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Environmental and economic impacts of using brewers spent grains for animal feed and anaerobic digestion

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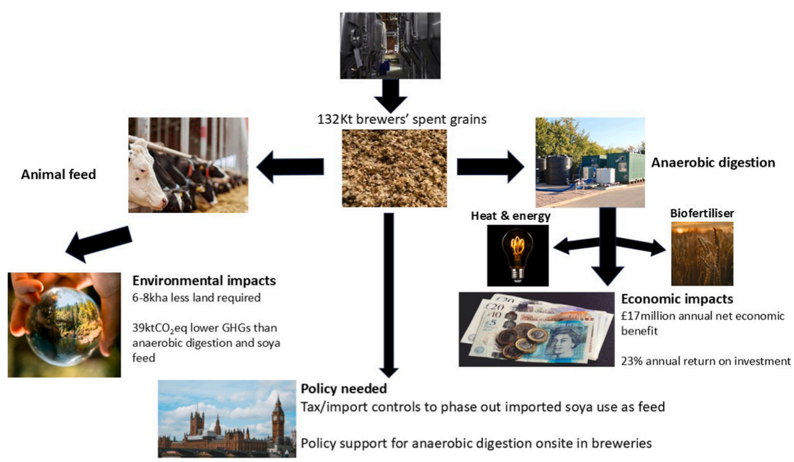
HIGHLIGHTS

- AD of UK BSG provided a net economic gain of 16 million GBP.
- AD of BSG increased GHGs by 39 Kt of CO_2eq if soya was used as a replacement feed.
- AD of BSG decreased GHGs by 27 Kt of CO_2eq if field beans were the replacement feed.
- AD of BSG increased land requirements which could increase GHGs.
- Cattle growth rates and enteric fermentation had substantial implications on GHGs.

GRAPHICAL ABSTRACT



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ABSTRACT

Over 130,000 tonnes of brewer's spent grains are generated annually in the UK. Most brewer's spent grains are utilised as a low-carbon animal feed, although anaerobic digestion provides economic benefits, through generating heat, energy, and biofertilizer. This study addresses a research gap by comparing both the economic and environmental impacts of using brewer's spent grains for animal feed versus anaerobic digestion. Specifically, it explores replacing brewer's spent grains-derived cattle feed with either high-carbon soya or UK-grown field beans, including dietary implications on methane generation and indirect land use change.

Life Cycle Assessment and Life Cycle Costing were used to evaluate the environmental and economic impacts of utilising all brewer's spent grains generated in the UK for anaerobic digestion, as opposed to feeding cattle. Anaerobically digesting brewer's spent grains and using soya feed to replace brewer's spent grains as a cattle feed increased greenhouse gases by 39 Kt of CO_2eq, while a field bean diet reduced emissions by 27 Kt of CO_2eq.

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Additionally, the brewer's spent grain cattle diet required 6 and 8 thousand hectares less land than the field beans and soya diets respectively. However, anaerobic digestion of brewer's spent grains proved more profitable, offering an annual net economic benefit of £16 million. Thus, policy mechanisms such as an eventual ban could be introduced in order to phase out use of imported soya as an animal feed in the UK. Moreover, additional consultancy support, or interest free loans could be provided to facilitate breweries incorporating onsite anaerobic digestion.

Key abbreviations

BSG	Brewers' spent grains
AD	Anaerobic digestion
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
NPV	Net Present Value
ROI	Return on investment
LUC	Land use change

1. Introduction

1.1. Background

The brewing process generates between 17 and 20 kg of brewer's spent grains (BSG) per hl of beer in breweries during the mashing process (Milew et al., 2022). BSG is high in protein (21 % of dry matter), and therefore can be used as animal feed to replace other high-protein feeds (Christodoulou et al., 2025). BSG can be used wet (as generated) and is typically collected by local cattle farms and used as cake for ruminant feeds. It can also be dried by the brewery and collected by farmers to feed monogastrics (Stahn et al., 2023). A further use of BSG is energy generation (Petit et al., 2020). This can include pretreatment steps to dry the high-moisture feedstock before combustion, or gasification of the dried BSG, or the further pretreatment step of pyrolysis before combustion to increase fuel qualities (Chetrariu and Dabija, 2020). Gasification can provide a low cost option for generating combustible gas from BSG (Ferreira et al., 2019). Furthermore, anaerobic digestion (AD) provides a utilisation pathway for the high-moisture BSG which does not require pre-treatment. AD can convert BSG into a combustible gas and is becoming an increasingly popular method for treating BSG (Sganzerla et al., 2021). BSG can be anaerobically digested, using an inoculum containing methanogens to break carbon down into a biogas which includes methane and carbon dioxide, while a solid and liquid biofertilizer called digestate is also produced (Buller et al., 2022). The biogas can be used directly as a low quality cooking fuel, or can be upgraded to produce biomethane (Davison, 2023). This biomethane can be used as a transport fuel (Browne et al., 2011), but is typically combusted to generate heat, or both heat and energy using a combined heat and power system (Davison et al., 2022, 2023).

Approximately 132 kilotonnes of BSG are generated in the UK every year from the brewery industry (Morgan et al., 2021; Milew et al., 2022). The majority of BSG are sold, or collected for free as a cheap, low carbon source of animal feed for cattle and other animals, with factors such as location (urban, or rural), as well as brewery size (small, medium, or large) affecting how BSG is utilised. For urban breweries, small and medium breweries (batch capacity less than 2000L) around 80 % of BSG is used as animal feed, and less than 10 % is used for AD, with the rest mostly being composted, while for large urban breweries (batch capacity less than 2000L) almost 100 % of BSG is used as animal feed. With regards to rural breweries, almost 100 % of BSG is used as animal feed, with only negligible amounts used for AD, or other uses (Kerby and Vriesekoop, 2017).

Utilising BSG as an animal feed leads to considerable greenhouse gas mitigation through substituting high carbon feeds such as those derived from soya (Petit et al., 2020). Moreover, recent studies have found that BSG (Duthie et al., 2015; Williams et al., 2014), as well as field beans (Johnston et al., 2019) could reduce methane emissions in cattle from enteric fermentation, further contributing to mitigation efforts. The remaining BSG is often used to generate low-cost heat, energy and biofertilizer through AD (Kerby and Vriesekoop, 2017). Following the conflict in Ukraine, and associated rising energy, heat and fertiliser costs, there is an increasing amount of pressure on breweries to reevaluate BSG utilisation pathways, and consider favouring AD, in place of animal feed (Davison et al., 2023). The study presented here addresses this requirement, through the application of Life Cycle Assessment (LCA) and Life Cycle Costing (LCC).

1.2. Key benefits of using brewer's spent grains as animal feed

Utilising BSG as a cattle feed offers numerous benefits. It is often straightforward for breweries to arrange for local farms to pick up the material, something that only requires low transport distances and does not require any treatment facility (Kerby and Vriesekoop, 2017). It also provides livestock farms with a cost-effective, reliable, nutritious source of feed, thus reducing costs and contributing to healthy cattle diets (Williams et al., 2014). Moreover, using BSG can help to substitute high carbon animal feeds such as soya (Petit et al., 2020). Soya makes up a large proportion of the high-protein component in cattle diets in the UK and has a large environmental footprint due to the extensive deforestation that has occurred in South America to free up land for cultivation (EFECA, 2020). Even when animal feed is not associated with deleterious land use change (LUC), large environmental impacts can be attributed to the fertiliser and machinery usage, associated with feed production, processing, storage and transportation (Petit et al., 2020). As BSG is an industrial by-product that is generated through beer production, its environmental impacts are substantially lower than for other feeds (Reckmann et al., 2016) and may lead to a reduction in indirect LUC (Sandström et al., 2022). When included in assessments indirect LUC can substantially impact the climate change impacts of different food-based scenarios (Smith et al., 2019). Altogether, using BSG as an animal feed provides farmers with a low cost, low carbon alternative to expensive, high-carbon feeds such as soya (Williams et al., 2014; Petit et al., 2020), while allowing breweries to have their BSG removed without requiring investment in on-site treatment facilities (Kerby and Vriesekoop, 2017).

In addition to the environmental benefits of substituting high carbon animal feeds, previous publications have shown that BSG has the potential to reduce methane emissions in cattle farming, which is the greatest source of GHGs in beef production (Duthie et al., 2015; Williams et al., 2014). A large proportion of methane from cattle is emitted as enteric fermentation, where methane is released from cattle as gas while microorganisms break down carbohydrates into simple molecules for absorption into the bloodstream (Buccioni et al., 2015). On the one hand, feeding cattle BSG has been found to reduce enteric methane by around 17 %, due to its high oil content (Duthie et al., 2015), although methane reduction from changing dietary components may be dependent on the nutritional approaches, such as replacing a protein source or silages (Duthie et al., 2015; O'Brien et al., 2010), as well as the different nutrient composition and inclusion levels (Johnston et al., 2019). On the other hand, the high tannin and starch content in alternative high protein cattle feeds such as field beans can also reduce enteric methane (Johnston et al., 2019). Enteric methane implications from BSG and alternative cattle diets could play a key role in determining GHG benefits from using BSG as an animal feed (Williams et al., 2014; Johnston et al., 2019).

1.3. Key benefits of using brewer's spent grains for anaerobic digestion

Since the invasion of Ukraine, heat, energy, and fertiliser prices have risen sharply in the UK, alongside a drive to increase energy security in response to supply chain shocks (Mbah and Wasum, 2022; Benton et al., 2022). Specifically, a movement away from using Russian natural gas (with natural gas being the main heat source in the UK, a key energy source and a key component in the chemical fertiliser production process) substantially drove up heat, energy and chemical fertiliser prices in the UK. As AD can generate heat, energy and biofertilizer, which can substitute natural gas, UK grid energy and chemical fertilisers, this has resulted in vastly improved economic benefits from the utilisation of BSG within AD plants (Davison, 2023). Furthermore, the recycling of BSG is in-line with the current drive for circular economies, and there is considerable potential for BSG to be used onsite to power the brewing process, while the nutrients in the digestate derived from AD could be used for growing crops (Sganzerla et al., 2021).

