.20 kg/kg DM and a metabolisable energy content of 11.1 MJ/kg DM. Crude protein and metabolisable energy for ruminants of whole faba bean were extracted from (O'kiely et al., 2017), while the same data points for hulls were extracted from (Minakowski et al., 1996). Data on soybean meal, barley grain, and malt residuals were extracted from Feedipedia (Heuzé et al., 2020; Heuzé et al., 2015, 2016). Table A2 records the crude protein and metabolisable energy contents of faba bean, soybean, and barley products for ruminants and amount of soybean meal and barley grain substituted (negative values) per kg dry matter product using linear optimisation. Linear optimisation was performed using the SymPy package in Python 3.6 (Sympy, 2021).

Currently, spent grains are collected by Keenan recycling for anaerobic digestion (Keenan Recycling, 2020). In this study, anaerobic digestion was not modelled, as the spent grains are sent to a plant and mixed with other products before producing biogas, therefore the amount of biogas produced from the spent grains themselves is unknown. However, the spent grains also hold potential in substituting animal feed. Therefore, the LCA was modelled with extended system boundaries to include substitution of cattle feed from spent grains. To balance the resulting soybean oil not being produced because of the substituted soybean meal from the beer production co-products, the additional compensating palm oil produced (Dalgaard et al., 2008) was modelled, with 0.22 kg of soybean oil avoided for every kg of soybean meal spared, as shown in the consequential database of Ecoinvent 3.7.1 (Wernet et al., 2016). In the scenarios where system expansion was not modelled, no allocation was performed for malting or brewing co-products, as recommended by the PEFCR of beer (European Commission, 2018a).

Due to the lack of life cycle inventory data for hops, other LCA studies used a proxy, such as barley cultivation (Amienyo and Azapagic, 2016), or ignored the hops claiming the quantity added is small compared to the barley (Kløverpris and Spillane, 2010). (The Climate Conservancy, 2008) reported the carbon footprint of hops production to be only of 0.2 % of the total carbon footprint of beer. Hops were therefore not accounted in this study, as the same quantity is used across all types of beers assessed, and their modelling would not make any difference to the relative impacts of the different beers.

A third party is contracted for packaging the beer. The beer is sent in tanks, then cooled, filtered, and put into bottles. Energy for bottling was extracted from de Marco et al. (2016).

Faba bean beer goes through the same stages as the barley beer, except that faba beans need to be pre-cooked at 80 °C. According to the brewer, if the bean beer becomes commercially successful and needs to be produced at a larger scale, an efficient cooker with more-stable thermal control capacity, will be purchased and will replace the liquor tank currently used to pre-cook the beans. In this study, we modelled

