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Climate mitigation efficacy of anaerobic digestion in a decarbonising economy

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ABSTRACT

Anaerobic digestion (AD) is at the interface of biowaste management, energy generation, food production and land-based carbon dioxide removal. Strategic deployment of AD requires careful scoping of interactions with *prospective* alternative biowaste management, energy generation technologies and land uses to ensure effective delivery of climate neutrality and circularity. There remains a need to assess the greenhouse gas (GHG) mitigation efficacy of AD in the context of future alternative (counterfactual) processes associated with differential rates of decarbonisation across energy, waste management and land (including agriculture) sectors. To address this gap, prospective life cycle assessment (LCA) is applied to AD deployment scenarios across three decarbonisation contexts, using the UK as an example. Food waste prevention and diversion to animal feed always achieve more GHG mitigation than AD, even with sustainable intensification of food and feed production. Compared with maize- or grass-biomethane transport fuel, solar electricity generation can avoid 16 times more fossil energy and afforestation can mitigate six times more GHG per hectare of land occupied. Transport biomethane is currently the most effective biogas use for GHG mitigation, but large-scale combustion of biogas for electricity or industrial heat generation is the most effective long-term option as transport is electrified and bioenergy carbon capture & storage (BECCS) is deployed. Prioritising waste prevention and diversion to animal feed (including via insect meal) instead of maximising AD deployment could simultaneously: offset an additional 10–15% of national GHG emissions; meet an additional 2–4% of national energy demand; free enough arable land to provide 20–21% of national recommended protein and kcal intake. However, AD is likely to remain the best option to manage substantial volumes of residual food wastes and manures that will remain available even if ambitious projections on waste prevention and diet change are realised.

1. Introduction

1.1. Anaerobic digestion in a circular economy

Anaerobic digestion (AD) is a multi-faceted technology at the interface of waste management, energy generation and food production. It is promoted as an effective option to mitigate greenhouse gas (GHG) emissions and improve circularity in the economy via renewable energy generation from biomethane and nutrient cycling in digestate co-products (ADBA, 2018; Mesa-Dominguez et al., 2015; Slorach et al., 2019; Smyth et al., 2011; Wainaina et al., 2020). As such, AD sits at the climate-energy-food nexus (Rasul and Sharma, 2016). Expanded boundary life cycle assessment (LCA) that accounts for activity-specific emissions and substitution effects across multiple sectors is critical to evaluate the environmental performance of AD, including net GHG mitigation efficacy (Liu et al., 2015; Styles et al., 2018; Tonini et al., 2018). Slorach et al. (2019) recently demonstrated the environmental superiority of AD treatment of food waste in the UK compared with incineration, in-vessel composting and landfill. Using LCA, they found that AD incurred the smallest environmental burdens across 13 out of the 19 impact categories considered. Albizzati et al. (2021a) found that waste prevention and diversion to animal feed remain the best options

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for food waste management at EU level. Nonetheless, biomethane use as a transport fuel has been shown to be an effective GHG mitigation option (Styles et al., 2016; van den Oever et al., 2021), providing a cost-effective pathway to decarbonise urban transport systems (D'Adamo et al., 2021), and there is considerable scope to enhance energy yields through process optimisation (Antoniou et al., 2019; Diamantis et al., 2021). However, realising the potentially multi-faceted and multi-sectoral sustainability benefits of AD requires carefully co-ordinated deployment (Lindfors et al., 2020). Recent energy-related incentives across Europe have driven expansion of crop-fed digesters to generate electricity (Nevzorova and Karakaya, 2020), despite low useful energy yields per hectare and low environmental efficacy (Styles et al., 2015). There remains some debate about the environmental superiority of AD over alternative waste management options such as composting and incineration (Evangelisti et al., 2014; Slorach et al., 2019; Di Maria and Micale, 2015). Waste prevention and diversion of prospective biological waste streams to animal feed typically support larger environmental "credits" via avoidance of food and feed production, compared with credits generated by digestion of those same waste streams via avoidance of fossil energy generation and fertiliser application (Albizzati et al., 2021b; De Menna et al., 2019; Leinonen et al., 2018; Schestak et al., 2022; Tufvesson et al., 2013). Furthermore, previous studies have highlighted significant environmental impacts from methane and ammonia emitted via digester leakage and digestate management (Duan et al., 2020; Rehl and Müller, 2011; van den Oever et al., 2021), and high opportunity costs for land required for food and feed production (Searchinger et al., 2018) were not fully factored in to previous comparisons of biowaste options. There remains a need to examine the sustainable niche for AD in the context of future AD performance and marginal (substituted) waste management and energy generation technologies, considering high opportunity costs of land use for AD-crops and avoidable food and animal feed production.

1.2. Need for prospective evaluation

Sustainable policy and investment decisions should be informed by prospective evaluation of technologies based on explicit accounting of marginal direct and indirect effects of deployment (Adrianto et al., 2021), ideally through application of consequential LCA (Weidema et al., 2018). Extending this logic, it is argued that prospective LCA studies with longer time horizons should account for changing marginal technologies through time via dynamic accounting (AzariJafari et al., 2019; Buyle et al., 2019; Levasseur et al., 2010). These are pertinent issues in the context of the dramatic reductions in GHG emissions that will be required to achieve the objective of climate stabilisation set out in the Paris Agreement (Huppmann et al., 2018; Masson-Delmotte et al., 2019). The concept of a circular economy (Stahel, 2016) is closely aligned with climate stabilisation, and requires inter-systems thinking (Liu et al., 2015) to drive integration of economic sectors around extended value chains that produce, use, re-use and finally recycle resources (Vaneeckhaute et al., 2018). Thus, the future context in which specific technologies operate will be different. Widespread deployment of green technologies should be informed by multi-decadal strategic investment decisions (Guo et al., 2020). The performance of these technologies therefore needs to be assured within the context of more circular and decarbonised economies (Adrianto et al., 2021; Forster et al., 2021), requiring evidence beyond incremental reduction in the GHG intensity of production.

Recent studies have applied "anticipatory" LCA by applying projected emission factors for e.g. electricity grid mixes (Albizzati et al., 2021b; Lefebvre et al., 2021; Vandepaer et al., 2019) or energy carrier transitions (Maes et al., 2021) to identify the future likely performance of specific technologies. Forster et al. (2021) showed that the climate mitigation efficacy of new forests is highly sensitive to future substitution "credits" which depend on decarbonisation of concrete, steel and energy, and on the deployment of carbon capture & storage (CCS) technology (Stavrakas et al., 2018). Indeed, bioenergy CCS (BECCS) deployment is regarded as central to meeting 1.5 °C climate stabilisation (Masson-Delmotte et al., 2019; Muri, 2018), and could transform AD into a negative emission technology–. However, there are concerns over land areas require to scale out BECCS (IPCC, 2019). Changes in land requirements associated with different waste management strategies and AD-crop production will have significant implications for alternative "nature based solutions" to climate change, food production and energy generation – yet are not typically included in LCA studies of waste management.

To date, there has been no comprehensive assessment of the future comparative environmental sustainability of AD in the context of simultaneous but differential decarbonisation trends across the waste, energy and land (including agriculture) sectors that this technology straddles. Here, we address that gap by providing new evidence on the comparative environmental efficiency of AD in relation to interactions across: (i) use of biomethane; (ii) composition of digested food waste; (iii) alternative management of biowastes; (iv) alternative uses of land spared via waste prevention or diversion to animal feed for GHG mitigation, energy generation or food production; (v) degree of (future) decarbonisation across the wider economy.

2. Methodology

2.1. Goal and scope

The aim of this study is to evaluate the environmental performance of AD against the most promising circular biowaste management, GHG mitigation and renewable energy generation options, now and under future contexts of decarbonisation across critical interlinked systems. Particular emphasis is placed on prevention and management of food waste, categorised along five stages of the food supply chain associated with different prevention and management options: primary production (PP); manufacturing (M); Retail (R); Catering (C); Household (HH). Other dominant AD feedstocks are evaluated, namely, industrial biowastes, manures (pig, poultry and cattle) and purpose-grown crops (maize and grass) (Table 1). An LCA approach is applied with a focus on two core impact categories pertinent to the climate-energy-food nexus: global warming potential (GWP), measured as kg CO_2 eq. (CO_2, CH_4 and N_2O = 1, 25 and 298, respectively: IPCC, 2007) and land occupation (LO) measured as m^2.year. Additional results are expressed for relevant (avoided) processes in terms of eutrophication potential (kg PO_4 eq.), acidification potential (kg SO_2 eq.) and fossil resource depletion potential (MJ eq.) (CML - Department of Industrial Ecology, 2010) to indicate outcomes for important impacts relating to nutrient leakage and energy security. Flows of land, food and energy are balanced within the life cycle inventories of two main scenarios representing higher and lower prioritisation of AD (Table S2-2a-f), to elucidate relationships in the food-energy-climate nexus (Fig. 1). System boundaries start at the point of waste collection, and are expanded to account for displaced *(inter alia)* marginal separated food waste management (in-vessel composting), energy generation, and food and animal feed production as environmental credits (Fig. 1), with a consequential LCA framework similar to Styles et al. (2016) and Bishop et al. (2021).