Breweries can have their BSG collected by specialist waste management companies where the BSG is transported to a centralised site for large-scale AD (Kerby and Vriesekoop, 2017). This typically requires longer transport distances than when BSG is utilised as an animal feed, but similarly breweries do not require any treatment facilities and AD companies procure a high quality AD feedstock usually for free (Kerby and Vriesekoop, 2017). Conversely, breweries can anaerobically digest BSG on-site (Buller et al., 2022). This usually requires substantial initial outlay to install the AD facilities, but avoids transport requirements and can provide considerable economic benefits by producing heat and/or energy that can be used onsite, as well as a biofertilizer that can be used to produce ingredients for brewing (Sganzerla et al., 2021). Altogether, collection of BSG and offsite utilisation is often highly beneficial for AD companies, but represents a low risk, low reward strategy for breweries (Kerby and Vriesekoop, 2017), while onsite AD represents a high-risk, high reward strategy for the breweries (Sganzerla et al., 2021).

1.4. Previous studies assessing environmental and economic impacts of utilising brewer's spent grains

1.4.1. Greenhouse gas implications of utilising brewer's spent grains

The animal feed-route has been found to lead to substantially lower GHG impacts when compared to AD. Specifically, Petit et al. (2020) found AD of BSG to be a net contributor to GHG emissions, whereas BSG feed was calculated to lead to a net GHG mitigation, with the GHG mitigation being higher if the BSG was used to replace the carbon-intensive soya component in cattle, as opposed to the relatively less carbon-intensive rapeseed in a pigs diet. The same study also calculated a better performance across all environmental indicators including land use and water depletion when BSG was utilised as an animal feed as opposed to an AD feedstock. This study did not consider environmental implications associated with animal feed nutrition however, with different livestock diets resulting in different growth rates and enteric methane emissions (Christodoulou et al., 2025), which, if considered, could greatly influence climate and other environmental impacts. Utilising BSG to substitute wheat in cattle diets only reduced the climate impact of milk from dairy cows by 2 %, with the mitigation resulting from reduced enteric methane, as well as emissions from the production of cattle feed (Williams et al., 2014). It is possible that this overall GHG reduction would be greater if the BSG was used to substitute higher-carbon feeds such as soya (Johnston et al., 2019).

1.4.2. Land use implications of utilising brewer's spent grains

Additionally, studies have found BSG to have lower land use impacts when used as an animal feed rather than for AD, as producing animal feed requires more land than producing the heat, energy and fertiliser products that can be substituted by AD (Reckmann et al., 2016; Petit et al., 2020). Besides the direct benefit of having lower land requirements from utilising BSG as an animal feed as opposed to AD, indirect LUC (such as conversion of grassland, or forest to cropland, or conversion of cropland to grassland, or forest) associated with these land requirements could have substantial impacts on climate change (Smith et al., 2019).

1.4.3. Economic implications of utilising brewer's spent grains

Economic assessments suggest that AD of BSG could provide substantial benefits. A previous study of a digester within a Brazilian brewery revealed a four-year payback period for capital and installation costs. The same study highlighted alternative revenue streams through the sale of biofertilizer and avoided costs of heat and/or energy (Sganzerla et al., 2021). However, as the market value of BSG as an animal feed is very low in the UK, compared to products that AD outputs can substitute (energy, natural gas and fertilisers), selling BSG as an animal feed has comparatively low economic opportunities (Redman, 2022). Moreover, evidence indicates that most breweries in the UK receive no payment for the BSG collected by farms or other companies for animal feed and many may even have to pay to have it collected. Moreover, if the breweries generating the BSG do not utilise it onsite for AD, then the BSG may be collected for free by an AD company, with the AD company achieving the economic benefits associated with AD of BSG (Kerby and Vriesekoop, 2017).

1.5. Aims and objectives

While previous studies have looked at either the environmental, or economic impacts of utilising BSG as an animal feed or AD feedstock, to the author's knowledge, no study to date has compared both the economic and potential environmental impact reduction opportunities for these different utilisation pathways, in a UK context. Moreover, when comparing the potential environmental impacts of utilising BSG as an animal or AD feed, previous research has failed to consider the GHG implications of feed on enteric methane generation. Additionally, recent cost increases in fuel and fertiliser, associated with the conflict in Ukraine, warrant an updated economic assessment to understand implications on the economic performance of the utilisation of BSG as an AD and animal feed. To address this knowledge gap, this paper explores the economic and environmental opportunities and risks associated with anaerobically digesting brewer's spent grain (BSG) in the UK. The overall aim is to compare the economic viability and potential environmental impacts of using BSG as a feedstock for AD versus its current primary use as animal feed. The specific objectives of the study are as follows:

- To understand the environmental trade-offs associated with different BSG utilisation pathways.
- To compare the economic implications of the different BSG utilisation pathways.
- To quantify the GHG and land use implications of different BSG utilisation scenarios.
- To outline potential BSG utilisation strategies for the UK.

To achieve the above objectives, we use a combined Life Cycle Costing (LCC) and Life Cycle Assessment (LCA) to determine impacts and identify opportunities for improvement within the agriculture and food sector.

2. Methodology

2.1. Methods outline

A quantitative assessment of environmental and economic impacts was made per kg of beef liveweight gain at sale. These outcomes were then scaled up to a “100 % uptake in the UK” level, for the specific utilisation pathways assessed. The assumptions in the methodology are stated in more detail in the Supplementary Material.

2.2. Methodological framework

The methodology comprised of six distinct processes: 1) preliminary data collection; 2) calculating LCA and LCC inputs; 3) calculating LCA impacts; 4) calculating LCC impacts; 5) conducting sensitivity analyses for the LCA and LCC; and 6) analysing and discussing the results (see Fig. 1).

As a preliminary data collection stage, key data was collected from the associated cattle trial (Christodoulou et al., 2025) including dietary components, growth rates and methane generation from BSG and alternative diets. Additionally, data was collected for expected AD outputs such as methane and biofertilizer generation, total BSG generation in the UK, as well as market costs associated with the use of BSG for AD, or feed. These data were formatted and converted into the required LCA inputs (energy and material flows) for direct integration into the LCA software (SimaPro). LCC inputs were also calculated on a per-tonne-of-BSG basis, including AD costs and revenues, as well as feed savings. Environmental impacts were then calculated for the defined scenarios and GHG values were adjusted to IPCC 2019 values. Furthermore, land use and climate change impacts were scaled up to consider

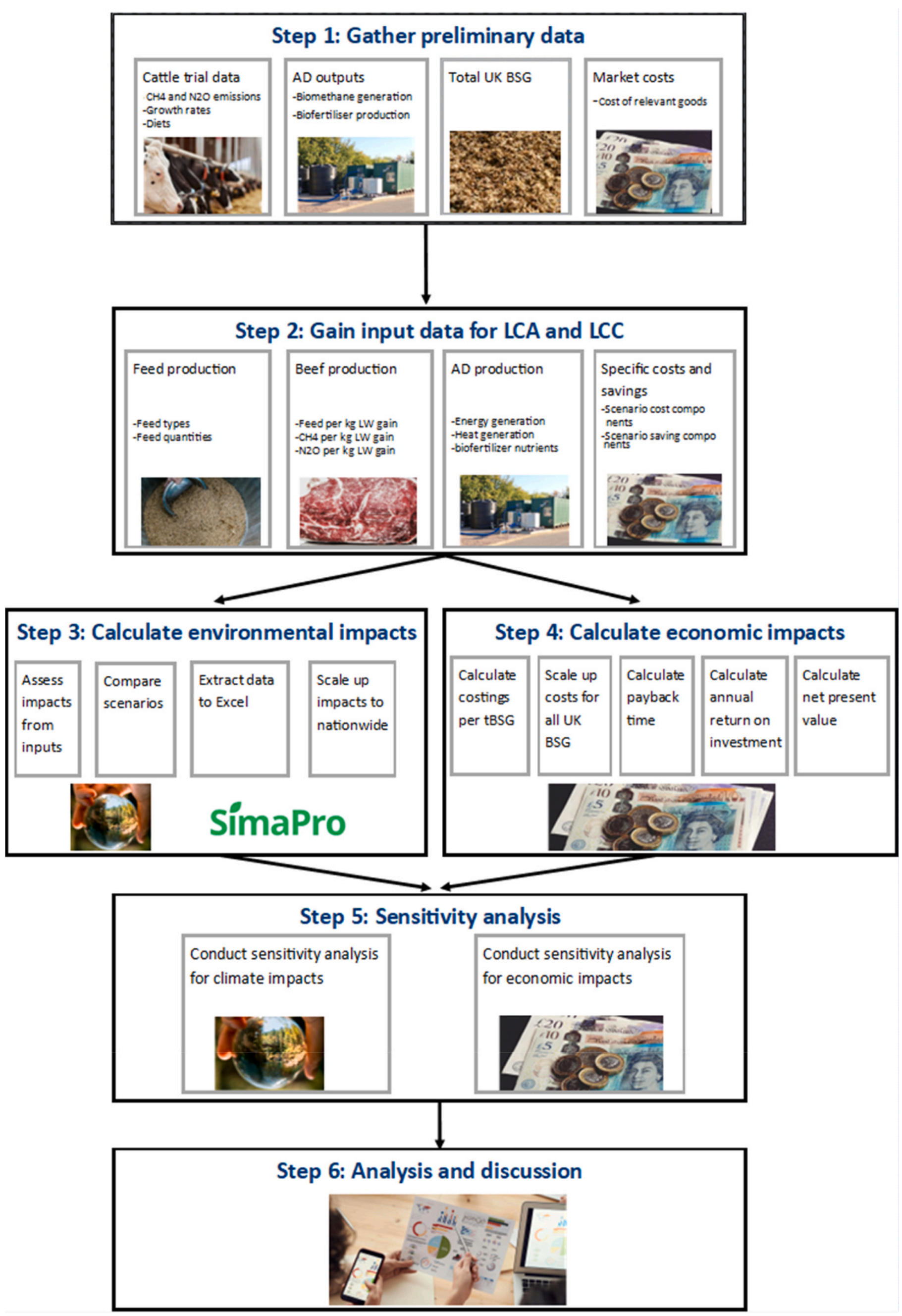

Fig. 1. Methodological framework used in this study.

impacts if all UK BSG were to be utilised. Concurrently, the LCC was calculated, utilising input data on specific costs, revenues and savings. Sensitivity analyses were then conducted for both GHG and economic impacts, before the results were further analysed and discussed.