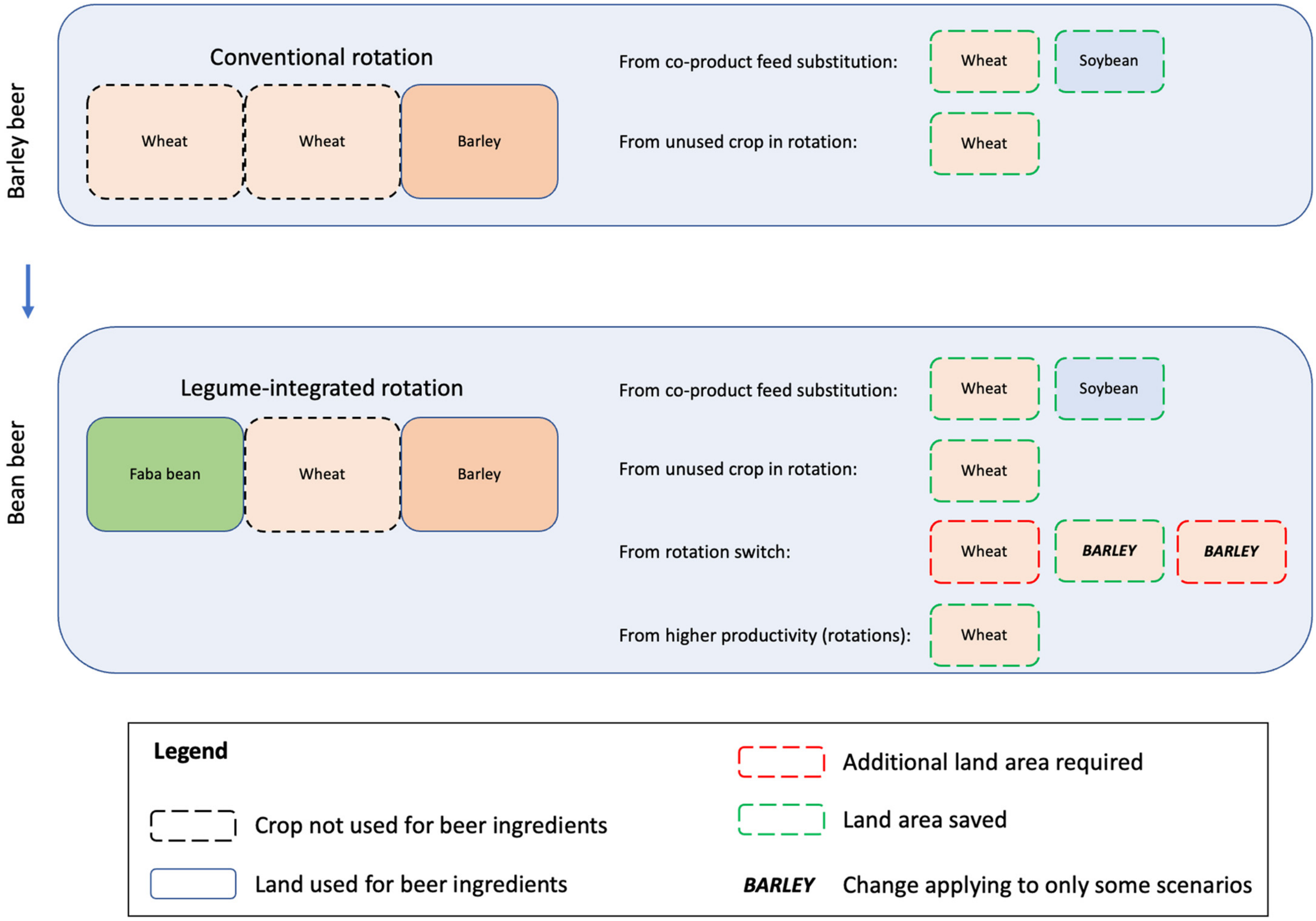


Fig. 2. Crop-related elements present in the scenarios that includes feed substitution of co-products and rotations.

the pre-cooking as if it was happening in the same tank as the other processes. Energy for pre-cooking, mashing, wort boiling, fermentation, maturation, and the two cooling stages was calculated theoretically using the equations from (Zogla et al., 2015). Ambient temperature was modelled at 10 °C, a single layer in the machinery, and the other parameters were the same as in (Zogla et al., 2015). For the first stage, 52 kg of whole beans were pre-cooked at 80 °C with 250 L of water and 5 kg of barley. The specific heat capacities used were for faba beans 1.50 kJ/kg/K (Fraser et al., 1978), barley 1.485 kJ/kg/K (Markowski and Białobrzewski, 2013), hops 1.4 kJ/kg/K (Doe and Menary, 1975), and water (4.18 kJ/kg/K). The first cooling stage takes place using a heat exchanger, heating water for the next brew, but was modelled as if cooling happened in the same tank as the other stages for simplicity. Yeast production was excluded from all assessments due to the lack of brewers' yeast data in the databases.

2.4. Impact assessment

The beers were compared across sixteen environmental impact categories recommended by the Product Environmental Footprint (PEF) guidelines (European Commission, 2018b), from cradle to factory gate. The EF 3.0 (adapted) methods package downloaded from the OpenLCA website (GreenDelta, 2022) was used to perform the impact assessment, following the PEF recommendations (European Commission, 2018b). Through a modified Null Hypothesis Significance Test (mNHST) following (Mendoza Beltran et al., 2018), we investigated whether results obtained from the LCAs were statistically significant ($p < 0.05$). We applied a Bonferroni correction of $\alpha b = 0.05/80 = 0.000625$, as there were 16 impact categories and 5 alternative pairs, and an effect size of $\delta 0 = 0.2$.

3. Results

3.1. Simple attributional LCA (no feed substitution, no rotation modelled)

Aggregated results of the modified Null Hypothesis Significance Tests for the most basic (attributional) scenario are recorded in Table 2. In this scenario, where no feed substitution was modelled for co-products nor rotations were integrated, when comparing the environmental burdens related to the production of *Bly* (the conventional barley-only beer), with *Bn(ac)* and *dBn(ac)* (the conventional barley-beer where whole or dehulled faba bean (respectively) was used as an additional starch source), *Bly* outperformed significantly ($p < 0.05$) *Bn(ac)* and *dBn(ac)* over 4 and 11 categories, respectively. For example, *Bly* had a climate change burden that was 6 % and 28 % smaller, land use 36 % and 47 % smaller, and resource use energy carriers 4 % and 37 % smaller than *Bn(ac)* and *dBn(ac)*, respectively (Supplementary Information). The production of a *dBn(ac)* was associated with a highly defavourable environmental impact, with the production of all other beers having a significantly lower ($p < 0.05$) burden than *dBn(ac)* across 10 to 11 impact categories. On the other hand, when looking at the bean beers with optimised brewing of the bean starch, the *Bn(th)* appeared to have the best environmental performance overall, having a significantly lower ($p < 0.05$) burden than the other products across 6 to 11 impact categories, and had no burden that was significantly higher ($p < 0.05$) than other beers.

Table 1
Inventory of inputs and outputs for one 330 mL bottle of beer. *Bly* - conventional malted barley beer; *Bn(ac)* - barley-whole bean beer with actual alcohol yields; *dBn(ac)* - barley-dehulled bean beer with actual alcohol yields; *Bn(th)* - barley-whole bean beer with theoretical alcohol yields; *dBn(th)* - barley-dehulled bean beer with theoretical alcohol yields.