A factorial approach is taken to enable efficient exploration of pertinent factors, based on two scenarios (testing the comparative GHG mitigation efficacy of AD against alternative options) and three contexts (testing the influence of wider decarbonisation on comparative GHG mitigation efficiency). Two national scenarios represent maximum industry projections of AD deployment (*AD_{max}*) or maximum circularity (*Circular*) – based on the waste hierarchy and findings from recent studies that indicate higher-value, more circular uses of prospective AD feedstocks (Albizzati et al., 2021b; Bishop et al., 2021; Moult et al., 2018; Salemdeeb et al., 2017; Schestak et al., 2022). These scenarios are stylised and assume future modification of health & safety constraints around use of waste-derived animal feeds a (Salemdeeb et al., 2017; van

Table 1
Quantities of feedstock going to different end-of-life options under *AD-max* and *Circular* scenarios, across the three decarbonisation contexts, expressed as Gg fresh matter (FM) per year for the UK.

Feedstock	Management	CURRENT		Low-GHG		NZ-GHG	
		AD_{max}	*Circular*	AD_{max}	*Circular*	AD_{max}	*Circular*
		Gg yr^{-1} FM					
Primary production food waste	Prevention	260	1,286	260	1,286	260	1,286
	Animal feed	1,994	1,511	1,994	1,511	1,994	1,511
	AD	1,346	803	1,346	803	1,344	803
Manufacturing food waste	Prevention	376	901	376	901	376	901
	Animal feed	866	731	866	731	866	731
	Animal feed-insects						
	AD	1,285	894	1,285	894	1,285	894
Retail food waste	Prevention	113	118	113	118	113	118
	Animal feed	45	45	45	45	45	45
	AD	134	131	134	131	134	131
Catering food waste	Prevention	141	357	141	357	141	357
	Animal feed		153		153		153
	AD	879	510	879	510	879	510
Household food waste	Prevention	1,491	3,551	1,491	3,551	1,491	3,551
	Animal feed						
	Animal feed-insects						1,777
	AD	5,609	3,551	5,609	3,551	5,609	1,777
Food waste total	**Prevention**	**2,381**	**6,213**	**2,381**	**6,213**	**2,381**	**6,213**
	Animal feed	**2,905**	**2,440**	**2,905**	**2,440**	**2,905**	**2,440**
	Animal feed-insects						**1,777**
	AD	**9,253**	**5,891**	**9,253**	**5,891**	**9,253**	**4,114**
Industrial waste	**Animal feed**	**0**	**453**	**0**	**453**	**0**	**453**
	AD	**905**	**453**	**905**	**453**	**905**	**453**
Maize	**AD**	**6,102**	**0**	**6,102**	**0**	**6,102**	**0**
Grass	**AD**	**7,322**	**0**	**7,322**	**0**	**7,322**	**0**
Pig slurry	**AD**	**19,149**	**19,149**	**19,149**	**19,149**	**10,978**	**10,978**
Cattle slurry	**AD**	**87,540**	**87,540**	**87,540**	**87,540**	**50,184**	**50,184**
Poultry manure	**AD**	**13,131**	**13,131**	**13,131**	**13,131**	**7,528**	**7,528**
Insect manure	**AD**	**0**	**0**			**0**	**1,144**

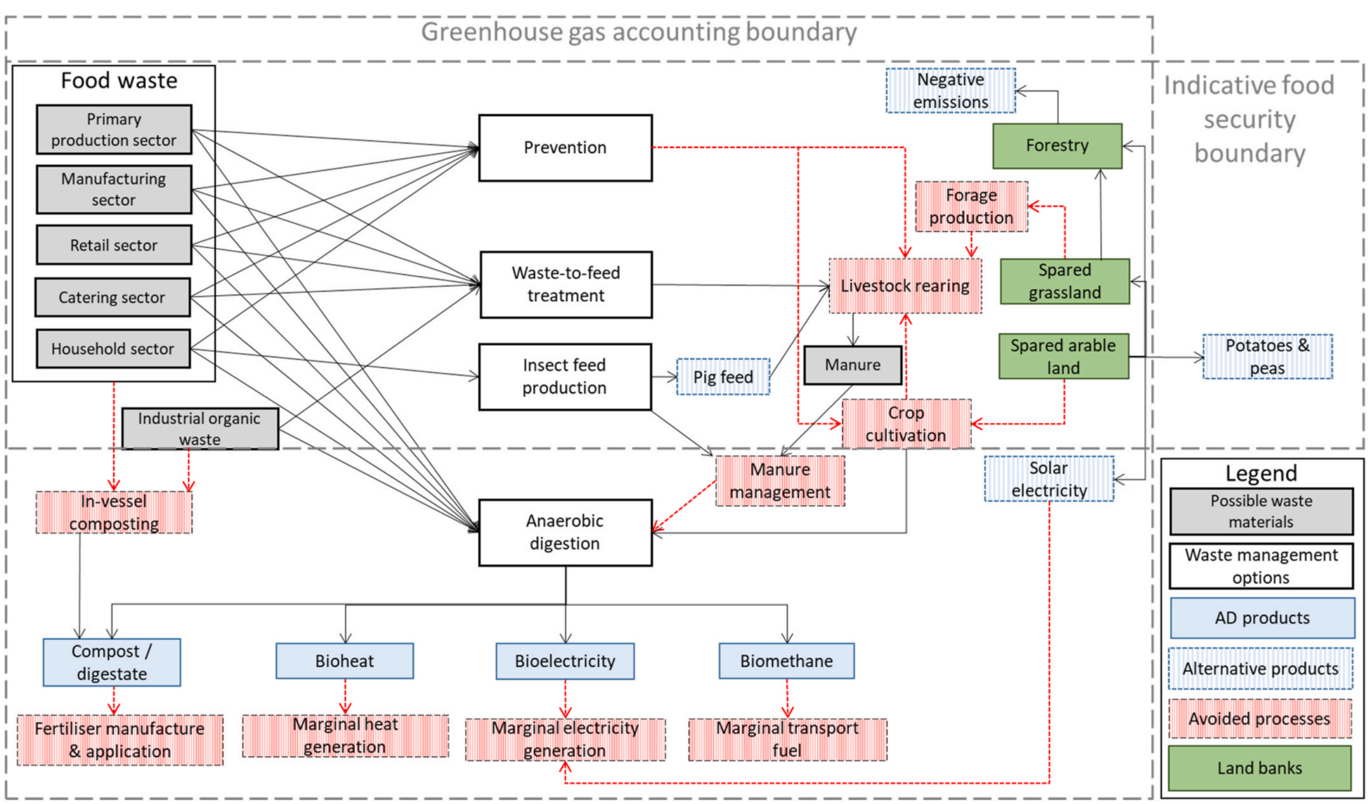

Fig. 1. Major incurred and potentially avoided (dashed boxes) processes accounted for within the life cycle assessment boundary. Potato and pea cultivation not included within GWP calculations, but used to present alternative energy and food security implications of land sparing within scenarios.

Zanten et al., 2015; zu Ermgassen et al., 2016).

Scenarios are evaluated within three decarbonisation “contexts”: (i) current technology (*CURRENT*); (ii) 80% decarbonisation (*LOW-GHG*) in line with core projections for the year 2050 made by the UK Committee on Climate Change (CCC, 2019); (iii) net zero GHG emissions (*NZ-GHG*) in line with UK CCC “Further Ambition” projections and representing near full deployment of lowest-emission technologies. The two scenarios are independent of the three decarbonisation contexts, with the exception of treatment of HH food waste in the *NZ-GHG* context (Table 2), where a higher degree of legislative and technological ambition is linked with diversion of 50% HH food waste diversion to animal feed via insect feed production (van Zanten et al., 2015).