2.3. Brewer's spent grains utilisation pathways

The study assessed three BSG utilisation pathways which are detailed in Fig. 2. Scenario 1 (S1) was based on the most common BSG utilisation strategy of using BSG as an animal feed, specifically to make up the high-protein component in the diet of beef cattle (BSG feed scenario) which can reduce enteric methane by up to 17 % (Duthie et al., 2015). Scenario 2 (S2) involved AD of BSG, with the high protein component of the cattle diet instead coming from soya (BSG AD soya scenario). Scenario 3 (S3) again involved AD of BSG, but in this case, the high protein component of the cattle diet was sourced from UK-grown field beans (BSG AD field beans scenario). The field beans diet may also reduce enteric methane due to its higher starch content, relative to BSG and soya (Johnston et al., 2019; Christodoulou et al., 2025). The anaerobically digested BSG would produce heat and energy from biomethane, generated using a combined heat and power (CHP) boiler, while liquid and solid bio-fertilizer would be produced in the form of digestate.

For the scenarios where BSG is anaerobically digested (S2 and S3), BSG generated biogas is assumed to substitute natural gas, as well as UK National Grid energy. Moreover, the N in digestate is assumed to substitute urea (Davison et al., 2023), a commonly used N fertiliser that is often substituted by digestate (Chatzistathis et al., 2022), and the P is assumed to substitute P_2O_5. For the economic assessment, it was assumed that the liquid digestate substituted urea and the solid digestate substituted green waste compost (Davison, 2023).

For S1 (BSG feed scenario), the BSG makes up the high protein component of a carefully designed cattle diet (Ewing, 1997). As close to 100 % of BSG generated in the UK is currently utilised as an animal feed, this is effectively the baseline scenario. For S2 (BSG AD soya scenario), the BSG is replaced by the high carbon soya feed, as this is a common component of UK beef cattle diets (EFECA, 2020). For S3 (BSG AD field beans scenario), BSG is replaced by field beans, as this is a well-used domestically sourced alternative to soya in the UK cattle diet (Wilkins and Jones, 2000). The exact quantity of soya and field beans required to replace the BSG was based on protein, energy and general nutritional recommendations to ensure that there was sufficient BSG to replace soya, or field beans (Christodoulou et al., 2025). For the environmental assessment, the additional feed impacts of growing soya (S2), or field beans (S3) is accounted for when compared to using BSG as feed (S1). There is potential additional impact mitigation from the field beans, soya beans (Johnston et al., 2019) and BSG (Duthie et al., 2015)

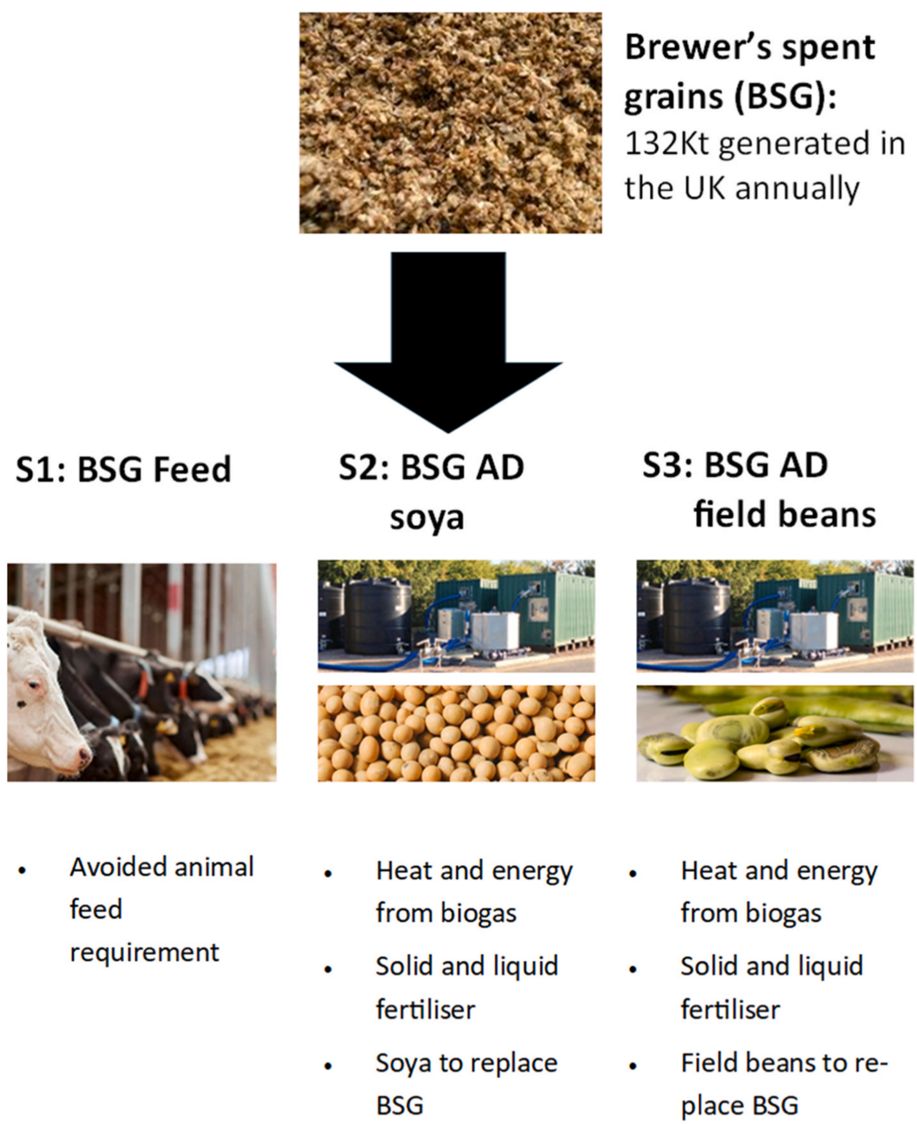

Fig. 2. Utilisation scenarios of brewer's spent grains explored in this study.

reducing methane from enteric fermentation. The specific diets per kg LW gain are listed in Supplementary Material Table A3. For the economic assessment of the BSG scenario, it was assumed that BSG would be directly sold to farmers at market value of 45 GBP as an animal feed, although many companies currently collect BSG for free from breweries (Redman, 2022). For the economic assessment of the AD scenarios (S2 and S3), it was assumed that sufficient anaerobic digesters would need to be purchased and installed by breweries to process all UK BSG. Running costs associated with maintenance, materials, and staffing of new anaerobic digesters were also estimated. Additionally, it was assumed that heat, energy and biofertilizer were sold at the UK market value (Davison, 2023).

Growth rates (kg/day) and enteric methane generation (g/day) for the different cattle diets were taken from a cattle trial conducted by Christodoulou et al. (2025). This involved 3 adaptation weeks followed by 16 intensive measurement weeks of 24 Aberdeen Angus x Holstein beef steers and heifers over 9 months old and at the most productive stage of their lifecycle. Eight cattle were fed on the BSG diet. Eight were fed on the field beans diet, a typical low carbon source of the high-protein component in cattle feed in the UK. A further eight were fed on the soya diet, a typical high carbon source of the high-protein component in the UK. Emissions for nitrous oxide, as well as methane from manure management were calculated using IPCC tier 2 equations using the assumptions and equations summarised in Table 1, Table 2 and within the Supplementary Material (IPCC, 2019). The cattle growth rates were very high, due to the cattle being housed at their most productive period (Alonso et al., 2018).

2.4. LCA goal and scope

Attributional LCA methods were used to compare the potential environmental impacts of using BSG as an AD feedstock, or as a cattle feed. The functional unit (FU) used was 1 kg of beef cattle liveweight gain at the farm gate. The LCA excluded all impacts before the point of BSG generation and all impacts after the point of end usage. This was due to the comparative impacts of the different utilisation pathways of BSG being the focus of the research. Consequently, brewery processes before the creation of BSG and on farm processes before or after beef fattening were considered irrelevant, as they are not likely to differ under the various BSG utilisation pathways (Fig. 2). The system boundary is illustrated in Fig. 3 and described in more detail in Table 1, including detailing of the different components that are included and excluded in the assessment with 5* and 6* referring to scenarios that involve AD of BSG only (S2 and S3). The asterisks refer to stages that are only relevant to some, but not all scenarios (5* and 6* are only relevant to the scenarios involving AD). Dashed lines refer to energy flows, while solid lines refer to material flows.

Data came from a mixture of literature sources, supplier quotes and animal trials (Christodoulou et al., 2025) with some figures on livestock emissions and AD-derived GHG mitigation being calculated using formulas and equations from the literature. Lifecycle inventory data are summarised in Table 2 and shown in greater detail in the Supplementary Material Table A1. Data were analysed using SimaPro software (v9.3) using inventory databases from Ecoinvent 3.0 and Agribalyse 3.1 where specific impacts were not calculated. The environmental impact categories were calculated using the ReCiPe midpoint (H) method (V1.04/World, 2010), as this provided a harmonised and established method to convert life cycle inventories to a limited number of lifecycle impact scores including global warming potential, water use, land use and more, over the commonly assessed 100 year impact period (Huijbregts et al., 2017). Data was extracted from SimaPro to Excel where figures for global warming potential relating to methane and nitrous oxide were adjusted to align them with the most recent IPCC methodology (IPCC, 2019).

Environmental impacts were scaled up by estimating the total maximum liveweight (LW) gain possible from utilising all BSG available in the UK for the high-protein component in cattle feed. This was in-line with the assumption that all BSG was currently used as cattle feed in the UK, although a small proportion is used to feed other animals or treated in other ways in actuality (Kerby and Vriesekoop, 2017). Firstly, BSG generation in the UK, was calculated based on total beer production in hectolitres (hL) (Morgan et al., 2021) and typical BSG generation per hL (Milew et al., 2022). It was estimated that 42 million hL of beer generated 131.7 Kt of BSG in the UK annually based on 1 hL of beer generating 20 kg of BSG (Milew et al., 2022). Moreover, the BSG diet

Table 1
Summary of input data and associated outputs in the Life Cycle Assessments presented in this study (* excluded generation of BSG and Slaughter House and packaging from the LCA, as out of scope).