Stage	Input/output/process	Units	*Bly*		*dBn(ac)*		*Bn(ac)*		*dBn(th)*		*Bn(th)*	
			In	Out	In	Out	In	Out	In	Out	In	Out
Cultivation	Fertilizer –N	kg	0.0019		0.0018		0.0018		0.0014		0.0014	
	Fertilizer – P	kg	0.0007		0.0011		0.001		0.0007		0.0007	
	Fertilizer – K	kg	0.0007		0.0013		0.0011		0.0008		0.0007	
	Lime	kg	0.0041		0.0089		0.0074		0.0048		0.0045	
	Sowing and harvesting	m^2	0.18		0.32		0.26		0.20		0.20	
	Fertilizer application	m^2	0.18		0.32		0.26		0.20		0.20	
	Tillage, ploughing	m^2	0.18		0.32		0.26		0.20		0.20	
	Seed (faba beans)	kg			0.0031		0.0021		0.0011		0.0009	
	Seed (barley)	kg	0.0018		0.0018		0.0018		0.0014		0.0014	
	Land occupation, arable (barley)	m^2	0.089		0.11		0.086		0.068		0.068	
	Faba beans (DM)	kg				0.063		0.044		0.022		0.018
	Barley grain (DM)	kg		0.071		0.069		0.069		0.054		0.054
	Wheat grain surplus (DM)	kg		0.17		0.11		0.1		0.1		0.1
	Barley grain surplus (DM)	kg				0.015						
	Avoided wheat grain (DM)	kg		−0.17		−0.11		−0.1		−0.1		−0.1
	Avoided barley grain (DM)	kg				−0.015						
	Electricity mix, low voltage (drying barley)	MJ	0.04		0.04		0.04		0.03		0.03	
Cleaning/de-hulling faba beans	Transport, truck >32 t, farm-de-hulling facility EURO 4	kg. km			5.8		5.8		1.8		1.7	
	Energy, electricity for cleaning/screening	kWh			0.0025		0.0025		0.00075		0.00071	
	Energy, electricity for de-hulling	kWh			0.26				0.078			
	Faba bean hulls	kg				0.006				0.0021		
	Kernels for pellet	kg				0.013				0.0046		
	Kernels for beer	kg				0.044				0.015		
	Whole beans for beer	kg				0		0.044				0.018
Avoided feed (hulls)	Energy, electricity for milling	kWh			7.10E−04				0.00021			
	Energy, electricity for pelleting	kWh			5.50E−04				0.00017			
	Transport, truck >32 t, processing facility-farm, EURO 4	kg. km			0.645				0.19			
	Avoided soybean meal	kg				−0.0068				−0.0024		
	Balancing palm oil	kg			0.00148				0.00052			
	Avoided barley grain feed	kg				−0.0096				−0.0034		
	Faba bean pellet	kg				0.019				0.0067		
Malting	Transport, truck >32 t, farm-processing plant, EURO 4	kg. km	3.5		3.4		3.4		2.66		2.66	
	Energy, electricity for malting	kWh	0.041		0.04		0.04		0.03		0.03	
	Water	L	0.28		0.27		0.27		0.21		0.21	
	Malted barley	kg		0.055		0.053		0.053		0.04		0.04
	Water vapour	L		0.28		0.27		0.27		0.21		0.21
	Malt residuals	kg		0.016		0.016		0.016		0.012		0.012
Malt pellets	Transport, truck >32 t, EURO 4	kg. km	1.8		1.8		1.8		1.4		1.4	
	Energy, electricity	kWh	0.0015		0.0015		0.0015		0.0011		0.0011	
	Malt residual pellets	kg		0.016		0.016		0.016		0.012		0.012
	Avoided soybean meal	kg		−0.0057		−0.0057		−0.0057		−0.0043		−0.0043
	Balancing palm oil	kg	0.0012		0.0012		0.0012		0.0093		0.0093	
	Avoided barley grain feed	kg		−0.0054		−0.0054		−0.0054		−0.0040		−0.0040
Milling faba beans	Transport, truck >32 t, EURO 4	kg. km			28		28		13		11	
	Energy, electricity for milling	kWh			0.002		0.002		0.001		0.0008	
	Faba bean flour	kg. km				0.044		0.044		0.019		0.018
Milling barley	Energy, electricity for milling	kWh	0.0029		0.0028		0.0028		0.0028		0.0028	
	Grist barley	kg		0.055		0.053		0.053		0.053		0.053
Pre-cooking	Energy, electricity for pre-cooking	kWh			0.011		0.011		0.0084		0.0084	
	Enzyme	kg			1.60E−05		1.60E−05		1.60E−05		1.60E−05	
	Transport, truck >32 t, faba beans, EURO 4	kg. km			4.2		4.2		1.5		1.7	
	Transport, truck >32 t	kg.			1.6		1.6		1.3		1.3	

(continued on next page)

Table 1 (*continued*)