National quantities of the five aforementioned food waste categories are used to estimate specific fractions of food waste that can be prevented or diverted (next section). Results are calculated separately per Mg of fresh matter for all waste and crop flows, and for all fates, across the three decarbonisation contexts, before aggregated results are calculated for total flows at national level in the two indicative scenarios. Avoided food, feed and AD-crop production result in land sparing. Spared land is assigned to indicative best-case uses in line with climate neutrality, energy- and food-security objectives: afforestation of spared grassland to sequester CO_2, generation of solar photovoltaic (PV) electricity on cropland spared from purpose-grown AD crops, and indigenous food production on cropland spared from food and animal feed production (Fig. 1). The geographic scope of analysis is the UK for foreground data (though background data for incurred or avoided activities, including food and feed production, also represent overseas activities). The temporal scope ranges from today up to circa 2050, in line with decarbonisation projections (CCC, 2019).

2.2. Scenarios

Two stylised national scenarios are evaluated to assess the comparative GHG mitigation efficacy of four categories of AD feedstock: food waste, industrial biowaste, purpose-grown crops and animal manures. Food waste is studied in particular detail, considering three prospective circular management options: (i) anaerobic digestion; (ii) preventing food waste arising via changes in business practises and consumer behaviour; (iii) diversion to animal feed (following heat treatment for retail and catering wastes, and following fly-egg larvae production for HH food waste in the *NZ-GHG* context). Once food wastes are separated from packaging, there are few constraints to treatment via AD. In contrast, prevention of food waste depends on the specific fraction (e.g. fruit stones and meat bones are “unavoidable” waste) and diversion of food waste to animal feed is governed by strict food safety legislation in Europe (REGULATION (EC) No 1069/2009, 2009; zu Ermgassen et al., 2016). Thus, in order to estimate plausible levels of prevention and diversion to animal feed, it is necessary to categorise food waste according to its origin and composition. We evaluate waste from five stages of the food chain (Table 1) based on data from the UK Waste & Resources Action Programme (WRAP, 2016; 2018b; 2018a, 2019). Compositions by stage are displayed in Tables S2–1. Aggregated food categories (e.g. “Meat”, “Meat & fish”, “Dairy & eggs”, “Produce”, Ready meals”) are disaggregated based on consumption data (detailed in Tables S1–1). Specific composition of each waste stream is used to calculate, *inter alia*, avoidable upstream production burdens via prevention, feed-replacement value, biogas yield and fertiliser replacement value of the digestate (or counterfactual compost).

Table 1 displays the quantities of food waste managed according to the possible options under the AD_{max} and *Circular* scenarios. For the AD_{max} scenario, food waste composition and management data are taken

Table 2
Evolution of key parameters pertinent to calculating the GHG and land balance of biowaste management options (prevention, diversion to animal feed and anaerobic digestion) within three decarbonisation (prevailing technology) contexts (*CURRENT* technology, *LOW-GHG* emissions and net zero *(NZ-) GHG* emissions). Food waste is categorised as arising from primary production (PP), manufacturing (M), retailing (R), catering (C) and households (HH). Red text and cell shading relates to avoided processes.

		Context		
		CURRENT	***LOW-GHG***	***NZ-GHG***
Food waste flows	AD_{max} scenario (details in Table S2-1)	Prevention and diversion to animal feed of fractions of waste streams based on WRAP (2016, 2018, 2019) projections. All remaining separated food waste* goes to AD.		
	Circular scenario (details in Table S2-1)	Additional prevention and diversion to animal feed of fractions of projected waste streams, to achieve a 50% reduction in food waste relative to current situation. All remaining separated food waste* goes to AD.		In addition, 50% of remaining HH waste is converted to animal feed via housefly larvae meal.
	Counterfactual management food waste	In-vessel composting of all separated food waste, with energy inputs and fertiliser substitution credits based on marginal burdens across the three contexts		
Manure flows	AD_{max} scenario	87% handled cattle, pig & poultry slurry diverted to AD		100% of cattle, pig, poultry & insect slurry diverted to AD (50% reduction in livestock)
	Circular scenario	87% handled cattle, pig & poultry slurry diverted to AD		100% cattle, pig & poultry slurry diverted to AD (50% reduction in livestock)
	Counterfactual management of manures	Open tank storage, broadcast application	50% reduction in counterfactual manure storage & application emissions	75% reduction in counterfactual manure storage & application emissions
Energy generation	Biomethane use 1	CHP elec. gen. (heat used for digester)	CHP elec. gen., 50% CCS	CHP elec. gen., 100% CCS
	Biomethane use 2	Transport fuel (90% biomethane, 10% parasitic demand)		
	Biomethane use 3	Heat (10% parasitic use)	Heat (10% parasitic use)	Heat (10% parasitic use)
Substituted energy	Marginal electricity	Natural gas	Natural gas, 50% CCS	Solar PV
	Marginal transport fuel	Diesel	Electricity	Electricity
	Marginal heat	Natural gas	Natural gas	Biomass (or hydrogen)
Feed (from “waste”) prod.	Processes	Transport (all FW stream), sterilisation (M & R streams)	Transport (all food waste streams), sterilisation (M & R streams)	Transport (all food waste stream), sterilisation (M & R streams), insect feed production (C & HH streams)
Substituted food & feed	Marginal (substituted) animal feed	Soybean meal (protein) & maize (energy)	Soybean meal (protein) & maize (energy)	Soybean meal (protein) & maize (energy)
	Marginal food & feed production	Current burdens (Ecoinvent v3.6)	Intermediate current and NZ-GHG burdens	Ecoinvent v3.6 burdens scaled down according to Lamb et al. (2016) projections
Digestate use	Spreading emissions	MANNER-NPK for shallow injection application, annual average and IPCC (2006) emission factors		
	Fertilisation efficacy	MANNER-NPK for shallow injection application, annual average		
Substituted fertilisers	Fertiliser manufacture	Current burdens (Ecoinvent v3.6)	50% of current burdens	10% of current burdens
	Spreading emissions	IPCC (2006) emission factors		

*”waste” excludes “surplus”, defined as streams redistributed for human consumption, sent to animal feed, or used for bio-products.

from WRAP (2016, 2018, 2019), reflecting targets for a reduction in annual post-farm-gate food waste from 10.2 million tonnes in 2007 to 7.7 million tonnes by 2030 (WRAP, 2019; WRAP, 2021). We generate a stylised scenario of maximum AD deployment by assuming all waste that is not prevented or diverted to animal feed goes to AD, alongside quantities of industrial biowastes, manures and crops in line with AD industry projections for 80 TWh of biomethane to be produced by 2030 in the UK (ADBA, 2018). For the *Circular* scenario, appropriate food waste streams are prevented or diverted to animal feed in order to meet the UN Sustainable Development Goal target to halve food waste, using a 2015 baseline – from 11.8 to 5.9 million tonnes yr^{-1}. Some regulatory change is assumed to allow catering waste and some meat products to go into the non-ruminant animal feed chain following heat treatment (Dou et al., 2018; zu Ermgassen et al., 2016). The volume of food waste going to AD reduces by 36%–56% relative to the AD_{max} scenario (Table 1). The largest share of food waste sent to AD is from households (Table 1), reflecting the dominance of post-consumer waste generation in industrialised countries (Parfitt et al., 2010) and the difficulty diverting this waste to alternative, higher-value uses owing to hygiene and regulatory constraints (Luyckx et al., 2019).

ADBA (2018) projections of future biomethane production include circa 1 TWh yr^{-1} from "industrial wastes", such as solid residues from alcohol production, and 13 TWh yr^{-1} from bioenergy crops. In the absence of a detailed breakdown for industrial biowaste, we use aggregate food waste as a proxy and infer a volume of 906 Gg FM going to AD in the AD_{max} scenario, half of which may be diverted to animal feed in the *Circular* scenario (Table 1). We split bioenergy crops evenly between maize and ryegrass, and assume zero use of bioenergy crops in the *Circular* scenario (Table 1).

Projections for up to 20 TWh of biomethane from farm animal wastes by 2030 (ADBA, 2018), equate to 119,821 Gg FM (87% of the manure quantity collected in 2008: Tables S1–3) based on the upper end of specific biomethane yields (Styles et al., 2016). We use the total quantity of manure inferred from ADBA and the composition reported by ADAS (2009) to determine manure quantities by livestock type sent to AD (Table 1). For the *NZ-GHG* context, we assume that the volume of handled manure declines by 50% (68,689 Gg FM), representing a dietary shift away from meat (CCC, 2019), but that all this manure is sent to AD, resulting in a net 43% reduction in digestion of manures compared with *CURRENT* and *Low-GHG* contexts (Table 1). Insect manure is also sent to AD in the *Circular* scenario, *NZ-GHG* context. Note that we do not model the upstream food system and land sparing effects of the implied dietary shift, which is outside the scope of this study.