Life Cycle Assessment (LCA)		
Input data	**Calculations/input values**	**Associated outputs**
1. Generation of BSG*		
Total beer produced in UK annually, kg BSG per hl beer	*Total beer* × *kg BSG per hl beer*	Total annual BSG generated in UK
2. Feed production and fattening		
Feed components and quantities per kg LW gain	See Supplementary Material A3	Environmental impacts from animal feed
3. Beef		
Energy for lighting (UK grid energy)	0.72 *kWh* ÷ *kg liveweight*	Environmental impacts from energy use
Diesel for manure management	0.42*Kg* ÷ *kg liveweight*	Environmental impacts from diesel
Enteric methane per kg LW gain	S1: 0.21, S2: 0.23, S3: 0.22	CH4 impacts from enteric methane
CH4 from manure	See Supplementary Material A1	CH4 impacts from manure management
N2O from manure	See Supplementary Material A1	N2O impacts from manure management
4. Slaughter House and packaging*		
5. Anaerobic digestion		
Methane generated, calorific value of methane, heat generation efficiency, parasitic load	*methane generated* × *calorific value of methane* (× *heat generation efficiency fraction* (× *parasitic load*)	Heat output
Methane generated, calorific value of methane, energy generation efficiency, parasitic load	*methane generated* × *calorific value of methane* (× *energy generation efficiency fraction* (× *parasitic load*)	Energy output
Fraction N in BSG, dry weight fraction of BSG	*Fraction N in BSG* × *dry weight fraction of BSG*	N output
Fraction P in BSG, dry weight fraction of BSG	*Fraction P in BSG* × *dry weight fraction of BSG*	P output
6. Total emissions		
Emissions from feed, beef, mitigation from AD	*Feed GHGs* + *beef GHGs* − *AD mitigation*	Impacts per kg LW gain
Impacts per LW gain, total UK BSG generated per year	*Impacts per kg LW gain* × *Total BSG*	Total impacts

Table 2
Summary of formulas and input figures used in the Life Cycle Assessments presented in this study.

Assessment type	Equation/figures	Units	Sources
Feed impacts	Based on feed rations	Impacts per kg LW gain	Christodoulou et al. (2025)
Anaerobic digestion	Based on literature figures and supplier quotes	Impacts per kg LW gain	Sganzerla et al., 2021; Davison (2023)
Energy and diesel use	Default values from literature	kWh/LW gain, kg/LW gain	Nguyen et al. (2010)
Livestock emissions (CH_4 & N_2O)	Based on daily weight gain and enteric methane from animal trials and IPCC tier 2 equations	$kgCH_4$/LW gain, kgN_2O/LW gain	Christodoulou et al. (2025); IPCC, 2019
Scaling up			
Total annual BSG in UK	*Total beer production × BSG per beer*	Tonnes/year	Morgan et al. (2021); Milew et al. (2022);
Total liveweight gain possible	*Total BSG per year ÷ BSG required per liveweight gain*	kg/year	

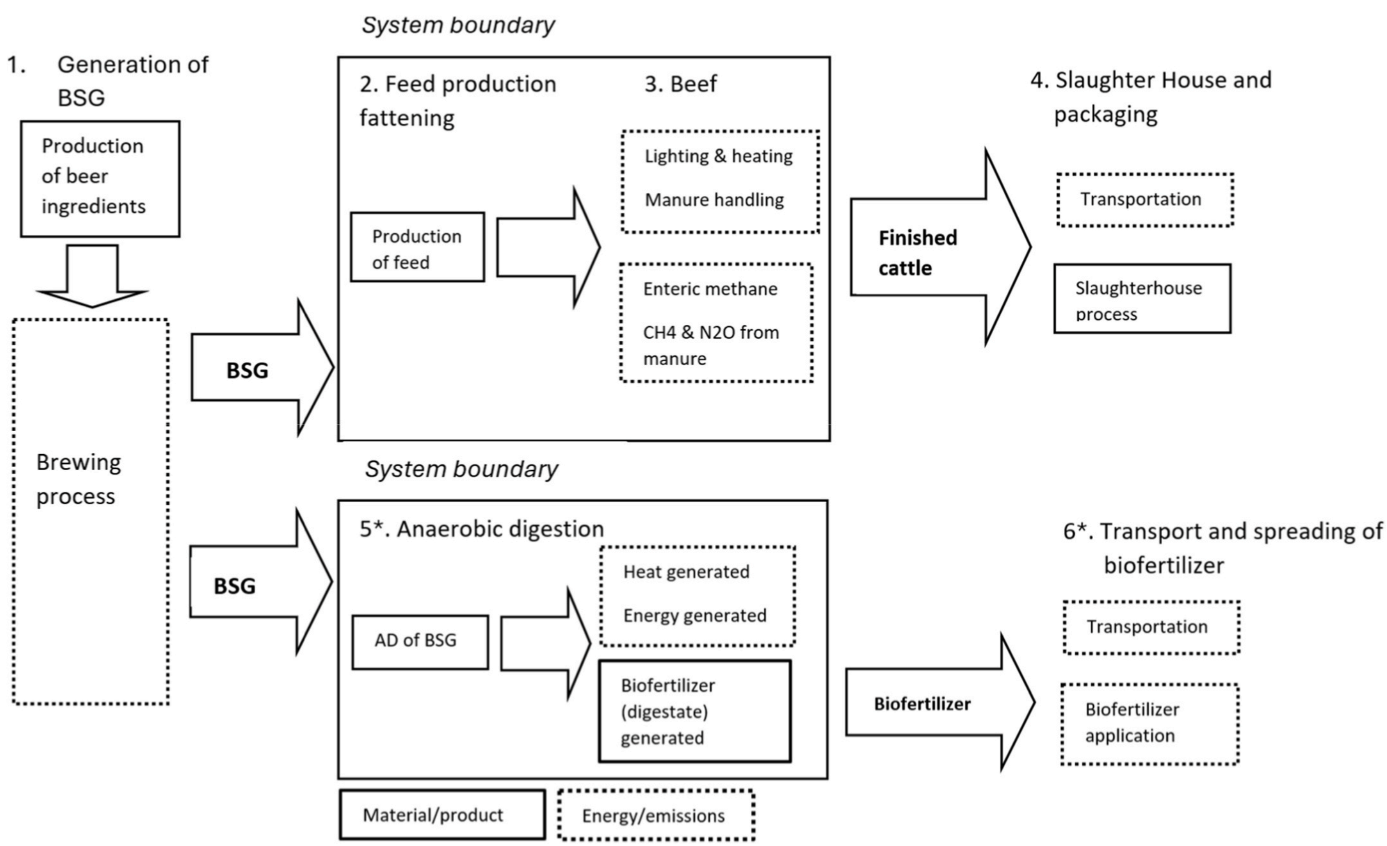

Fig. 3. System boundary for LCAs applied in this study.

required 4.4 kg of BSG per kg of beef cattle LW gain. From this, it was estimated that 29.9 Kt LW gain could be achieved annually if all UK BSG was used as a cattle feed. Potential environmental impacts per kg LW gain were scaled-up accordingly.

2.5. Lifecycle cost

Economic costs were calculated for the utilisation of all BSG in the UK using a 20-year lifecycle, based on the typical lifespan of anaerobic digestors (Davison, 2023). Life Cycle Costing input data and associated outputs are presented in Table 3, while formulas and input figures used in this study are detailed in Table 4, and are described in greater detail in the Supplementary Material Table A2. Capital and installation costs were calculated based on AD supplier quotes and scaled up, while animal feed was considered to have no associated capital and installation costs. Annual costs were calculated based on suppliers quotes for staff requirements and literature values for labour costs. Annual savings were calculated using national market values for products generated, supplier quotes for AD efficiency rates and literature values for the biomethane generation potential from BSG. The economic assessment used capital and installation costs, annual costs, and annual savings to calculate the payback time, LCC, annual return on investment (ROI) as well as the net annual cost. The net present value (NPV) was calculated using a 10 % discount rate, with the “n” referring to the number of time periods and “t” the investment lifespan (lifecycle of AD). Additionally, annual net profit is calculated as the sum of annual cost minus annual savings.

2.6. Estimating climate impact from indirect land use change

Comparative land use requirements for the different scenarios were assessed in the LCA. Total additional land use requirements compared to S1 were calculated. Scenarios were then formed based on “no indirect

Table 3
Summary of Life Cycle Costing input data and associated output used in this study.

Life Cycle Costing (LCC)		
Input data	**Calculations/input values**	**Associated outputs**
1. BSG costs	N/A	N/A
2. BSG feed revenue		
BSG value per tonne BSG, total UK BSG	See Table 4	Lifecycle revenue BSG feed
3. BSG AD costs capital & installation cost		
Cost of AD system (160t/day capacity), total UK BSG	See Table 4	System cost
4. BSG AD annual costs		
Labour requirements (hr/tBSG), labour cost (£/hr)	Labour requirements × labour cost	Labour costs
5. BSG AD annual savings		
Heat generation (kWh/tBSG), cost per kWh	*Heat generation (kWh) × cost per kWh*	Value of heat generation
Energy generation (kWh/tBSG), cost per kWh	*Energy generation (kWh) × cost per kWh*	Value of energy generation
Liquid fertiliser generation (kgN/tBSG), cost per kgN	*Liquid fertiliser generation (kWh) × cost per kgN*	Value of liquid fertiliser generation
Soil amendment generation (kg/tBSG), cost per kg compost	*Soil amendment generation (kWh) X cost per kg compost*	Value of soil amendment generation
Value of heat, energy, fertiliser and soil amendment product generated	*Value of heat + energy + fertiliser + soil amendment product generated*	Total savings per kg BSG
6. Net annual savings		
Capital and installation cost, annual cost, annual savings	See Table 4	Net annual savings/tBSG
Net annual savings/tBSG, total UK BSG generated per year	*Net annual savings ÷ tBSG × total BSG*	Net annual savings total BSG
7. LCC		
Net annual savings, lifecycle (20 yrs)	*Net annual savings* × 20	LCC
8. Payback time		
Capital and installation cost, Net annual savings	See Table 4	Payback time
9. ROI		
Capital and installation cost, Net annual savings	See Table 4	ROI
10. NPV		
Capital and installation cost, Net annual savings	See Table 4	NPV

Table 4
Summary of Life Cycle Costing formulas and input figures used in this study.