Stage	Input/output/process	Units	*Bly* In	*Bly* Out	*dBn(ac)* In	*dBn(ac)* Out	*Bn(ac)* In	*Bn(ac)* Out	*dBn(th)* In	*dBn(th)* Out	*Bn(th)* In	*Bn(th)* Out
	grist, EURO 4	km										
	Water	L			0.12		0.12		0.093		0.093	
	Water vapour	L				0.0018		0.0018		0.0014		0.0014
	Pre-cooked faba beans with grist	kg				0.16		0.16		0.11		0.11
Mashing	Transport, truck >32 t grist, EURO 4	kg. km	35		32		32		25		25	
	Water	L	0.35		0.24		0.24		0.25		0.25	
	Energy, electricity	kWh	0.027		0.018		0.018		0.019		0.019	
	Spent grains (dry weight)	kg		0.055		0.1		0.097		0.057		0.059
	Water in spent grains	kg		0.015		0.036		0.036		0.021		0.022
	Transport spent grains	kg. km	6.2		11		11		6.5		6.7	
	Avoided soybean meal	kg		−0.022		−0.042		−0.04		−0.024		−0.024
	Balancing palm oil	kg	0.0048		0.0091		0.0087		0.0052		0.0052	
	Avoided barley grain feed	kg		−0.017		−0.041		−0.040		−0.021		−0.020
	Water vapour	L		0.004		0.004		0.004		0.004		0.004
	Wastewater	L		0.008		0.007		0.007		0.003		0.002
	Wort	L		0.32		0.31		0.31		0.32		0.32
Hop production	Hop cones	kg	0.002		0.002		0.002		0.002		0.002	
	Transport, truck >32 t, EURO 4	kg. km	2.3		2.3		2.3		2.3		2.3	
	Transport, ship	kg. km	36.7		36.7		36.7		36.7		36.7	
Yeast transport (without yeast)	Transport, truck >32 t, EURO 4	kg. km	0.002		0.002		0.002		0.002		0.002	
	Transport, ship	kg. km	0.004		0.004		0.004		0.004		0.004	
	Transport, train	kg. km	0.003		0.003		0.003		0.003		0.003	
	Yeast			1.00E−05		1.00E−05		1.00E−05		1.00E−05		1.00E−05
Brewer's clarex production	Brewer's clarex	kg	1.50E−05		1.50E−05		1.50E−05		1.50E−05		1.50E−05	
	Transport, truck >32 t, EURO 4	kg. km	0.004		0.004		0.004		0.004		0.004	
	Transport, ship	kg. km	0.005		0.005		0.005		0.005		0.005	
	Transport, train	kg. km	0.004		0.004		0.004		0.004		0.004	
Wort boiling	Water	L	0.016		0.016		0.016		0.016		0.016	
	Energy, electricity	kWh	0.017		0.016		0.016		0.016		0.016	
	Grist barley	kg	0.002		0.002		0.002		0.002		0.002	
	Water vapour	L		0.004		0.003		0.003		0.003		0.003
	Sterilised Wort	L		0.33		0.33		0.33		0.33		0.33
	Energy, electricity for cooling (1)	kWh	−0.03		−0.03		−0.03		−0.03		−0.03	
Post-sterilization	Energy, electricity for fermentation	kWh	2.70E−05		3.50E−05		3.50E−05		3.50E−05		3.50E−05	
	Energy, electricity for maturation	kWh	0.005		0.005		0.005		0.005		0.005	
	Energy, electricity for cooling (2)	kWh	0.003		0.003		0.003		0.003		0.003	
	Energy, electricity for filtration	kWh	0.0002		0.0002		0.0002		0.0002		0.0002	
	Beer	L		0.33		0.33		0.33		0.33		0.33
Packaging	Transport, truck >32 t, EURO 4, to packaging factory	kg. km	133		133		133		133		133	
	Packaging glass, brown	kg	0.22		0.22		0.22		0.22		0.22	
	Label production (polypropylene extrusion)	kg	0.0022		0.0022		0.0022		0.0022		0.0022	
	Cap, steel	kg	0.0026		0.0026		0.0026		0.0026		0.0026	
	Energy, electricity for bottling	MJ	0.009		0.009		0.009		0.009		0.009	
	330 mL beer bottle at brewery	Item		1		1		1		1		1

This included a 3 % smaller acidification, 8 % smaller marine eutrophication, 6 % smaller terrestrial eutrophication, and 2 % smaller resource use energy carriers burdens than *Bly*. However, *Bly* had a significantly lower ($p < 0.05$) climate change footprint than the bean beers, except for *Bn(th)*, for which the impact was comparable, with *Bly* being associated with 0.29 kg CO_2 eq. and *Bn(th)* with 0.28 kg CO_2 eq. (Supplementary Information).

3.2. Attributional LCA with expanded boundaries (feed substitution, rotations modelled)

Aggregated results of the modified Null Hypothesis Significance Tests for the scenario with expanded system boundaries and wheat modelling from this study are recorded in Table 3. When both system boundaries were expanded to include feed substitution and rotations,

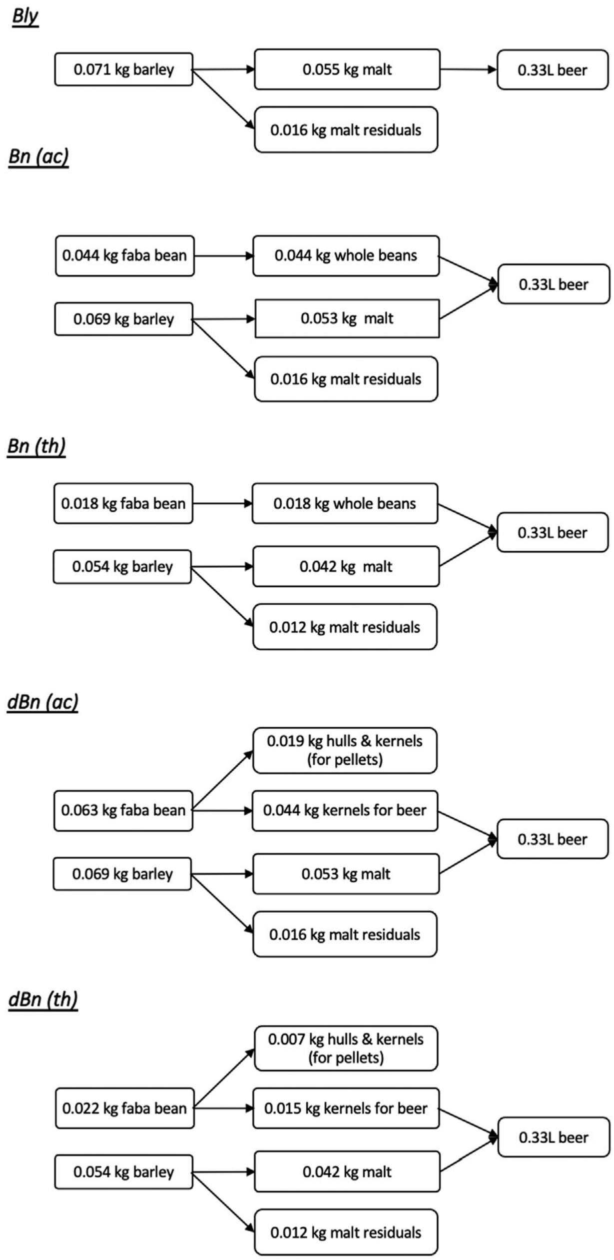


Fig. 3. Faba bean and barley ingredients used to produce one 0.33 L of beer for all products assessed. *Bly* - conventional malted barley beer; *Bn(ac)* - barley-whole bean beer with actual alcohol yields; *dBn(ac)* - barley-dehulled bean beer with actual alcohol yields; *Bn(th)* - barley-whole bean beer with theoretical alcohol yields; *dBn(th)* - barley-dehulled bean beer with theoretical alcohol yields.