2.3. Decarbonisation contexts

Three indicative decarbonisation contexts are considered to evaluate the influence of wider decarbonisation on the comparative GHG mitigation efficacy of AD. Table 2 summarises key parameters across the three decarbonisation contexts for the two scenarios. The *CURRENT* context represents current marginal energy generation and food and feed production GHG intensities; (2) the *LOW-GHG* context represents strong decarbonisation across food, feed and energy sectors, in line with UK CCC core projections (CCC, 2019), and; (3) the *NZ-GHG* context represents ambitious decarbonisation plus offset across energy and land use sectors (CCC, 2019), including advanced "sustainable intensification" (Lamb et al., 2016) – full details in Tables S2–3. Best practise is assumed for AD digestate management in all cases (i.e. sealed storage tanks and shallow-injection application), but the efficiency of AD increases from average biomethane yields and 40% conversion efficiency of biomethane lower heating value (LHV) to electricity in the *CURRENT* context (Styles et al., 2016) to high biomethane yields and 55% conversion of biomethane LHV to electricity in the *LOW-GHG* and *NZ-GHG* contexts. Biomethane leakage of 1% is assumed from the digester and 1.5% from digestate storage (Adams and McManus, 2019; Styles et al., 2016). Emissions intensities and land requirements for food and feed production decline across the increasingly ambitious decarbonisation contexts, but less markedly than for energy generation – based on sustainable intensification projections for major UK crop and animal systems (Lamb et al., 2016). For most food and feed products, GHG intensities decline by around 50–75%, and land requirements by 25–65% (details in Tables S2–3), relative to current values taken from Ecoinvent v3.6 (Wernet et al., 2016).

We model biomethane use for electricity generation, heat production and transport fuel to compare performance against evolving counterfactual marginal energy sources along the increasingly ambitious decarbonisation contexts (Table 2). The same marginal energy sources also satisfy additional energy and transport inputs across scenarios. Notably, CCS is applied to 50% of natural gas and biomethae combustion for electricity generation in the *LOW-GHG* context, and to 100% of biomethane combustion for electricity generation in the *NZ-GHG* context, in line with CCC (2019) projections. Thus, electricity generated from biomethane replaces electricity generation from natural gas without or with CCS, or from solar PV, across the increasingly ambitious decarbonisation contexts (Table 2). Electrification of transport is accompanied by reduced burdens from battery life cycles as decarbonisation progresses (Tables S2–3), and extends to heavy goods vehicles (HGVs) in the *LOW-GHG* and *NZ-GHG* contexts based on recent feasibility assessment (Ainalis et al., 2020). Similarly, counterfactual (avoided) emissions of CH_4 and N_2O from the storage and application of manures also reduce with increasing decarbonisation, by up to 75% in the *NZ-GHG* context compared with the *CURRENT* context – this ambitious level of emission reduction in the absence of AD (Lanigan and Donnellan, 2018) is conservative with respect to study conclusions, and is varied in sensitivity analyses. Whilst energy inputs to in-vessel composting (prevailing counterfactual management avoided by all modelled food waste management options) decline through time, the embodied emissions associated with manufacture of substituted fertilisers also decline through time by 90%, in line with energy decarbonisation, so that the net GWP burden of avoided in-vessel composting actually increases slightly (Tables S2–3). The assumptions underpinning these decarbonisation contexts are uncertain and not intended as projections of the future, but, when combined with appropriate sensitivity analyses, allow for exploration of AD efficacy when interacting with plausible, transparently-parameterised future systems.

Sensitivity analyses are applied to explore the sensitivity of results to differential decarbonisation pathways across food production, waste management and energy generation. *CURRENT* and *NZ-GHG* context processes are mixed to identify the robustness of the main scenario results. The following three sensitivity contexts are explored:

- S1: *CURRENT* (avoided) energy burdens, *NZ-GHG* (avoided) food & waste burdens (creating GHG mitigation "bias" towards energy generating credits, that could improve comparative GHG mitigation in the AD_{max} scenarios)
- S2: *CURRENT* food & waste burdens, *NZ-GHG* energy burdens ("bias" towards food production and waste avoidance, that could improve comparative GHG mitigation in the *Circular* scenarios)
- S3: *NZ-GHG* without successful CCS deployment on biogas-CHP, to test long-term sensitivity to this uncertain technology (Muri, 2018).

2.4. Life cycle inventories

Varying compositions and counterfactual activities across the five food waste categories (by stage), two scenarios and three decarbonisation contexts require separate modelling of 30 food waste streams. Disaggregated life cycle inventories, expressed as material flows and processes related to one Mg fresh matter AD feedstock, are displayed in Table S2-2a-f, representing AD_{max} and *Circular* scenarios across the three decarbonisation contexts. Pertinent details are elaborated below. Environmental burdens for all background processes are obtained from Ecoinvent v3.6 (Wernet et al., 2016), modified to account for future efficiency improvements (elaborated later).

The environmental balance of AD is calculated for the three main biomethane use options under each context (Table 2). To aggregate results at national level, the biomethane use option that generates the greatest GHG mitigation is selected (Table 3) – a conservative approach in the context of our conclusions. Similarly, afforestation of all spared land is modelled to estimate maximum GHG mitigation potential of waste prevention and diversion to animal feed. To aggregate results at national level, relevant alternative land uses are linked to specific "parcels" of spared land. Grassland spared from animal rearing and AD-grass is afforested, whilst all arable land spared from food and feed production is used to produce food directly for human consumption (potatoes and peas as proxies for carbohydrate and protein production) and all arable land spared from AD-maize cropping is used for solar PV electricity generation – or forestry in the case of *NZ-GHG* where solar PV is already the marginal energy source (Table 3).

2.5. Livestock feed production via insect larvae meal

Conversion of HH food waste into animal feed via insects within the *Circular* scenario *(NZ-GHG* context) is modelled based on an LCA study producing house fly (*Hermetia illucens*) meal from food waste (van Zanten et al., 2015). One Mg of DM larvae meal requires 12.2 Mg waste, 378 kWh of electricity and 183 kWh of natural gas for heating. We simplify the scenario by substituting the ca. 12% of feed as chicken manure considered in that study with food waste on a dry matter basis, avoiding manure handling emissions. Energy is sourced from renewables in the *NZ-GHG* context (Table 1). Based on data presented by van Zanten et al. (2015), one Mg of DM larvae meal can replace 0.5 Mg DM soybean meal, and gives rise to 7.88 Mg of insect manure with N, P_2O_5 and K_2O nutrient concentrations of 12.46, 6.53 and 4.49 kg Mg^{-1}, respectively. This manure is sent to AD, in line with the principle of circularity.

2.6. Credits for avoided food & feed production

Food waste prevention across all stages (Table 1) leads to avoided production of constituent food groups, and thus environmental credits – directly (Tables S2–3) and indirectly via alternative use of spared land (Fig. 1). Food waste diverted to animal feed is first heat treated, with heat and electricity inputs taken from De Menna et al. (2019). Context-specific marginal heat and electricity sources are applied (Table 1). Aggregate energy and protein contents per Mg of food waste are used to calculate quantities of marginal feed ingredients avoided using linear optimisation to balance out digestible energy and crude protein against replaced maize grain as a marginal energy feed and soybean meal as a marginal protein feed (Tables S1–3). Avoided burdens and areas of land spared via animal feed substitution are then calculated using context-specific burdens for soybean meal and maize listed in Tables S2–3, scaled (Table 2) from Ecoinvent v3.6 values (Wernet et al., 2016). Land requirements for food and feed production in the *NZ-GHG* context are based on technical potential yields for cereals, oil seeds, potatoes, sugar beet, fruit & vegetables and grass summarised in Table 1 of Lamb et al. (2016). For beef, dairy and lamb production, land area requirement is reduced through multiplication by the ratio of feed conversion factor improvement (MJ feed per kg output in 2050 divided by MJ feed per kg output in 2010) reported in Lamb et al. (2016). GWP reductions for crop-derived products are set at twice the yield improvement, reflecting concurrent decarbonisation of energy (Table 2 & Tables S2–3) required for fertiliser manufacture, field operations, processing and transport. Following land (feed) efficiency scaling, pork and poultry GWP burdens are scaled down by a further 25% to represent potential advancements in housing and manure management technologies to reduce animal-related emissions. Beef, dairy and sheep production GHG emissions are not scaled down beyond feed conversion ratio and grassland use efficiency, reflecting constraints to mitigation of enteric methane emissions that dominate carbon footprints from cattle and sheep systems (FAO, 2018). Nonetheless, the GWP footprint of beef reduces by 63% between *CURRENT* and *NZ-GHG* contexts (Tables S2–3). Optimistic reductions in the *NZ-GHG* context reflect outcomes associated with widespread and deep "sustainable intensification" (Lamb et al., 2016). Food and feed footprints in the *LOW-GHG* context are fixed as median points between *CURRENT* and *NZ-GHG* contexts.