Assessment type	Equation	Units	Sources
Capital & installation cost	*Purchasing cost + installation cost*	£/yr	Supplier quotes and Davison (2023)
Annual cost	(*Labour requirement* × hourly labour cost) + *maintenence cost*	£/yr	Supplier quotes and Davison (2023)
Annual savings	*Product sales* and *avoided purchase × respective product values*	£/yr	Market costs Ofgem (2024); Nicks, 2022
Net annual cost	(*capital and installation cost* ÷ 20) + *Annual cost* − *Annual savings*	£/yr	
Life Cycle Cost	*Net annual cost* × 20	£/lifecycle	
Annual cost difference	*BSG animal feed Net annual cost − BSG AD feed net annual cost*	£/yr	
Payback time	*Capital and installation cost* ÷ (*Annual cost − Annual savings*)	yrs	
Annual return on investment	*ROI* = (*Annual net profit* ÷ capital and installation cost) × 100	%	
Net present value	$NPV = \sum_{t=1}^{n} \frac{cash\ flow_t}{(1 + cost\ of\ capital)^t} - Capital\ and\ installation\ cost$	£	

LUC" and "25 %", "50 %", and "100 %" indirect LUC scenarios, with the land required coming from either grassland, or forest. Impacts, as well as standard deviations for grassland and forest conversion were calculated using PAS2050 LUC values (Specification, 2008). These impacts were added to total comparative GHG values to illustrate how indirect LUC could impact the performance of the scenarios. Direct LUC was included in the main impact assessment on SimaPro software (v9.3) using inventory databases from Ecoinvent 3.0 and Agribalyse 3.1.

2.7. Sensitivity analysis

Sensitivity analyses were included within both the LCA and LCC. This included assessing GHG impacts based on a 20-year global warming timeframe (GWP20), as opposed to a 100 year timeframe (GWP100). This was due to the methane emissions from cattle having a greater impact over a shorter timeframe, with methane reduction being prioritised to bring about short-term GHG reductions (Nisbet et al., 2020). The sensitivity analyses also included an evaluation of different rates of methane reduction from BSG. The trial data used did not show any reduction in enteric fermentation from feeding cattle BSG, although a similar study showed BSG can reduce enteric methane by up to 17 % (Duthie et al., 2015). It is uncertain how factors such as cattle breed, age, and the dietary component replaced by BSG would influence the overall methane reduction. Consequently, the following scenarios were tested: BSG enteric fermentation reduction of 17 % (Duthie et al., 2015) 10 %, 5 % and 0 % (Williams et al., 2014; O'Brien et al., 2010), based on contrasting findings from the literature and the animal trial. Moreover, the AD performance figures were derived from a combination of literature and supplier figures, and performance may differ in-practice, depending on a range of factors, such as design and build efficiency. Differing heat and energy generation efficiencies (± 20 %) were therefore assessed (Flesch et al., 2011). Furthermore, the UK is transitioning towards net zero and is targeting a decarbonization of the grid energy mix before the end of the lifecycle in the assessment (start of lifecycle is the year 2024 and end of 20-year lifecycle is the year 2044), thus we assessed the GHG impacts of grid energy being derived from 100 % renewable sources. The sensitivity analysis was performed to evaluate the most relevant parameters that might affect the results.

For economics, the impacts of incorporating the social cost of carbon (CO_2 equivalent emissions) was assessed, alongside potential changes in capital costs, annual running costs and savings within the different scenarios. The social cost of carbon was considered to account for the economic value of any potential increases or decreases in GHGs relative to the baseline scenario (S1), with breweries hypothetically being paid for BSG utilisation-related GHG reductions, or having to pay for BSG utilisation-related GHG increases. For incorporating the social cost of carbon, total annual CO_2 equivalent emissions (tCO_2eq) compared to the BSG diet were multiplied by low (£47/tCO_2eq), medium (£94/tCO_2eq)

and high (£164/tCO_2eq) market cost of CO_2eq offset and added to the annual costs in the LCC (Watkiss and Downing, 2008; CEICTM, 2020). Furthermore, machinery and labour costs, as well as market values of heat, energy and animal feed have been fluctuating greatly in recent years (Mbah and Wasum, 2022). To assess scenario sensitivity to realistic variability, machinery purchasing costs, annual costs, and annual savings were evaluated with a range of ± 20 %.

3. Results

3.1. Life Cycle Assessment

3.1.1. Environmental impacts per kg of liveweight gain at sale

The comparative potential environmental impacts per kg of LW gain were calculated for Scenarios 1–3 (Fig. 4). Impacts are displayed in percentage terms (%), with the worst performing scenario for each category scoring 100 % and the other scenarios showing comparatively lower scores. S2 results in the greatest impact across eight of the environmental indicators (global warming, land use, water consumption, marine eutrophication, freshwater eutrophication, marine ecotoxicity, freshwater ecotoxicity, and stratospheric ozone depletion). In particular, water consumption is 22 % higher than S3, land use is 30 % higher than S1, freshwater eutrophication is 49 % higher than S3, and freshwater ecotoxicity is 41 % higher than S3. These impacts are in part due to the high water requirements and the relatively low yield of soya, as well as the low growth rate associated with the soya diet, leading to higher consumption of other dietary components (besides the high-protein component) per kg of LW gain. When comparing S1 and S3, the potential environmental impacts are more variable. When compared to S1, S3 has lower global warming Impacts (14 % lower), water consumption (16 % lower) and terrestrial acidification impacts (14 % lower) primarily due to having a higher growth rate and less feed consumed per kg LW gain. S3 also has substantially lower impacts on fossil resource scarcity (30 % lower), due to AD generating heat and electricity and biofertilizer to substitute fossil-fuels and fossil fuel derived products. Conversely, S1 has substantially lower land use impacts (22 % lower) and performs more favourably on other environmental indicators such as human toxicity (almost 100 % lower for non-carcinogenic and 7 % lower for carcinogenic toxicity), and ozone formation (17 % lower for terrestrial and 20 % lower for human health impacts) due to utilising a by-product for feed rather than specifically growing field beans as feed (requiring land and polluting Agri-chemicals).

When looking specifically at GHG impacts (Fig. 5), methane and nitrous oxide from enteric fermentation and manure management are the key contributors to GHGs for all scenarios (70 % of GHGs for S1, 57 % for S2, and 65 % for S3), followed by animal feed emissions (21 % of GHGs for S1, 40 % for S2, and 28 % for S3). The soya diet has substantially higher animal feed emissions (118 % higher than S1), due to the carbon intense soya component, while the field beans diet has slightly greater feed emissions than BSG (14 % higher) due to feed production processes. Conversely, the field beans diet has the lowest emissions from methane and nitrous oxide (11 % lower than S1 and 15 % lower than S2), due to the high starch and tannin content in the beans reducing methane from enteric fermentation (increased enteric methane reduction compared to BSG) and this diet providing the greatest growth rate and feed efficiency. Anaerobic digestion of BSG provided a GHG mitigation of around 0.6kgCO_2eq per kg of liveweight gain at sale, mainly because of biofertilizer substituting manufactured N and P fertilisers, which offset 8 % of GHGs from S2, and 10 % of GHGs from S3.

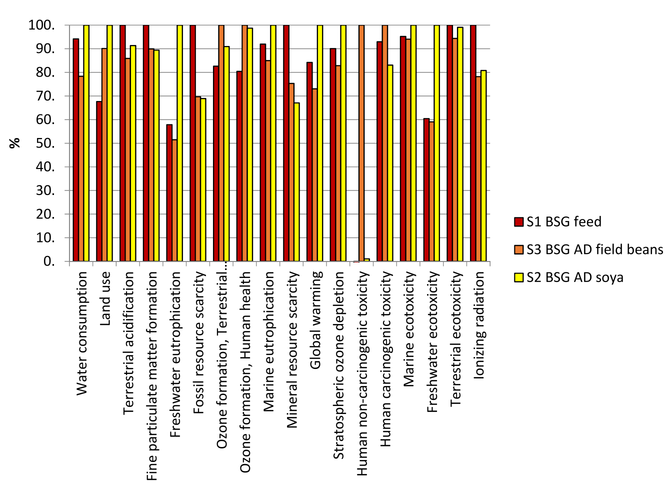

Fig. 4. Comparative potential environmental impacts of the different BSG utilisation scenarios for the different impact categories.

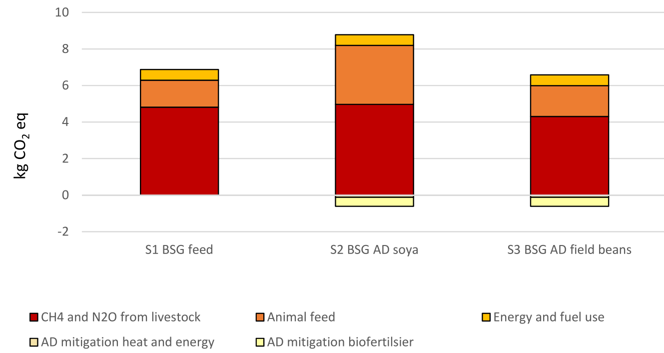

Fig. 5. Comparative climate impacts of the different BSG utilisation scenarios by GHG emission sources and mitigations from AD.

3.1.2. Scaled up impacts

On the one hand, when compared to S1, S2 resulted in an extra 1.3kgCO_2eq per kg LW gain, which increased to 39 kt CO_2eq if all BSG was used for AD instead of cattle feed to substitute soya (Table 5), due to GHG mitigation from AD being substantially lower than additional GHGs from producing soya. On the other hand, S3 had lower GHGs than

Table 5
Scaled up land use and GHG impacts of BSG scenarios to include utilisation of all BSG in UK.

	S1: BSG feed	S2: BSG AD Soya	S3: BSG AD Field beans	Difference between S2 and S1	Difference between S3 and S1
Net impact per kg liveweight gain					
Net GHGs per kg LW gain (kgCO_2eq/kg LW)	6.88	8.17	5.97	1.3	−0.9
Net land use per liveweight gain (m2a crop eq/kg LW gain)	5.49	8.12	7.32	2.6	1.7
Total annual impact					
Total BSG (Kt/year)	131.7	131.7	131.7	–	–
Total LW gain possible (Kt/year)	29.9	29.9	29.9	–	–
Net GHGs (KtCO_2eq/year)	206	244	179	**39**	**−27**
Net land use (Kha)	16.4	24.2	21.9	**7.8**	**5.5**

the BSG diet (0.9 kg kgCO_2eq per kg LW gain), as the comparatively lower enteric methane, as well as the GHG mitigation obtained through the AD of BSG, substantially outweighed the reduced feed and enteric methane emissions from S1. Altogether S3 could lead to a sizable GHG saving of 27 kt of CO_2eq per year when compared to BSG, when scaling up the impacts.