Bn (ac) appeared to show more environmental advantages than the other products, with 6 to 8 categories across which results were significantly lower than other beers when feed substitution was modelled (Table 3). As shown in Table 3 and the Supplementary Information, when system boundaries were expanded, *Bn (ac)* had a 10 % lower acidification burden, a 15 % lower climate change burden, and a 50 % lower freshwater eutrophication burden than *Bly*. Both d*Bn (ac)* and d*Bn (th)* showed less favourable results than their whole beans counterparts (Table 3), *Bn (ac)* and *Bn (th)*, suggesting that the dehulling of faba beans for beer does not provide environmental benefits.

Results from the sensitivity analysis where system boundaries were expanded with feed substitution modelled with the Ecoinvent wheat process showed that *Bn (ac)* had more environmental advantages than the other products, with 3 to 8 categories across which results were significantly lower than other beers (Supplementary Information sheet, Sections 1 and 2 of the "S.A. Eco. Wheat" tab). Both *Bly* and *Bn (ac)* had significant environmental sustainability advantages, but across different categories. For example, *Bly* had a 45 % lower marine and 23 % lower terrestrial eutrophication burdens than *Bn (ac)*, while *Bn (ac)* had a 17 % lower climate change, a 77 % lower freshwater ecotoxicity, and 13 % lower photochemical ozone formation than *Bly*.

Table 2
Results of the modified Null Hypothesis Significance Tests for the simple attributional life cycle assessment.

j↓ k→	Bly	Bn (ac)	dBn (ac)	Bn (th)	dBn (th)
Bly		4	11	0	4
Bn (ac)	0		10	0	2
dBn (ac)	0	0		0	0
Bn (th)	6	8	11		8
dBn (th)	0	1	11	0	

The table shows the number of categories across which the mean impact of the "j" product was at least 0.2 standard deviation units significantly lower than that of product "k" when performing the modified Null Hypothesis Significance across the simple attributional scenario (where no feed substitution nor rotations were modelled). *Bly* - conventional malted barley beer; *Bn(ac)* - barley-whole bean beer with actual alcohol yields; *dBn(ac)* - barley-dehulled bean beer with actual alcohol yields; *Bn(th)* - barley-whole bean beer with theoretical alcohol yields; *dBn(th)* - barley-dehulled bean beer with theoretical alcohol yields.

3.3. Process contributions to the total environmental impact

Normalised results in person year equivalents following Product Environmental Footprint (PEF) guidelines (European Commission, 2018b) are recorded in the Supplementary Information file across all scenarios assessed in the study. The impact categories with the highest normalised results were energy use, respiratory inorganics, and acidification across all scenarios.

As shown in Fig. 4, in which process contributions are recorded for all scenarios assessed across six selected categories, packaging was responsible for most of the environmental burdens across most categories for all products. Packaging was associated with between 56 % (*dBn (ac)* in the simple aLCA) and 120 % (*Bn (ac)* and *Bn (th)* with expanded system boundaries, wheat modelled from study) of the total climate change burdens. Packaging was also associated with between 68 % (*dBn (ac)* in the simple aLCA) and 163 % (*Bly* with expanded system boundaries, wheat modelled from study) of the total acidification burdens. The high acidification contribution of the packaging was due to emissions of sulphur dioxide from glass production, which requires high amounts of energy and high temperatures, while the large GHG emissions were due to carbon dioxide emission from fuels and raw materials during packaging glass production. Aside from the high contribution of the packaging step, the high energy use of *dBn(ac)* stemmed

Table 3
Results of the modified Null Hypothesis Significance Tests for the scenario with expanded system boundaries.

j↓ k→	Bly	Bn (ac)	dBn (ac)	Bn (th)	dBn (th)
Bly		0	3	0	2
Bn (ac)	8		6	6	8
dBn (ac)	3	1		2	2
Bn (th)	4	0	3		3
dBn (th)	2	0	2	1	

The table shows the number of categories across which the mean impact of the "j" product was at least 0.2 standard deviation units significantly lower than that of product "k" when performing the modified Null Hypothesis Significance Tests across the scenario with expanded system boundaries (where feed substitution and rotations were modelled where additional wheat produced substituted wheat modelled in this study). *Bly* - conventional malted barley beer; *Bn(ac)* - barley-whole bean beer with actual alcohol yields; *dBn(ac)* - barley-dehulled bean beer with actual alcohol yields; *Bn(th)* - barley-whole bean beer with theoretical alcohol yields; *dBn(th)* - barley-dehulled bean beer with theoretical alcohol yields.

from the faba bean cleaning and dehulling step due to a high electricity use. Besides packaging and dehulling, the stage that was responsible for a high share of environmental burdens in the simple aLCA was barley cultivation. It represented 12–18 % of total acidification burdens, 8–13 % of total climate change, 39–48 % of total marine eutrophication, 27–32 % of total terrestrial eutrophication, and between 34 and 66 % of total land use.

As shown in Fig. 4B and the Supplementary Information sheet (Section 4 of the "S.A. Eco. wheat" tab), the influence of explicit rotation modelling on results varied by impact category and by the product. For example, including the rotation in the system boundaries with wheat (Ecoinvent) increased the climate change burden of the agricultural part of *dBn (th)* by 46 % when compared to the simple aLCA, while it decreased the marine eutrophication burden by 268 %. Across the climate change impact category, the rotation effect provided an environmental saving for *Bly* while it was a burden for the bean beers when the Ecoinvent wheat process was used (Fig. 4B).