Table 3
Best-case biomethane uses, and indicative best case land uses attributed to land spared from food production (prevention), animal feed production and AD-cropping, in the national extrapolation.

Management option	Context	Biomethane use	Spared grassland	Spared arable land
Prevention	ALL	NA	Forestry	Potato & pea cultivation
Animal feed	ALL	NA	NA	Potato & pea cultivation
Anaerobic digestion (alternative land use)	*CURRENT*	Transport fuel	Forestry	Solar PV
	LOW-GHG	Heating fuel	Forestry	Solar PV
	NZ-GHG	Electricity generation (CCS)	Forestry	Forestry

2.7. Utilisation of spared land

Land areas spared from waste prevention, substitution of animal feeds and avoided AD-crop cultivation are calculated based on context-specific land footprints listed in Tables S2–3. Land occupation is categorised as "arable" or "grassland" based on the following approximations: all crops, 100% arable; fruit & veg., 50% arable; dairy derived products, 20% arable; meat derived products, 5% arable. Afforestation of spared land (grassland plus arable land spared from food and feed production) results in annual C sequestration of 3600 kg C ha^{-1} based on average values for temperate forest regeneration provided in Searchinger et al. (2018). Solar PV electricity generation on land spared from AD-maize cultivation is calculated based on annual electricity output of 44 kWh m^{-2} yr^{-1} (Westmill Solar park, 2020), generating a GWP credit based on substitution of an equivalent quantity of marginal electricity generation (Table 2) minus the current GWP footprint for electricity generated by a 570 kWp open ground installation listed in Tables S2–3 (Wernet et al., 2016). Emissions associated with additional electricity storage requirements for solar PV vs bioelectricity (Vandepaer et al., 2019) are not explicitly considered, but are implicitly accommodated by conservatively holding the GWP footprint of solar PV electricity at current levels through the *LOW-GHG* and *NZ-GHG* contexts. As a proxy for food security implications attributable to waste diversion, potatoes and peas are harvested at average UK yields (2013–2017) of 41.6 Mg ha^{-1} yr^{-1} and 4.4 Mg ha^{-1} yr^{-1}, respectively (UN FAO Stat, 2019) on spared arable land (50/50 area split): these yields increase in line with aforementioned crop productivity improvements based on Lamb et al. (2016) across the *LOW-GHG* and *NZ-GHG* contexts. Calculation of GHG emissions incurred and avoided (through import substitution) from this simple food security measure are outside the scope of this study.

3. Results

3.1. GHG mitigation efficacy of anaerobic digestion

Per Mg fresh matter (FM) digested, food waste and poultry manure generate the largest net GWP credits, owing to a combination of avoided waste management, soil C sequestration and fertiliser substitution, in addition to energy substitution (Fig. 2a & Tables S2–4). Cattle and pig manures generate smaller credits owing to lower avoided counterfactual storage emissions and lower biomethane yield (reflecting low dry matter content, just 4% in the case of pig manure). Meanwhile, maize and grass

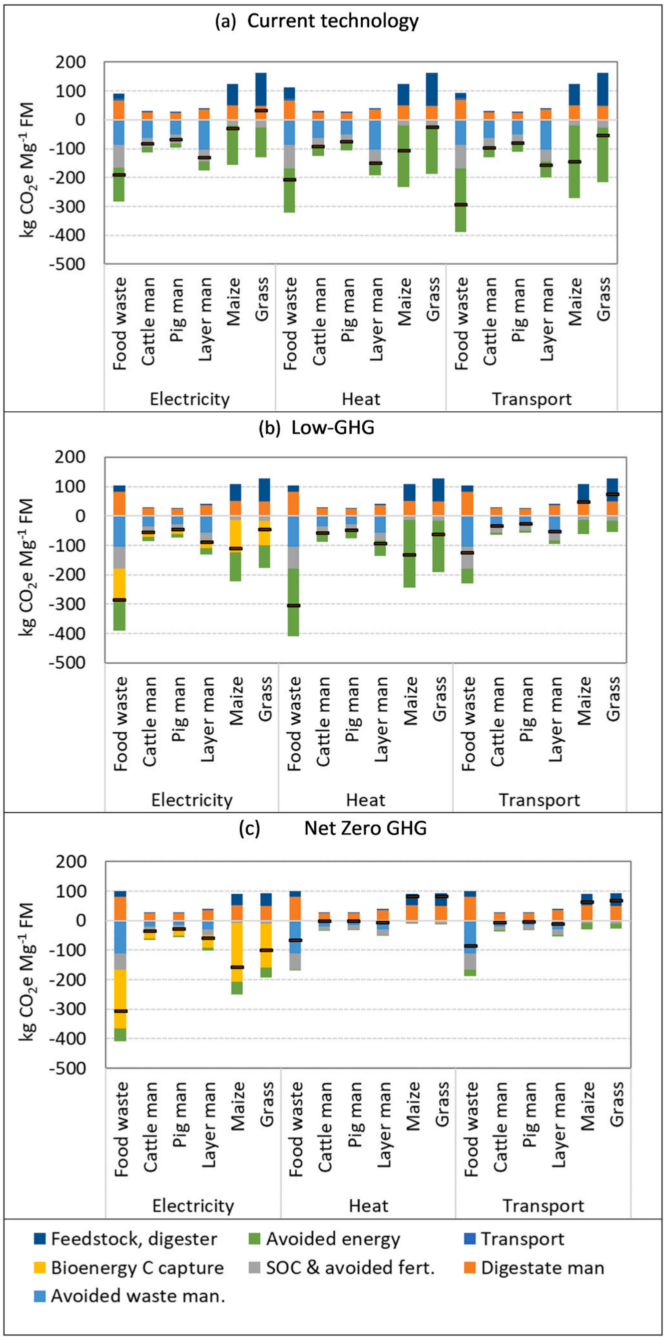

Fig. 2. Global warming potential balance of anaerobic digestion of different feedstocks under different end uses of the biomethane (for electricity generation, heat production or as a transport fuel), and under different contexts – *CURRENT* technology (top), *LOW-GHG* (middle), net zero *(NZ-) GHG* (bottom). The net balance represents sum of emissions from incurred processes (e.g. transport of feedstock, fugitive and combustion emissions from digestion, emissions from digestate management) minus: (i) credits (avoided emissions) from avoided waste management, avoided synthetic fertiliser production and use, and avoided energy carriers; (ii) soil organic carbon storage (SOC) associated with digestate application; (iii) bioenergy carbon capture & storage. Carbon opportunity costs of land use are excluded here for crop feedstocks.

generate relatively large energy credits per Mg FM but also considerable emissions during cultivation (fertiliser manufacture and soil nitrous oxide emission) and digestion (methane leakage). Thus, even in the *CURRENT* context with high GHG-intensities from counterfactual energy, grass bioelectricity generation does not result in a net GWP saving (Fig. 2a). Energy credits are larger where biomethane replaces natural gas heating or diesel transport fuel, with net GWP credits from biomethane transport fuel ranging from 56 kg CO_2 eq Mg^{-1} FM grass to 295 kg CO_2 eq Mg^{-1} FM food waste under the *CURRENT* context (Fig. 2a).