Scenario 2 had considerably greater land use requirements than S1. Altogether, S2 required almost 50 percent more land (m^2a crop eq) per kg LW gain, due to substantially more land being required to produce animal feed than the heat, energy and biofertilizer generated through AD. When scaled up, this led to a total extra land requirement of almost 8 k hectares when compared to the BSG diet. While S3 had a lower land use requirement than S2 (due to greater cattle growth rates per kg of feed consumed), the land required for this scenario was still substantially greater than for S1. Scenario 3 also required 5.5 k hectares more than the S1 would require when scaled up. Land is limited in the UK, with many competing land use requirements (Smith et al., 2019). The extra land requirements could lead to social, economic and potential environmental impacts, including GHGs associated with LUC (Sandström et al., 2022).

3.1.3. Potential impact of land use requirements on greenhouse gases

Fig. 6 shows the increased or decreased GHGs associated with implementing S2 and S3 using S1 as the reference value if the potential impacts of LUC are considered. If there is no LUC, then the upscaled field beans diet (S3) results in the lowest GHGs; however, if the extra land required came from newly cultivated, non-agricultural land then the field beans diet could have a higher climate impact. If 100 % of the extra land came from grassland there would be a marginal increase in the climate impact when compared to the BSG diet (S1). Even if just 25 % of the extra land required was derived from forest conversion, then the field beans diet would lead to a marginal increase in climate impact. If 100 % of the “new land” came from converted forests, then the field bean diet would go from decreasing GHGs by 27ktCO_2eq to increasing GHGs by 120ktCO_2eq annually. Deforestation results in substantially greater GHG emissions than grassland conversion because of the greater aboveground carbon stocks being contained in forests (Flynn et al., 2012).

While S2 (BSG AD soya) had a greater climate impact than S1 (BSG feed) before LUC was considered, the climate change risks associated with LUC are clearly much greater than those associated with feed production. If 100 % of the extra land requirement came from grassland conversion then the additional GHGs associated with S2 would more than double, from around 39 thousand tonnes of CO_2eq to 93 thousand tonnes of CO_2eq. Additionally, if 100 % of the additional land required came from forest conversion the soya diet would contribute to an annual increase of 250 kt CO_2eq when compared to S1. This figure is more than seven times greater than if LUC was not accounted for. It is clear therefore that LUC could play a key role in determining the optimal scenario for GHG mitigation and if extra land use requirements were met by land conversion, LUC impacts would completely overshadow all other GHG considerations.

3.1.4. Greenhouse gas sensitivity analysis

Despite altering the timeframe of climate change impacts, the level of enteric methane reduction from the BSG diet and AD and energy related scenarios S3 (BSG AD soya) and S2 (BSG AD field beans) remained the best and worst performing scenarios respectively (Fig. 7). Changing the global warming potential timeframe from 100 years to 20 years substantially improved the comparative GHG performance of S2, due to an increased global warming potential of methane increasing the GHG mitigation from the enteric methane reduction from the bean diets. Conversely, if the BSG diet led to an increased enteric methane reduction in-line with the literature then this would improve the performance of S1 (BSG diet), due to methane being the greatest source of GHGs. Changes in the AD performance (generation of heat and energy), as well as having zero carbon grid energy made little difference to overall GHGs, as AD only mitigated a fraction of the GHGs associated with beef LW gain and this was mostly provided by biofertilizer generation.

3.2. Life cycle cost

3.2.1. Life cycle cost comparison of animal feed and anaerobic digestion

Scenario 2 and 3 involving AD of BSG were more profitable over their lifecycle than S1 where BSG was sold as cattle feed, although they had a substantially higher initial cost and payback time, as shown in Table 6. If all available BSG in the UK was anaerobically digested, a net gain of over 16 million GBP over the 20-years could be achieved, when compared to selling BSG as an animal feed. This was because AD generated products (especially heat substituting natural gas) were substantially more valuable than BSG was as low-cost animal feed. Nevertheless, if all UK BSG were to be anaerobically digested, substantial initial costs would be required (>£120 million GBP) to purchase sufficient anaerobic digestion equipment. This investment would have a payback time of four years and an annual ROI of 22 %. When discounting annual net profit over the lifecycle of the anaerobic digesters, the NPV of the BSG AD scenarios (S2 and S3) was 117 million GBP, 44 million GBP higher than for cattle feed

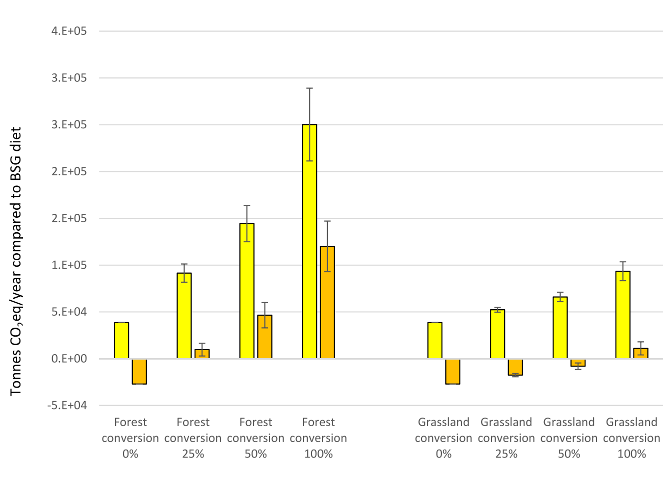

Fig. 6. Potential implications of land use on GHGs for soya and field beans diets with error bars for different grassland and forest conversion land use change scenarios.

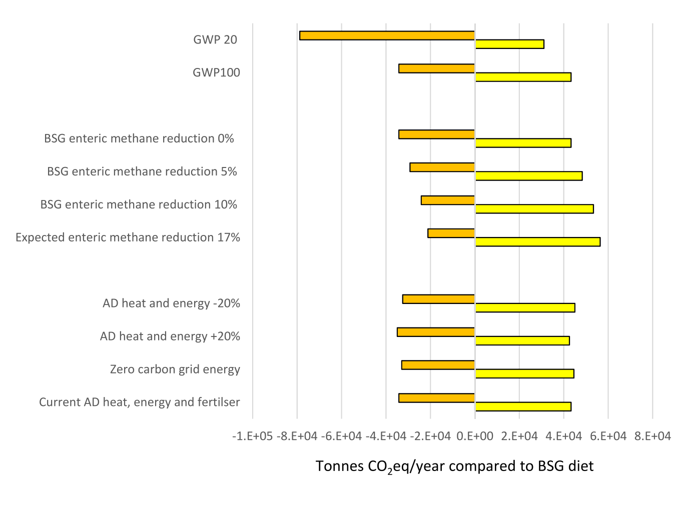

Fig. 7. Sensitivity of GHG impacts to different potential developments or scenarios involving global warming potential timeframes, enteric fermentation reduction and AD mitigation from heat and energy generation.

Table 6
Economic implications of using all UK BSG as a cattle feed, or anaerobic digestion feedstock, with the key cost categories and most noteworthy values highlighted in bold.

	S1 BSG cattle feed	S2 and S3 BSG AD feed	S2 and S3 BSG AD feed vs S1 cattle feed
Capital & installation cost (£ million)	0	123	**123**
Annual costs (£ million)	0	7.8	7.8
Annual savings (£ million)	5.9	36	30
Net annual cost (£ million)	5.9	22.1	**−16.1**
Net Life Cycle Cost (£ million)	**−119**	**−441**	**−323**
Payback time (years)	0	4.3	**4.3**
Return on investment (%)	22.3	N/A	**18.1**
Net present value **(£ million)**	72.8	117.1	44.3

(73 million GBP). Altogether, while the BSG of AD would require a greater investment, a payback time of under 5 years is highly attractive, under current market conditions, and a lifecycle saving of over 300 million GBP could potentially make this a financially sound option for the UK brewing industry, if the current high prices for gas and electricity remain in place and/or increase.

3.2.2. *Economic sensitivity analysis*

The economic sensitivity analysis found that AD of BSG (S2 and S3) substantially outperformed BSG for animal feed (S1) under all scenarios, with comparative annual net savings not reducing below 5 million GBP (Fig. 8). Incorporating the social cost of carbon had the greatest impact on comparative net annual costs. While this made little difference for S3 (BSG AD field beans), it substantially decreased the net annual savings for S2 (AD BSG soya), due to the comparatively high climate impact of the scenario. While the low social cost of carbon scenario had a modest impact, the high social cost of carbon scenario reduced comparative net annual savings of the S2 by almost two-thirds from around 16 million GBP to around 6 million GBP.

The impact of adjusting annual savings from generating heat and energy, as well as selling biofertilizer for the AD scenarios (S2 and S3), or selling cattle feed for the cattle feed scenario (S1) by increasing, or decreasing market values was assessed. These adjustments made a substantial impact to net savings associated with AD of BSG (S2 and S3) compared to the animal feed scenario (S1), due to the comparatively high value of AD products, especially heat substituting natural gas. A 20

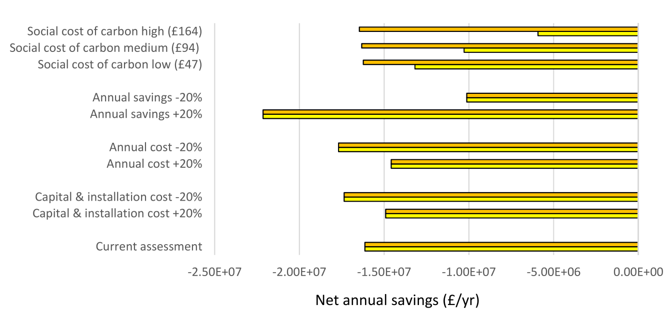

Fig. 8. Sensitivity of economic impacts to different potential developments or scenarios involving the implementation of the social cost of carbon, as well as increases and decreases in annual savings, annual costs as well as capital and installation costs.

% increase in the BSG associated revenue would increase net annual savings by 37 % from around 16 to 22 million GBP, while a 20 % decrease in revenue would lead to a 37 % decrease from 16 to 10 million GBP. The market values of fuel, fertiliser and feed have been volatile over the past few years (Mbah and Wasum, 2022) therefore the economics of the scenarios may be sensitive to much greater changes than we have assessed. While changes in the capital and installation cost do not greatly change the net annual savings, they do have a greater impact on payback time, with an increase of 20 % pushing the payback time of AD over the desirable 5-year period.