On the other hand, modelling feed substitution (Fig. 4B and Supplementary Information, Section 4 of the "S.A. Eco. wheat" tab) always presented environmental savings over the simple attributional modelling presented in Fig. 4A, indicating that the obtained feed from the brewing process had a comparatively lower environmental burden associated to it than the traditional soymeal, and barley feeds. Despite higher climate change savings resulting from a higher amount of feed substitution due to the use of more faba beans in the current beer with dehulled beans (*dBn-ac*), the cleaning and dehulling step of faba beans prevented the corresponding beer from having a lower climate change impact than the other beers, being associated with 0.09 kg CO_2 equivalents, representing around 39 % of the beer's total climate change burdens (Fig. 4B).

4. Discussion

The first hypothesis "The environmental impact of the barley-bean beer is significantly lower than that of a conventional malted barley beer, potentially providing a more environmentally sustainable alternative to traditional beers" was validated across some scenarios. Indeed, the potential environmental impacts ranking of the beers varied drastically depending on the adopted system boundaries. Across no modelling approach (simple aLCA or aLCA with expanded boundaries), however, did the barley beer show overall lower environmental burdens than all the faba bean/barley beers across most of the categories. It is important to note that the actual (ac) barley-faba bean beers calculations use data from beer production under non-optimum conditions and, as a result, poor alcohol yields from the faba beans were seen. Recent research investigated the optimal conditions for using faba bean kernels as a brewing material (Black et al., 2020). However, this non-optimal condition was shown to be advantageous in this LCA when system boundaries were expanded, as a higher required amount of faba beans resulted in higher environmental savings through feed substitution. This saving is however not applicable to the beer using dehulled faba beans, as the dehulling step requires large amounts of energy. On the other hand, producing a beer with whole beans may pose flavour challenges which kernel-only beer would not (Black et al., 2019). Using paled hulled, low-tannin beans may also avoid that flavour risk.

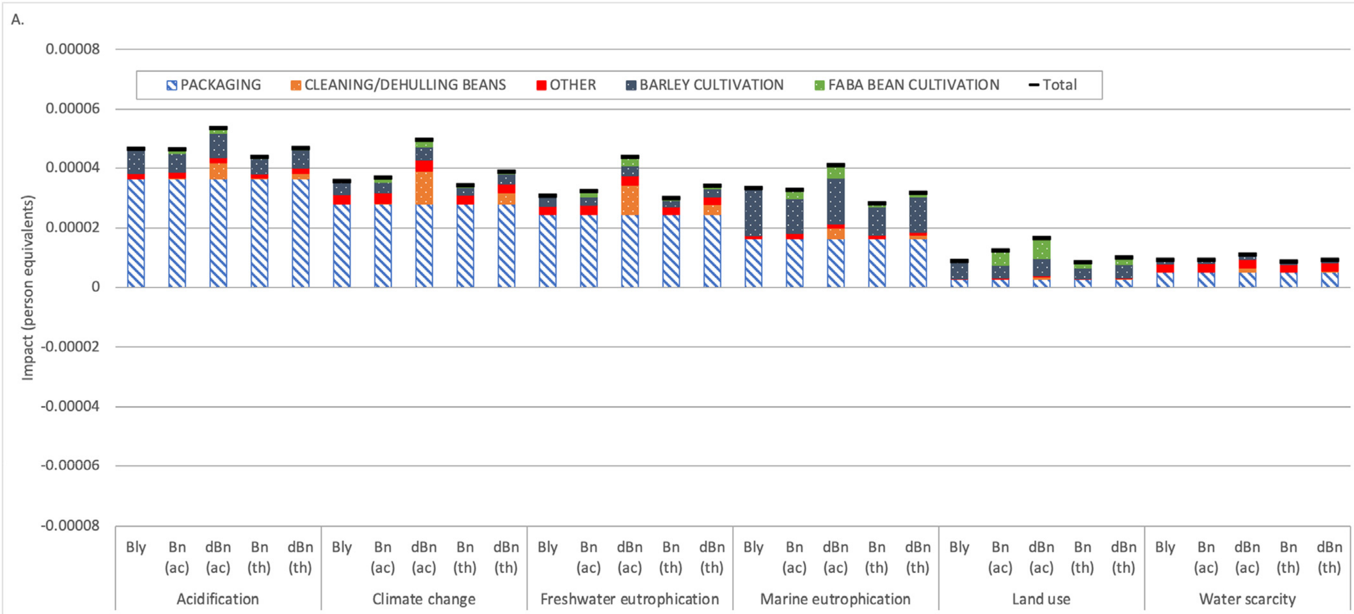
The second hypothesis "The expansion of system boundaries to account for entire crop rotations lowers the environmental impact of bean-barley beer" was also validated across certain scenarios. The inclusion of entire rotations in the system boundaries ensured that the benefits of legume integration in cropping systems were accounted for following from studies showing the potential importance of such effects (Costa et al., 2020). Environmental advantages and disadvantages of including rotations in the system boundaries varied widely depending on the impact category and beer product assessed. It is worth noting, however, that current LCA methodologies do not fully capture environmental sustainability of agri-food systems, and can be improved in the areas of biodiversity (Teillard et al., 2016; Winter et al., 2017). Integration of faba beans into crop rotations could provide crop-diversification benefits (Zornoza et al., 2021). Fauna such as bumblebees, honeybees, and butterflies use faba beans as a habitat (Bockholt, 2018). These potential advantages would need to be assessed through a wider sustainability lens, and such multi-disciplinary tools are being developed in European-funded projects such as RADIANT (RADIANT, 2022).