As decarbonisation progresses along the *LOW-GHG* to *NZ-GHG* contexts (Fig. 2b&c), the efficiency of AD (biomethane yield, electrical conversion) increases, leading to larger credits, whilst emissions from crop cultivation decrease (Tables S2–3). Credits from avoided manure storage also decrease, but credits from avoided waste management (via composting) remain relatively constant owing to counteracting effects (lower energy burdens but also smaller fertiliser credits from compost use). For electricity generation, CCS contributes substantially to net emission avoidance (though also curtails emissions credits from avoided natural gas electricity generation). Biomethane generation of electricity and heat achieves larger GWP savings in the *LOW-GHG* context compared with the *CURRENT* context, on the assumption that natural gas remains the marginal energy source replaced by biomethane (CCC, 2019). Net GWP credits from AD when biomethane is used to replace natural gas heating range from 64 kg CO_2 eq Mg^{-1} grass to 308 kg CO_2 eq Mg^{-1} food waste (Fig. 2b). However, transport electrification in the *LOW-GHG* context means that avoided transport credits are much smaller, and growing maize or grass to produce transport biomethane leads to a net increase in GWP burden (Fig. 2b). The GHG mitigation efficacy of AD diminishes dramatically under the *NZ-GHG* context owing to extensive decarbonisation of energy carriers and reduced credits from avoided manure management emissions (Fig. 2c). Food waste is the only feedstock to generate a significant credit when biomethane is used for heating or transport fuel. However, using biogas to generate electricity results in substantial GHG mitigation, ranging from 30 kg CO_2 eq Mg^{-1} FM pig manure to 308 kg CO_2 eq Mg^{-1} FM food waste (Fig. 2c).

3.2. Comparative mitigation efficiency of alternative options

Table 4 displays the main environmental credits generated by AD of food wastes and crops compared with alternative food waste and land use options, based on environmental balance of: (i) the most favourable biomethane uses in each context; (ii) avoided food production (waste prevention); (iii) avoided animal feed production (waste diversion); (iv) afforestation or solar PV electricity generation as alternative land use options. Results for individual food waste categories are shown in Tables S2–5, whilst full LCA results are displayed for GWP in Figs. S1-1 to S1-3 (net credits include avoided waste management and sterilisation burdens, but are similar to gross credits displayed in Table 4). Notably, animal feed diversion or waste prevention credits are at least 1.5 to 3 times larger than AD credits for food waste in the *CURRENT* context, concurring with results of recent studies (Albizzati et al., 2021a; Moult et al., 2018; Salemdeeb et al., 2017). Waste prevention credits are highly sensitive to the waste composition, ranging from 1079 kg CO_2 eq. Mg^{-1} FM for PP waste in the AD_{max} scenario to 16,524 kg CO_2 eq. Mg^{-1} FM for M waste in the *Circular* scenario, under the *CURRENT* context (Tables S2–5) – reflecting a high share of meat, poultry, fish and dairy products in the M waste stream (Tables S2–1). Including potential afforestation of land spared from food and feed production increases GWP credits by up to a factor of four, to 9617 kg CO_2 eq. Mg^{-1} FM food waste prevented (Table 4). Despite declining prevention and animal feed credits through time owing to reduced carbon and land footprints of crop and animal production (Tables S2–3), food waste prevention and animal feed diversion remain considerably more effective than AD for GHG mitigation in the *NZ-GHG* context, but the differential is reduced compared with *CURRENT* and *LOW-GHG* contexts (Table 4).

Food waste also carries high embodied eutrophication, acidification and fossil resource depletion burdens, in particular the M & HH categories containing higher shares of animal-derived products (Tables S2–5) owing to high rates of reactive nitrogen leakage from livestock systems (Balmford et al., 2018; Pinder et al., 2012). Thus, average eutrophication and acidification burden savings are approximately 10 times higher for waste prevention than for AD, and avoided

Table 4
Environmental credits generated by anaerobic digestion of food waste, maize and grass compared with alternative (*Circular*) management options for food waste (prevention and diversion to animal feed) and land (afforestation or solar photovoltaic electricity generation) across the three decarbonisation contexts. Results displayed for global warming potential (GWP), with and without land sparing land use change (LUC) effects, eutrophication potential (EP), acidification potential (AP), fossil resource depletion potential (FRDP) and land occupation (LO). Negative values (red-shaded cells) indicate increased burdens.

		Option	GWP kg CO_2 eq. Mg^{-1}	GWP & LUC kg CO_2 eq. Mg^{-1}	EP kg PO_4 eq. Mg^{-1}	AP kg SO_2 eq. Mg^{-1}	FRDP MJ eq. Mg^{-1}	LO m^2.yr Mg^{-1}
CURRENT TECHNOLOGY	**Food waste**	AD (trans)	334	334	0.98	1.76	5,033	
		Prevention	1,889	9,617	10.13	13.93	4,819	5,849
		Animal Feed	525	1,539	3	4	1,927	767
	Maize	AD (trans)	146	146	-0.43	0.30	3,892	222
		Alt. solar PV		3,426	0.34	1.44	65,095	
	Grass	AD (trans)	56	56	0.70	0.00	2,732	250
		Alt. afforest.		330				
LOW-GHG	**Food waste**	AD (heat)	312	312	0.85	0.83	4,131	
		Prevention	1,262	6,666	7	9	2,997	4,084
		Animal Feed	329	1,182	2	3	1,226	645
	Maize	AD (heat)	134	134	-0.43	-0.44	3,376	190
		Alt. solar PV		1,464	0.3	1.2	55,657	
	Grass	AD (heat)	64	64	-0.57	-1.03	2,421	194
		Alt. afforest.		257				
NZ-GHG	**Food waste**	AD (CHP)	303	303	0.73	0.83	669	
		Prevention	686	3,755	4	6	1,501	2,319
		Animal Feed	115	553	1	2	406	332
	Maize	AD (CHP)	159	159	-0.25	-0.11	452	158
		Alt. afforest.		208				
	Grass	AD (CHP)	64	64	-0.57	-1.03	2,421	139
		Alt. afforest.		184				

fossil resource depletion is relatively similar for food waste prevention as for AD (Table 4) owing to avoided fossil fuel use in food value chains, including for fertiliser manufacture. Diversion of food waste to animal feed avoids crop cultivation, resulting in intermediate savings (Table 4 and Tables S2–5). Growing crops for AD is not environmentally advantageous overall, generating relatively small GWP credits per Mg, and incurring additional eutrophication and acidification burdens, across all contexts (Table 4). Alternative land uses (afforestation or solar PV electricity generation) are far more effective at mitigating GHG emissions and displacing fossil fuels. Solar PV electricity generation avoids 16 times more fossil energy and between four and 23 times more GHG mitigation compared with AD-maize grown on the same area of land, in the *CURRENT* and *LOW-GHG* contexts (Table 4). In the NZ-GHG context, solar-PV is the marginal electricity generating technology, so there would be no need for, and no credit associated with, solar PV generation on land spared from AD-maize cultivation. The GHG credits from afforestation of such land in this context remain larger than credits achievable with AD-BECCS (Table 4).

3.3. National mitigation potential of deployment scenarios

Fig. 3 and Tables S2–6 summarise national (UK) annual GHG mitigation potential for *Circular* and AD_{max} scenarios across the three decarbonisation contexts and for the three main alternative uses of biomethane. Table 5 summarises additional GHG mitigation, energy generation, and food protein and kcal production potential for the *Circular* vs the AD_{max} scenario, assuming best-case biomethane use. Despite considerable uncertainty around GHG mitigation achievable from alternative land use in particular, *Circular* scenarios clearly outperform AD_{max} scenarios for all metrics except direct GHG mitigation in the *NZ-GHG* context (owing to the strong mitigation potential of AD coupled with BECCS). Nonetheless, when alternative land use is factored in, the *Circular* scenario mitigates an additional 15% of projected gross UK GHG emissions in 2050 (CCC, 2019) in the *NZ-GHG* context (Table 5). Increasing crop yields through time translate into smaller areas of spared land as decarbonisation progresses, from 17% to 34% of arable and grassland areas in the *CURRENT* context, down to 8% and 14% of (current) arable and grassland areas in the *NZ-GHG* context (Table 5). These percentages are only indicative, because approximately half of UK food demand is imported (DEFRA, 2020), so that some of the land sparing realised by waste prevention (and indeed animal feed diversion) will occur outside of the UK. Despite producing less biomethane, *Circular* scenarios generate 118 to 237 PJ more energy than AD_{max} scenarios owing to solar PV generation. In terms of food security effects, yield