4. Discussion

4.1. *Comparison with the literature*

The results illustrate that the utilisation of BSG as a soya replacement in livestock diets could lead to substantially lower environmental impacts across a wide range of impact categories such as global warming, land use and water consumption (Fig. 4 and Table 3), when compared with AD. This outcome agrees with Petit et al. (2020) who found that BSG performs more favourably as an animal feed, across most environmental indicators when compared to AD. They also found substantial opportunities through avoided land use change, when assuming that the BSG is replaced by a high-carbon feed such as soya beans. Results for substituting BSG with domestic field beans are much less favourable however (Fig. 4 and Table 3) and less in-line with the literature. Substantially reduced enteric methane generation per kg of LW gain, through a higher growth rate and lower daily methane emissions assessed in the cattle trials (Christodoulou et al., 2025), meant that the BSG AD scenario performed better than S1 BSG feed scenario when field beans replaced BSG as cattle feed (S3). As far as we are aware, no other study comparing BSG for AD or feed has considered the enteric methane implications of feed on cattle, which could explain the differences between our study and Petit et al. (2020). As echoed in similar studies, methane generated from cattle was the key contributor to GHGs per kg LW gain (Williams et al., 2014; Nguyen et al., 2010; Wang et al., 2019). Moreover, the impacts of the different cattle diets on enteric methane was perhaps the most important factor in determining which scenario had the lowest GHGs, with the S3 (field beans diet) having 11 % lower enteric methane and manure management emissions than S1, and 15 % lower than S2 (Fig. 5). Williams et al. (2014) made similar findings when they determined the climate impacts of substituting cereal grains using three methane reducing diets (BSG, hominy and whole cotton seed) with the hominy and BSG diets reducing GHGs, primarily due to enteric methane reductions. Despite these findings, the role of enteric methane reductions in cattle diets remains underexplored, particularly regarding the potential reductions from beans due to their high tannin content and higher starch content relative to BSG (Johnston et al., 2019; Christodoulou et al., 2025).

Overall, the finding that Scenario 3 (BSG AD field beans diet) results in lower GHG emissions than Scenario 1 (BSG as feed) - primarily due to reduced enteric methane - contradicts previous studies that reported substantial benefits from using BSG as animal feed rather than as AD feedstock (Petit et al., 2020). Moreover, this finding challenges the conventional wisdom and frameworks that direct feed use is always environmentally superior (Papargyropoulou et al., 2014; Parsa et al., 2023), highlighting the critical role of enteric fermentation management in determining the GHG mitigation potential of feeding by-products to animals (Williams et al., 2014).

At the same time, using field beans or soya to feed cattle had much higher land use requirements than BSG (S2 requires 32 % more land, or an additional 7.8 k ha cropland, and S3 requires 22 % more land, or an additional 5.5 k ha cropland), as shown in Fig. 4 and Table 3. Additional land use requirements could risk substantial climate impacts from the associated indirect LUC in the form of converting grassland or forest to cropland and lead the S3 (field beans diet) to have a higher climate impact than S1 (BSG diet), as shown in Fig. 6. Other studies have also highlighted the low land use requirements associated with utilising industrial by-products including BSG, and the potential LUC risks from using both soya and field beans as an animal feed (Reckmann et al., 2016). Using by-products as feed can free up land for food production and increase food security (Sandström et al., 2022). Moreover, indirect LUC could play a key role in determining the food production scenarios with the greatest climate impact (Smith et al., 2019).

The economic analysis indicated sizable benefits associated with AD of BSG (S2 and S3), compared to BSG feed (S1). Specifically, net annual savings were £17 million higher, while NPV was £44 million higher than for animal feed respectively if all UK BSG was to be anaerobically digested instead of sold as animal feed (Table 4). The AD scenarios (S2 and S3) would have a payback time of around 4 years and an annual ROI of 23 %, although a relatively large initial investment of over £120 million would be required to adopt AD for all UK BSG. These findings concur with a study by Sganzerla et al. (2021) which found that AD of BSG could be highly profitable, although there are no previous studies looking at AD of BSG in the UK context. As with this study, the economic performance was most sensitive to the market values of heat, energy and fertiliser. Despite this, AD of BSG remained a net economic benefit despite decreasing total revenues by 20 % in this paper (Fig. 8), or decreasing individual revenue streams (heat, energy, biofertilizer) by 50 % in the literature (Sganzerla et al., 2021).

4.2. Limitations and trends concerning anaerobic digestion

For the assessment it was assumed that the AD process would be optimal, with the anaerobic digesters being run at maximum capacity and avoiding contamination, or fugitive methane, and cultivating methanogenic bacteria to obtain a high proportion of methene in the biogas. In practice, AD needs to be managed carefully and skilfully to achieve the benefits assumed in the assessment (Davison et al., 2023). If anaerobic digesters are contaminated then they may be shut down for several months, while lower than expected methane levels in the biogas (Babaee and Shayegan, 2011), or fugitive methane escaping (Flesch et al., 2011) would all reduce the economic and environmental performance of AD of BSG. Additionally, given the UK's legally binding net-zero target, the carbon intensity of grid energy would gradually decrease over the lifecycle of the AD plants, although results found limited GHG mitigation from substituting current UK grid energy due to UK grid energy already having relatively low carbon intensity levels (Davison et al., 2023).

While large and medium scale AD is common in the UK with well-known financial models and systems, small scale AD is less common due to a lack of access to finance to cover initial investment, as well as less tried and tested business models. Additionally, it is possible that AD may not be profitable below a certain capacity (O'Connor et al., 2021). While large breweries in the UK may find it easier to invest in their own AD systems, smaller scale breweries may find it more difficult to fund the large capital investment required and may see it as too great a risk. Small breweries could have their BSG collected and anaerobically digested by waste treatment companies, but would be unlikely to receive a higher revenue than if their BSG was collected and utilised as animal feed (Kerby and Vriesekoop, 2017). More research could be conducted on the economics and feasibility of breweries of different sizes purchasing anaerobic digesters for onsite AD of BSG. Moreover, this study presents a binary choice of all BSG going to animal feed, or all going to AD. It is likely that AD would present substantial opportunities for certain breweries, but not be practically, or economically feasible for other breweries depending on size, location and other factors. Further research could be conducted to identify breweries suited to adopting AD (such as large urban breweries) and ones that are not (such as small rural breweries). This research could then use these insights to have more detailed and nuanced scenarios based on differing levels of utilisation of BSG for AD in the UK.

Future market changes could also affect the economic outcomes presented here, as shown in Fig. 8. While BSG of AD would perform better than animal feed even if there were to be a 20 % increase in AD costs, or a 20 % reduction in revenue (3.2.2 sensitivity analysis), markets have been very volatile over recent years (Mbah and Wasum, 2022). Fuel prices are currently decreasing (Ofgem, 2024), while machinery and labour costs are rising (Oyegoke et al., 2024). If this trend continues, it is possible that the capital costs and payback time for AD of BSG could become undesirable and its net lifecycle savings may even decrease below that of the BSG animal feed scenario (S1).

4.3. Hidden costs of land use

The economic assessment for this study was primarily focussed on economic opportunities for breweries associated with BSG utilisation pathways and thus did not consider wider economic implications such as differing land use requirements from different scenarios. As highlighted in section 3.1.3, a key benefit associated with the utilisation of by-products is that it frees up land through substituting feed with substantial land use requirements. Thus, switching from utilising BSG as an animal feed (S1) to an AD feed requires 5.5 kha more land if the BSG feed is replaced by field beans (S3), and 7.8 kha more land if replaced by soya (S2), as detailed in Table 5. The average value of agricultural land in the UK is £27,191 per hectare (RICS, 2021). Altogether, the cost of purchasing the additional 5.5 kha required for the BSG feed diet (S3) in the UK would be £150 million, around one-half of the additional net economic benefit from S3 compared to S1 (£323 million) and more than three times greater than the NPV (£44.3 million), as shown in Table 6. Although additional soya would likely come from the main producing countries of Brazil, Argentina, or USA (dos Reis et al., 2025), if produced in the UK the cost of purchasing the additional 7.8 kha required for S2 would be £212 million, around two-thirds greater than the additional net economic benefit compared to S1 (£323 million) and around five times greater than the NPV (£44.3 million). Thus, while the economic cost of purchasing extra land required for replacing BSG as feed may not fall directly to the breweries if they were to AD BSG, it would likely have substantial implications on the farming and feed sectors and could lead to net negative impacts on the UK economy.

4.4. Limitations and trends concerning animal feed diets

The paper illustrates the potential environmental benefit of using BSG to substitute soya based feed (Fig. 4 and Table 3). Soyabean imports to the UK remain relatively steady at over 3.5 million tonnes per year, with the majority being used as animal feed (Statista, 2024). Despite this, efforts are being made by producers, retailers, and consumers to reduce soya use for animal feed, to reduce GHGs in animal agriculture, with post-BREXIT policy shifts offering opportunities to shift towards domestically produced lower carbon alternatives (Garnett et al., 2023). High protein domestically grown alternatives such as field beans align with this strategic shift, and UK field bean production increased by 17 % between 2020 and 2022, in-part to substitute soya use in animal feed (DEFRA, 2024a). With increased domestic production of beans, and pressure for soya alternatives, BSG derived feed could be more likely to replace low carbon alternatives in the future, potentially limiting the environmental benefit obtained. Moreover, field and soya beans help fix nitrogen from the atmosphere and thus can decrease reliance on chemical fertilisers (Fenta et al., 2020), something that was not considered in the environmental assessment. This has the potential to further improve the environmental performance of S2 and S3.

On the one hand, field bean diet (S3 BSG AD field beans scenario) had the greatest economic benefits (Table 4), lowest GHGs (Fig. 5 and Table 5), and performed the best across most environmental indicators (Fig. 4). On the other hand, field beans contain antinutritional factors, such as tannins, trypsin and protease inhibitors, which could reduce nutrient intake and digestibility (Dvořák et al., 2006; Huang et al., 2018;

Johnston et al., 2019). With this being said, previous studies have shown no significant reduction in cattle dietary intakes and digestibility (Puhakka et al., 2016; Johnston et al., 2019). It may therefore be possible to retain the environmental and economic benefits associated with the field bean diet (S3) without incurring antinutritional impacts, but careful consideration should be made to the overall dietary composition for cattle.