The third hypothesis "The expansion of system boundaries to account for soybean and barley feed substitution with beer co-products lowers the environmental impact of all beers" was validated. Regarding the barley-bean beer types, with current alcohol yields, a barley-whole bean beer could also offer environmental savings when feed substitution obtained from the use of co-products is modelled as well as rotations due to a higher protein content in the brewing co-products. This suggests that the use of faba beans for an additional starch source for beer holds potential to provide more sustainable feed options for Europe, providing more co-products to be utilised as domestic feed sources, as many of them are already entirely exploited (Karlsson et al., 2020). The provision of an enhanced high-protein feed to replace imported soy linked with deforestation is of high interest, as there are >150 countries and 500 companies that recently announced their zero deforestation commitments (ZDCs) (Donofrio et al., 2017). Soy imports represent one third of all protein used in the EU for animal feed (Karlsson et al., 2020), and the EU Farm to Fork Strategy aims for feed production within Europe to avoid dependency from other countries and alleviate land demand in deforestation areas (European Commission, 2020). However, a consequential LCA is required to evaluate whether a change in demand for soybean meal would affect production of oil from soybean or other crops which have lower yields, thus affecting the overall environmental effects balance of this change (Dalgaard et al., 2008).

While Amienyo and Azapagic (2016) recognised that barley production was an environmental hotspot in their LCA study of beer in the UK, concluding that this phase should be targeted in priority, they could not provide any quantification of the environmental impact of any action that could be taken to reduce environmental damage due to their use of an aggregated process from secondary data on European barley. By using a rotation generator (Reckling et al., 2016b), we managed in our study to use detailed, disaggregated data on barley production and explored another approach to reducing the use of fertilisers through the integration of legumes and entire cropping rotations in the system boundaries. This novelty and modelling approach should be considered in future LCA studies of other beers, as it was shown here to provide environmental benefits.

Amienyo and Azapagic (2016) found that raw material production (barley and hops, malting, sodium hydroxide, sulphuric acid, and carbon dioxide) was the main environmental hotspot of beer production, being associated with around 0.066 kg CO_2 equivalents per 0.33 L filled bottle of beer. This is in line with the findings of our study, since the cultivation of barley and its malting was associated with 0.051 kg CO_2 equivalents per 0.33 L filled bottle of conventional malted barley beer.

The categories 'resource use, energy carriers' and 'respiratory inorganics' were those with the highest normalised results, suggesting that these burdens should be tackled in priority. These hotspot categories were also identified in previous studies (Cordella et al., 2008; Melon et al., 2012). The use of "greener" energy sources may decrease the overall energy use burdens of all beer products. These sources will become more dominant as countries such as the UK move towards Net Zero targets by 2050, shifting away imported fossil fuels and towards low carbon technologies (Department for Business, 2021).



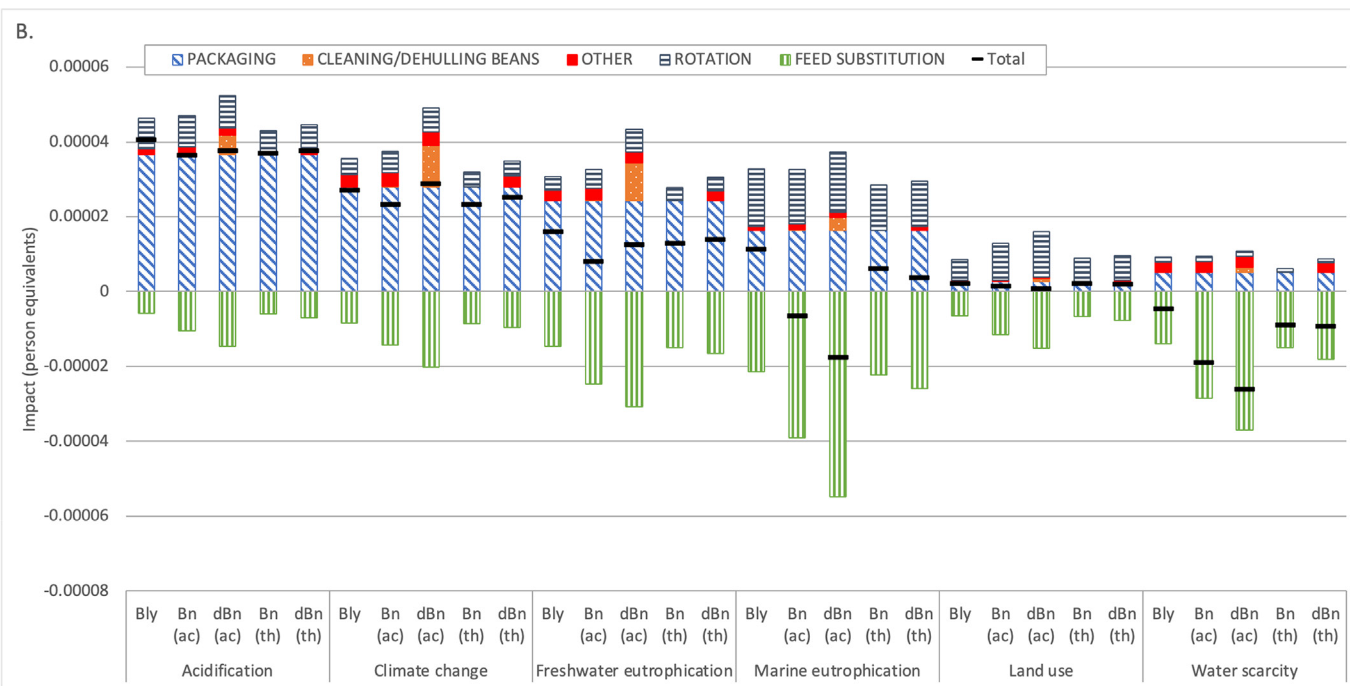


Fig. 4. Process contributions of the environmental burdens in person equivalents associated with all scenarios assessed across the acidification, climate change, freshwater and marine eutrophication, land use, and water scarcity categories for the simple attributional life cycle assessment (A) and attributional life cycle assessment with expanded system boundaries with wheat from the study (B). *Bly* - conventional malted barley beer; *Bn(ac)* - barley-whole bean beer with actual alcohol yields; *dBn(ac)* - barley-dehulled bean beer with actual alcohol yields; *Bn(th)* - barley-whole bean beer with theoretical alcohol yields; *dBn(th)* - barley-dehulled bean beer with theoretical alcohol yields.