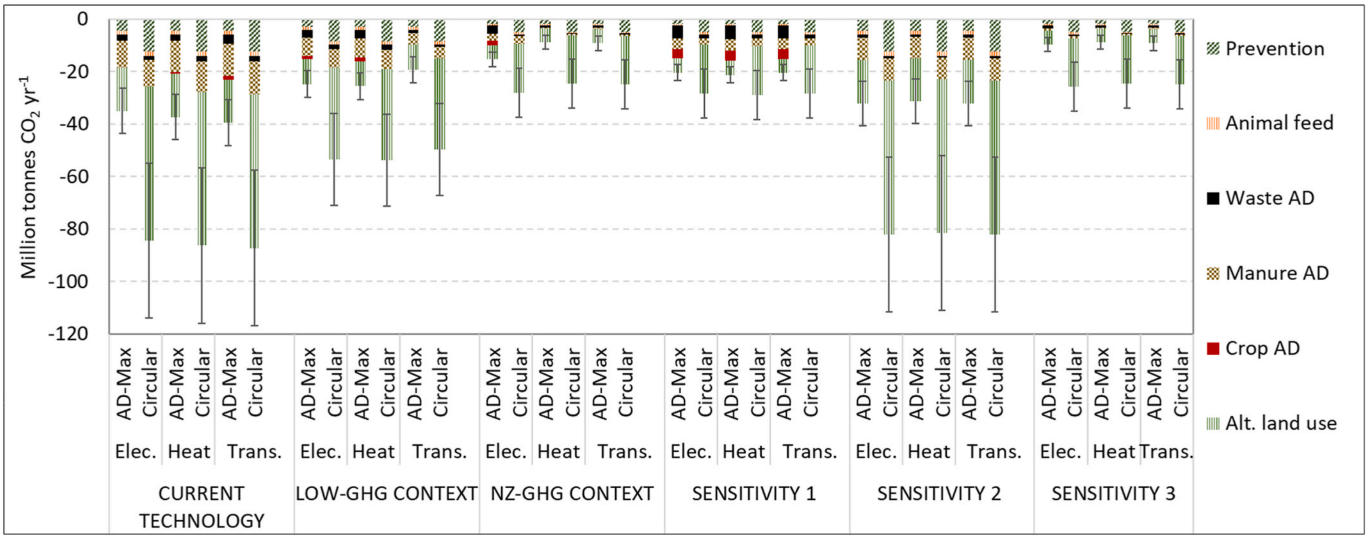

Fig. 3. Net GHG emission mitigation for the UK assuming maximum deployment of anaerobic digestion (AD_{max} scenario) or enhanced circularity (*Circular* scenario) under different contexts, from *CURRENT* technology, through *LOW-GHG* emissions to *Net Zero (NZ-)GHG* emissions. Sensitivity analyses systematically mix context assumptions (see S2-8). Contribution of waste prevention, waste conversion to animal feed, anaerobic digestion and potential alternative land uses are displayed, along with error bars representing uncertainty propagation across the aforementioned categories (see S2-6).

Table 5
Additional annual GHG mitigation and land sparing for the UK national *Circular* scenario compared with the AD_{max} scenario. Indicative alternative land uses (ALU) support further GHG mitigation (via afforestation of spared grassland), solar PV electricity generation (on land spared from AD-maize), and food protein and kcal production (on arable land spared from food and feed production). Negative values (red shading) indicate additional mitigation is achieved in the AD_{max} scenario. Annual differences are also expressed as a percentages of UK GHG emissions under the different contexts (Brown et al., 2019; CCC, 2019), and as a percentage of current primary energy (BEIS, 2019), food protein & kcal (British Nutrition Foundation, 2019) supplies.

	Dir. GHG mitigation	Spared arable land	Spared grassland	ALU GHG mitigation	ALU energy generation	ALU protein supply	ALU kcal supply
	Tg CO_2 eq.	M ha	M ha	Tg CO_2 eq.	PJ	Tg	trillion kcal
CURRENT	5.56	0.52	2.15	42.19	237.42	0.38	13.20
(% UK total)	(1%)	(17%)	(34%)	(9%)	(4%)	(21%)	(20%)
LOW-GHG	3.11	0.39	1.51	25.22	132.91	0.42	14.90
(% UK total)	(2%)	(13%)	(24%)	(13%)	(2%)	(23%)	(22%)
NZ-GHG	-0.62	0.26	0.87	13.24	117.85	0.38	13.64
(% UK total)	(-1%)	(8%)	(14%)	(16%)	(2%)	(21%)	(21%)

increases in energy and protein crops counter the declining land areas spared by enhanced circularity as decarbonisation progresses, so that additional arable land sparing in the *Circular* scenario is able to provide 20–23% of national protein and kcal requirements irrespective of the level of decarbonisation (Table 5).

3.4. Sensitivity analyses

Combining *CURRENT* (avoided) energy burdens with *NZ-GHG* (avoided) food production and waste management burdens (S1) increases GHG mitigation achieved by AD_{max} scenarios between 32% (AD-electricity) to 173% (AD-heat generation), relative to the straight *NZ-GHG* context (Table 6). *Circular* scenario mitigation increases by just 1% (AD-electricity) to 14% (AD-transport), but remains at least 36% higher than AD_{max} mitigation (Fig. 3; S2-8). Meanwhile, combining *CURRENT* (avoided) food production and waste management burdens with *NZ-GHG* (avoided) energy burdens (S2) increases AD_{max} mitigation by between 100% (AD-electricity) and 282% (AD-heat), and *Circular* mitigation by 193% (AD-electricity) to 229% (AD-heat) (Table 6). *Circular* mitigation remains approximately 2.7 greater than AD_{max} mitigation (Fig. 3). Finally, failure to successfully deploy BECCS on AD electricity generation in the *NZ-GHG* context would reduce GHG mitigation by 41% for the AD_{max} scenario, and 7% for the *Circular* scenario (Table 6). Nonetheless, AD-electricity remains the best performing energy conversion pathway in the NZ-GHG context (S2-8) owing to the significant embodied emissions in substituted solar PV generation (S2-3), from

Table 6
Sensitivity of net GHG mitigation results to mixed combinations of NZ-GHG and CURRENT context process assumptions, expressed as percentage change in mitigation vis-à-vis NZ-GHG results (full sensitivity results in S2-8).

Context variations	AD-electricity		AD-heat		AD-transport	
	AD-Max	Circular	AD-Max	Circular	AD-Max	Circular
S1: *CURRENT* energy burdens, *NZ-GHG* food & waste burdens	32%	1%	173%	17%	143%	14%
S2: *CURRENT* food & waste burdens, *NZ-GHG* energy burdens	100%	193%	282%	229%	265%	228%
S3: *NZ-GHG* without CCS	−41%	−7%	0%	0%	0%	0%

Ecoinvent (Wernet et al., 2016).

4. Discussion

4.1. Waste management

Anaerobic digestion is promoted as a green circular economy technology that supports energy generation and nutrient recycling (ADBA, 2018) whilst avoiding emissions from alternative biowaste management options such as landfilling, incineration, composting or conventional manure handling (Boulamanti et al., 2013a; Fusi et al., 2016; Lijó et al., 2014; Slorach et al., 2019). This study confirms that role, but also defines boundaries around the sustainable operating space for AD in the future as the waste management, energy and land sectors it straddles decarbonise at differential rates. Overall, the boundaries for sustainable AD deployment in future contexts are similar to those identified in the current context vis-à-vis biowaste management (Albizzati et al., 2021a; Styles et al., 2016; Tonini et al., 2018; Tufvesson et al., 2013). However, a key finding of this study is the magnitude of GHG mitigation, alternative renewable energy generation and food security that could be achieved through alternative uses of land spared from waste prevention or diversion to animal feed, and from cultivation of AD-crops. Agriculture continues to expand into native habitats globally (Persson et al., 2014), and nature-based solutions enabled by land sparing will be central to climate stabilisation (IPCC, 2019). Yet we are not aware of previous studies that have explicitly quantified these potential trade-offs in relation to food waste management and crop bioenergy via AD. Land opportunity costs help to maintain a clear GHG mitigation advantage for biowaste prevention and diversion to animal feed over AD under a *NZ-GHG* context where food production emissions are dramatically reduced. Wider LCA results presented here show that food waste prevention and animal feed diversion also confer environmental sustainability advantages compared with AD treatment in terms of nutrient cycling (avoided nutrient leakage), addressing key planetary boundary exceedances (Steffen et al., 2015). Perhaps counter-intuitively, waste prevention performs as well as AD in terms of (avoided) fossil resource depletion, reflecting the large amounts of fossil energy embodied in food and feed supply chains. National GHG mitigation estimates from indicative scenarios in this study are large compared with estimated mitigation of 10 Tg CO_2 eq. annually from a halving of meat consumption in the UK (CCC, 2020), confirming that waste management has a critical role to play alongside diet change in delivering climate neutrality. Nonetheless, even under optimistic projections for food waste prevention and diet change within the *NZ-GHG Circular* scenario presented here, over 74 million tonnes per year of residual wastes and manures remain available for sustainable management by AD in the UK.