The results highlighted the land use implications of the different scenarios and the potential GHG impacts that could result from increased land requirements, based on the assumption that the BSG used for AD must be replaced by newly cultivated soya or field beans in the cattle diet (Fig. 6). Results showed that if 25 % of the additional cropland required came from deforestation, or 100 % of the additional land came from grassland conversion, S3 (field beans diet) would have a greater climate impact than S1 (BSG diet). In reality however, there are many uncertainties associated with land use and LUC. If any additional land came from currently available unutilised cropland, then there would be no LUC, although if more cropland is required than is unutilised and available, then LUC and associated GHGs would be required (Smith et al., 2019). Further research could be carried out to identify the extent of underutilised land in the UK, and the maximum replacement of BSG by field beans as an animal feed that would be possible without incurring harmful LUC.

Furthermore, there may be some elasticity of supply for soya and field beans that could have implications on indirect LUC. Global production of soya is increasing, but global demand for soya is also rising at a similar rate, driven mostly by China as the largest soya importer globally (Volkova and Smolyaninova, 2024; dos Reis et al., 2025). While it is possible that on a given year there may be a surplus in supply that could make up the additional soya-based feed requirements in the UK, it is likely that the additional demand would only help drive the expansion of global soya production and exacerbate land use pressures (Liu et al., 2021). Additionally, there is a strategic drive to increase production of field beans and other legume crops in the UK as part of the national food strategy to provide benefits such as agricultural biodiversity, increase crop diversity, reduce agri-chemical inputs, and regenerate soils (Azam-Ali et al., 2024). A strategic increase in UK field bean production may lead to supply surpluses that could potentially provide a source of animal feed to replace BSG without specifically incurring LUC. Moreover, field beans are typically used as a break crop to reduce cereal pests, diseases and weeds in arable rotations and thus LUC impacts are likely to be lower than for permanent crops and could reduce requirements for environmentally harmful pesticides and herbicides (Angus et al., 2015).

Decreased methane emissions associated with an enteric fermentation reduction from the field beans diet greatly decreased the GHGs associated with S3 (BSG AD field beans), as shown in Fig. 5. Previous studies however, have also shown BSG can reduce enteric methane in cattle, depending on the nutritional approaches (replacing a protein source or silages), as well as the different nutrient composition and inclusion levels (Duthie et al., 2015; O'Brien et al., 2010; Johnston et al., 2019). As shown in the sensitivity analysis (Fig. 7), if a 17 % enteric fermentation reduction could be achieved (Duthie et al., 2015) then the BSG diet (S1) could have enhanced GHG benefits compared to the soya diet (S2). Different studies found different levels of methane reduction from BSG. Duthie et al. (2015) found that BSG reduced enteric methane by 17 %, but they replaced the grass silage part of the diet instead of the high protein part that was replaced in this paper. O'Brien et al. (2010) found BSG to reduce enteric methane by less than 10 % when BSG replaced wheat. Johnston et al. (2019) found that adding field beans to a cattle diet could reduce overall methane per milk production by over 6 % when replacing soya bean and rapeseed. Altogether, there are very few studies assessing the impact of BSG and beans on enteric methane. Moreover, as far as we are aware there have been no studies comparing the impact of BSG, field beans and soya beans on enteric methane generation per beef LW gain, and how aspects such as cattle breed, age, and the dietary component replaced by BSG may impact enteric methane reduction and GHGs associated with different cattle diets. This creates much uncertainty when scaling up potential impacts. Further research could be conducted to understand how cattle characteristics and diet formulation could impact enteric fermentation reduction from BSG, field beans and soya beans to determine the average enteric methane reduction per kg of LW gain that could be expected from the different scenarios assessed in this paper. Moreover, when scaling up impacts of the AD scenarios, there was an assumption that 100 % of the BSG currently goes to cattle, while in fact, some BSG is fed to monogastrics such as pigs. The main benefit of the field beans diet was the enteric methane reduction relative to LW gain, tackling the biggest source of emissions for beef (Duthie et al., 2015). Conversely, pigs and poultry generate considerably lower levels of enteric methane, with feed emissions being the largest emission source for both (Garcia-Launay et al., 2014). Thus for monogastrics, the GHG reduction associated with using BSG instead of field beans for feed may outweigh the mitigation benefits from AD as found by Petit et al. (2020).

4.5. Policy recommendations

In line with previous research, it is clear that utilising high-carbon feeds, namely imported soya, as the high-protein component in animal feed has very harmful impacts on a wide range of environmental indicators, including climate change and land use (Fig. 4, Table 5). In order to reduce environmental impacts from the high-protein component of animal feed, policy mechanisms could be introduced. The European landfill tax is an example where incremental increases in tax (from £10 per tonne in 1996 to over £80 per tonne in 2016) were implemented to make the environmentally harmful practice of landfilling organic waste become more costly than alternative waste treatment options such as AD and composting. This led to a reduction in landfilling of almost 80 % between 1996 and 2016 (around 50 million tonnes per year in 1996 to just over 10 million tonnes per year in 2016) (Elliott, 2016). A similar tax could be introduced on imported soya for animal feed, to encourage farmers to find suitable alternatives. An alternative option could be a phased ban on imported soya, drawing inspiration from policy measures like the UK's planned 2030 ban on commercial peat use in soil amendments (Hirschler et al., 2022). That policy has already contributed to annual reductions in peat use of around 5 % (HTA, 2025). A similar approach could be applied to gradually eliminate the use of imported soya as animal feed in the UK.

To support the adoption of onsite AD by UK breweries, targeted assistance could be introduced. Ackrill and Abdo (2020) identified that a lack of access to finance, as well as a lack of awareness of AD technologies, regulations and incentives for different enterprises formed key uptake barriers to the update of AD in the UK. Consequently, introducing interest-free loans alongside existing incentives could allow smaller breweries with minimal cash reserves to undergo the substantial initial investment required to install an anaerobic digester (O'Connor et al., 2021). Additionally, extra support for consultancy from advisory services such as those provided by Alder Bioinsights (2025) to offer advice on relevant technologies, regulations and incentives could substantially reduce uptake barriers for Breweries interested in AD in the UK (Ackrill and Abdo, 2020).

To avoid deleterious land use change resultant from increased cropland requirements, planning rules and regulations prohibiting conversion of grassland or forests to cropland in the UK could be introduced and strictly monitored. Environmental Impact Assessments are already required when changing uncultivated, semi-natural and rural land, such as forest and grasslands to cropland (DEFRA, 2024b). Altering this legislation to include an outright ban of conversion of forests and potentially grassland to cropland, supported by careful monitoring and prohibitively large fines for failing to abide by these rules could substantially reduce deleterious indirect LUC in the UK resulting from food system changes. On the other hand, any additional land requirements may lead to indirect LUC outside the UK (Smith et al., 2019), thus strong legislation could be brought in to avoid the import of food and feed products associated with damaging LUC (DEFRA, 2020). Moreover, a policy-led dietary shift towards a reduction in red meat consumption, as well as wider animal products in-line with the Eat-Lancet diet (Rockström et al., 2025) could reduce land use requirements and potentially avoid the land-use dilemma altogether.

5. Summary and conclusions

The assessment of the environmental and economic implications of brewer's spent grains utilisation strategies estimated the environmental and economic impacts of using all UK generated brewer's spent grains for anaerobic digestion, or as an animal feed to replace either soya, or field beans. The following impacts were identified:

- It is potentially more environmentally beneficial to utilise brewer's spent grain as an animal feed rather than as an anaerobic digestion feedstock, if the spent grains replace soya. Conversely, if the spent grains are used to replace field beans there are a number of environmental trade-offs across environmental impact categories. The brewer's spent grain diet has much lower land use requirements, but the field beans diet has lower climate change impacts, as well as lower water and fossil resource use.
- The net greenhouse gas and land-use impacts of brewer's spent grain utilisation pathways are highly sensitive to underlying assumptions regarding feed-type substitution: if all of the UK's brewer's spent grain were used for anaerobic digestion, instead of as a soya replacement in cattle feed, the increased demand for soya would result in a large increase in greenhouse gases and increased land requirements (39 Kt CO_2eq and 7.8 Kha of land). This effect would be mitigated if the soya demand was instead met by field beans, in this case there would be a large reduction in greenhouse gases, but a substantial additional land requirement (−27ktCO_2eq Kt CO_2eq and 5.5 Kha of land) following the utilisation of spent grains in anaerobic digestion.
- Utilising brewer's spent grain for anaerobic digestion could result in land use change which would lead to substantial greenhouse gas emissions that could dwarf all other components contributing to greenhouse gas emissions. This would lead the field beans diet to have higher emissions than the brewer's spent grains diet.
- Anaerobic digestion of brewer's spent grain is substantially more profitable than selling the by-product as an animal feed and could provide the UK brewing sector with a net gain of £16 million annually and an annual return of investment of 23 %. While it would require a large total initial investment of over £120 million and there may be barriers to smaller breweries investing in small-scale anaerobic digestion it would have a net present value 44 million GBP higher than selling brewer's spent grains as an animal feed.

If land use change can be avoided, anaerobic digestion of brewer's spent grains combined with the use of field beans in cattle diets could represent a favourable way forward. This is because of the combined economic and climate change mitigation opportunities presented by anaerobic digestion and field bean cultivation. Nevertheless, the current dominant utilisation pathway for most UK brewer's spent grains brings about enormous environmental benefits, especially by reducing the requirement for soya based feed. Using the same material for anaerobic digestion could bring about substantial economic benefits while maintaining a similar environmental effect, although this must be explicitly tempered by the three major caveats revealed in the study: 1) this is highly contingent on avoiding deleterious Land Use Change (LUC), 2) it may not be economically feasible if the cost of the additional land is accounted for, 3) field beans must fully replace brewer's spent grains as the high protein component of cattle feed, as opposed to soya.

Policymakers could take steps to make anaerobic digestion a more viable option for breweries by easing the burden of initial investment, while also supporting broader goals to reduce reliance on soya-based animal feed and protect natural land. Possible policy support measures could include the gradual introduction of taxes or restrictions on imported soya for animal feed to support its eventual phase-out; increased support for advisory services and the provision of interest-free loans to help breweries adopt anaerobic digestion; and planning measures that discourage the conversion of grassland and forests to cropland, helping to limit land use change within the UK.

CRediT authorship contribution statement

Nicholas Davison: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Christos Christodoulou:** Writing – review & editing, Methodology, Investigation. **David Humphries:** Writing – review & editing, Conceptualization. **Kirsty Kliem:** Writing – review & editing, Conceptualization. **Sokratis Stergiadis:** Writing – review & editing, Methodology, Conceptualization. **Laurence Smith:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.147365.

Data availability

Data will be made available on request.

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