Moreover, this study showed that the scale of the land savings from feed substitution can nearly equal or be bigger than land requirements, as across the scenarios where agricultural rotations were modelled. To our knowledge, this was the first time such land savings were shown for a beer LCA, due to the inclusion of rotations and multi-functionality of the beer value chain. This reflects relatively low protein and metabolisable energy yields from soybeans in Latin America when compared to higher protein and metabolizable energy yields from barley and faba beans in the UK on a per hectare basis. Current energy policies may impede realisation of this advantage because energy-based subsidies for anaerobic digestion drive high-value co-products into low-value energy generation. A full consequential LCA should however be performed to have further interpretation on land use.

The packaging adopted for these beers was the major contributor to the environmental impact of all beers assessed across most categories. Other studies have come to the same conclusion, such as in Koroneos et al. (2005) who looked at bottles made from recycled and virgin glass, and Mata and Costa (2022) who highlighted the environmental benefits of using reusable glass bottles. Melon et al. (2012) compared the environmental performance of using single use or reused bottles and kegs, and found that the reused keg approach had the lowest environmental burden overall, followed by the reused bottle approach. Morgan et al. (2022) found that kegs and reusable glass bottles were superior to single use bottles from an environmental sustainability perspective. Amienyo and Azapagic (2016) highlighted environmental trade-offs between steel, glass, and aluminium cans, with the glass bottles performing worse across most of the categories assessed. Cordella et al. (2008) also found that returnable stainless-steel kegs had a lower environmental impact overall than glass bottles.

5. Conclusions

We performed a simple and boundary-expanded attributional LCA of a novel Scottish beer, in which part of the conventional malted barley is substituted with faba bean and compared it with a traditional malted barley beer across the sixteen Product Environmental Footprint-recommended categories. Besides the fact of bringing novelty to a traditional product, this study showed that the partial substitution of malted barley with legumes into a brewing recipe could be associated with lower environmental burdens. The simple attributional LCA indicated that the barley-whole faba bean beer with optimised alcohol yields had the best environmental performance overall. When system boundaries were expanded to account for animal feed substitution by beer co-products, as well as for agricultural rotation effects of a switch to barley-bean beer, the current beer made with whole faba beans showed significant environmental advantages over the other beers across some categories, with a 15–17 % lower climate change burden than the traditional barley beer, thanks to a higher protein content in the co-products that can substitute animal feed. With different results arising from different modelling approaches, this study suggests that several scenarios should be assessed when performing a LCA of beer: (i) simple attributional LCA and (ii) attributional LCA with expanded system boundaries to include the use of co-products as animal feed, to understand the potential of brewers to offer local alternatives to imported soy-based animal feed with high environmental burdens, and to incite other stakeholders in the value chain to consider this option. Entire crop rotations should also be fully included in the LCAs of beer to capture a more accurate picture of the agricultural stage and identify possible reductions of the associated environmental burdens. Land use should also be assessed when boundaries are expanded to identify potential land savings.

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.

Acknowledgements

We are grateful to Andrew Barnett from Barney's Beer Ltd. for providing the majority of the life cycle inventory data for the beers, to Justin Barrett from Askew & Barrett Ltd. for providing the information specific to the life cycle inventory of the faba bean hulls, to Bottled In Cumbria for providing data on packaging, and to Roger Vickers and Steve Belcher from PGRO for providing information on faba bean cultivation in the UK. Funding for this research was also provided by the EU-H2020 framework via the Research and Innovation Actions www.TRUE-project.eu, and www.RADIANTproject.eu Grant Agreement numbers 727973, and 101000622, respectively. The James Hutton Institute is supported by the Rural & Environment Science & Analytical Services (RESAS), a division of the Scottish Government.

Appendix A

Table A1
Fertilizer application rates for each rotation crop in this study, in kg/ha. Extracted from (Reckling et al., 2016b).

	N	P_2O_5	K_2O
Winter wheat	203	66	72
Winter wheat after legume	193	66	72
Winter barley	181	66	72
Faba bean	0	38	50

Table A2
Crude protein and metabolizable energy contents of faba bean, soybean, and barley products for ruminants, and amount of soybean meal and barley grain substituted (negative values) per kg dry matter product using linear optimisation. NA stands for non-applicable.

	Dry matter (% fresh matter)	Crude protein (kg)	Metabolizable energy (MJ)	Substituted soybean meal (kg)	Balancing barley grain (kg)
Faba bean pellets	86.6	0.258	12.4	0.36	0.51
Soybean meal feed	88.0	0.552	13.4	NA	NA
Barley grain feed	87.1	0.118	12.4	NA	NA
Malt residuals pellets	89.9	0.235	9.7	0.35	0.33
Bean kernels	86.6	0.312	14.0	0.45	0.54
Whole beans	86.6	0.290	13.3	0.41	0.52
Barley spent grains	87.1	0.258	9.90	0.40	0.30

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2022.09.019.

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