4.2. Energy generation

This study provides new insight into the "sustainable niche" for AD in relation to decarbonising energy sectors, pertinent to policy and investment decisions in support of technological and behavioural transitions towards circularity and climate neutrality. The shift in optimal use of biomethane from transport fuel to large scale combustion as decarbonisation progresses is predicated on two important assumptions: (i) electrification (or hydrogen fuelling) of transport, including HGVs (Ainalis et al., 2020); (ii) widespread deployment of BECCS across large-scale biomethane combustion by 2050. Although commercially uncertain (Muri, 2018), BECCS features prominently in global scenario modelling for climate stabilisation (Huppmann et al., 2019), and is likely to be commercially viable at high carbon prices over the medium to long term. If this happens, AD will be transformed into a negative emission technology able to contribute towards maintaining climate neutrality (emissions and removals balance), gaining a comparative advantage over otherwise more land- and cost-efficient renewable energy sources such as wind and solar PV. Nonetheless, results presented here confirm that cultivation of crops specifically for AD should be avoided where possible, and confined to balance seasonal operation of AD facilities fed primarily by manures or wastes, confirming conclusions from previous studies (Adams and McManus, 2019; Styles et al., 2015). Meanwhile, it has recently been shown that forestry value chains provide an effective way to lock up carbon in biomass until BECCS becomes commercially viable (Forster et al., 2021), further supporting the important role of forestry identified in this study (here, we did not account for additional mitigation downstream in commercial forestry value chains). Thus, investment in alternative renewable energy technologies such as solar PV and wind combined with electricity storage, and afforestation, should be priorities for the transition to a circular, climate neutral future. Nonetheless, AD has an important role to play in providing a clean transport fuel in the short term (Ullah Khan et al., 2017), and a negative emission technology supplying dispatchable (carbon negative) renewable electricity or heat in the long term. Establishing flexible infrastructure and value chains for biomethane use in transport and industrial combustion could leverage maximum GHG mitigation over different time scales.

4.3. Limitations and wider applicability

Recent studies have called for the development of LCA databases containing future-oriented background data that would allow for harmonised modelling of prospective technologies in future contexts (Adrianto et al., 2021; Steubing and de Koning, 2021). Until such databases are developed to encompass all relevant processes, the targeted adaptation of specific processes in line with decarbonisation projections remains a state-of-the-art approach for undertaking forward-looking LCA comparison of prospective GHG mitigation strategies. The three stylised contexts presented here represent the current situation and general direction of travel towards a circular, net zero GHG emission economy, drawing on recent projections (CCC, 2019; Huppmann et al., 2019; IPCC, 2019; Lamb et al., 2016) to parameterise pertinent processes linked with AD deployment. The intention is not to predict particular time points in the future, but to show how the *comparative* performance of AD is likely to be influenced by *trends* associated with decarbonisation. We recognise the high uncertainty around the specific marginal consequences summarised in Table 2 and Tables S2–3; but this does not negate the value of those results in illuminating important relationships between decarbonisation across multiple interlinked systems (agriculture, energy generation, waste management) and the comparative environmental performance of AD. One specific simplification to constrain LCA boundaries and avoid a feedback loop was the substitution of the ca. 12% of insect feed made up by chicken manure with food waste. This simplification is not expected to meaningfully influence results because upstream land and GHG burdens of both these waste inputs are negligible (van Zanten et al., 2015).

Exploration of land use implications in relation to future AD deployment strategies is a critical novel component of this study, but is sensitive to the location of avoided food and feed production. Future studies could link food waste prevention and animal feed substitution with statistics on the origin of UK, European or global food and feed supplies to estimate where land sparing is likely to arise. Meanwhile, digestate management has a large influence on the environmental balance of AD. In line with the future-oriented focus of this study, tightly controlled digestate management is assumed to minimise eutrophication and acidification burdens (Boulamanti et al., 2013b; Duan et al., 2020; Rehl and Müller, 2011) and maximise fertiliser substitution. Future studies could explore deeper integration of AD into biorefining networks (Albizzati et al., 2021b; Stiles et al., 2018), including production of biofertilisers that can minimise emissions from digestate handling and improve nutrient cycling efficiency (Styles et al., 2018), or emerging bioeconomy "building blocks" such as polylactic and succinic acids (Albizzati et al., 2021b). Alternatively, food waste (Ardolino et al., 2018) or digestate could be gasified to maximise energy yield (Antoniou et al., 2019) – though there may be trade-offs with reduced nutrient recovery. Many permutations of AD deployment within the emerging bio-based, circular economy have yet to be explored in future prospective LCA studies.

Although the LCA modelling in this paper is framed in a UK context, the use of (adapted) *marginal* processes (rather than e.g. market mixes) from Ecoinvent means that results are generalisable across other industrialised countries where similar marginal processes predominate (e.g. natural gas power generation in the current context, with CCS in a significantly decarbonised context, and solar PV power generation in a net zero GHG context). Food waste composition may vary somewhat across countries, though variations in animal nutrition, biomethane yield and biofertiliser nutrient content across food waste categories studied here had only a modest influence on environmental balance, compared with large differences across management options. Furthermore, sensitivity analyses indicate that key conclusions on the sustainability advantages of *Circular* waste strategies over less targeted deployment of AD are robust, even under unlikely counterfactual combinations that favour AD, i.e. weak decarbonisation in the energy sector and strong decarbonisation in the agriculture sector.

5. Conclusions

Through application of prospective consequential LCA to stylised scenarios of AD deployment across three distinct decarbonisation contexts, this study provides new evidence on how the comparative environmental performance of AD might evolve as economies become more circular and move towards climate neutrality.

Many recent conclusions on sustainable AD deployment remain valid even with strong decarbonisation in the wider economy. Growing crops specifically for AD is an inefficient GHG mitigation option compared with alternative uses of land, such as solar PV electricity generation or afforestation, irrespective of wider decarbonisation context. But AD can leverage substantial environmental credits from avoidance of counterfactual food waste and manure management, though the latter credits are likely to decline as improved manure management is deployed. Net GHG mitigation from food waste AD is remarkably resilient to decarbonisation context, varying from 334 kg CO_2 eq. Mg^{-1} food waste in the current technology context to 303 kg CO_2 eq. Mg^{-1} food waste in the net zero GHG context – assuming optimal deployment and large-scale combustion of biomethane coupled with BECCS in future (transforming AD into a negative emissions technology). Adding to previous studies, we show that land sparing from waste prevention and diversion to animal feed (instead of AD treatment) can dramatically increase GHG mitigation, by up to 9.6 Mg CO_2 eq. per Mg food waste, though these counterfactual credits will decline with sustainable intensification. Compared with AD, biowaste prevention is also much more effective at reducing reactive nitrogen pollution, and saves similar amounts of fossil energy whilst sparing land to support energy and food security objectives. Nonetheless, even with optimistic projections of food waste reduction and diet change, large quantities of residual wastes and manures will remain available for sustainable treatment by AD in the future.

This study confirms that AD will remain an effective technology for GHG mitigation in future circular, low-carbon economies. However, it should be judiciously deployed (avoiding crop feedstocks) alongside ambitious waste prevention, alternative renewable energy generation and afforestation strategies in order to effectively deliver climate, food and energy security objectives. Carefully considered legislative revisions to allow the feeding of sterilised or insect-meal-converted food waste to livestock could constrain AD in favour of more climate-effective biowaste management. Strategic investment in AD infrastructure to allow flexible switching of biomethane use from transport to large scale combustion in BECCS systems could maximise GHG mitigation efficacy through time.

CRediT authorship contribution statement

David Styles: Conceptualization, Methodology, Formal analysis, Writing – review & editing, Project administration. **Jalil Yesufu:** Methodology, Formal analysis, Writing – original draft. **Martin Bowman:** Conceptualization, Writing – review & editing, Project administration. **A. Prysor Williams:** Methodology, Writing – review & editing. **Colm Duffy:** Methodology, Writing – review & editing. **Karen Luyckx:** Conceptualization, Writing – review & editing, Project administration.

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.

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Appendix A. Supplementary data

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