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David Styles[1,2], Jalil Yesufu[2], Martin Bowman[3], A. Prysor Williams[2], Colm Duffy[1], Karen Luyckx[3]

[1]Bernal Institute, School of Engineering, University of Limerick, Limerick, Ireland, V94 T9PX

[2]School of Natural Sciences, Bangor University, Bangor, Wales, LL57 2UW

[3]Feedback Global, 413 The Archives, Unit 10 High Cross Centre, Fountayne Road, Tottenham, UK N15 4BE

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.

Keywords: biogas; life cycle analysis; circular economy; insect feed; climate stabilisation; net zero

Graphical abstract
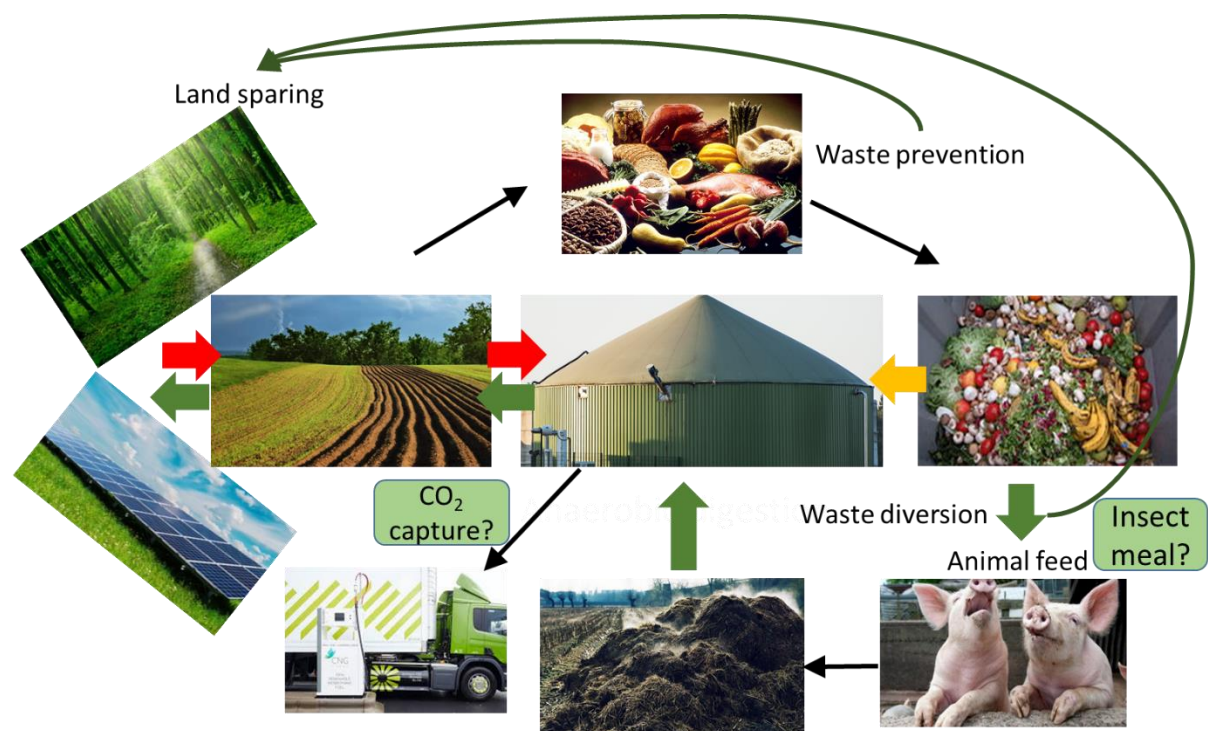
Highlights

- Consequential LCA of anaerobic digestion (AD) in future decarbonisation contexts
- GHG mitigation efficacy of AD declines as energy & transport systems decarbonise
- AD-crop cultivation is a highly inefficient land use for energy generation and GHG mitigation
- Carbon capture & storage could maintain effective mitigation from large-scale biogas use
- Sustainable niche for waste-AD alongside waste prevention & diversion to animal feed

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 & 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)(Liu et al., 2015; David Styles 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 remains the best option for food waste management at EU level. Nonetheless, biomethane use as a transport fuel has been shown to be an effective GHG mitigation option (D. 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 coordinated deployment (Lindfors et al., 2020). Recent energy-related incentives across Europe have driven expansion of crop-fed digesters to generate electricity (Nevzorova & 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 & 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; 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 & 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.,

89   2019; Buyle et al., 2019; Levasseur et al., 2010). These are pertinent issues in the context of the
90   dramatic reductions in GHG emissions that will be required to achieve the objective of climate
91   stabilisation set out in the Paris Agreement (Huppmann et al., 2018; Masson-Delmotte et al., 2019).
92   The concept of a circular economy (Stahel, 2016) is closely aligned with climate stabilisation, and
93   requires inter-systems thinking (Liu et al., 2015) to drive integration of economic sectors around
94   extended value chains that produce, use, re-use and finally recycle resources (Vaneeckhaute et al.,
95   2018). Thus, the future context in which specific technologies operate will be different. Widespread
96   deployment of green technologies should be informed by multi-decadal strategic investment
97   decisions (Guo et al., 2020). The performance of these technologies therefore needs to be assured
98   within the context of more circular and decarbonised economies (Adrianto et al., 2021; Forster et al.,
99   2021), requiring evidence beyond incremental reduction in the GHG intensity of production.

100   Recent studies have applied "anticipatory" LCA by applying projected emission factors for e.g.
101   electricity grid mixes (Albizzati et al., 2021b; Lefebvre et al., 2021; Vandepaer, Treyer, et al., 2019) or
102   energy carrier transitions (Maes et al., 2021) to identify the future likely performance of specific
103   technologies. Forster et al. (2021) showed that the climate mitigation efficacy of new forests is
104   highly sensitive to future substitution "credits" which depend on decarbonisation of concrete, steel
105   and energy, and on the deployment of carbon capture & storage (CCS) technology (Stavrakas et al.,
106   2018). Indeed, bioenergy CCS (BECCS) deployment is regarded as central to meeting 1.5 C climate
107   stabilisation (Masson-Delmotte et al., 2019; Muri, 2018), and could transform AD into a negative
108   emission technology–. However, there are concerns over land areas require to scale out BECCS
109   (IPCC, 2019). Changes in land requirements associated with different waste management strategies
110   and AD-crop production will have significant implications for alternative "nature based solutions" to
111   climate change, food production and energy generation – yet are not typically included in LCA
112   studies of waste management.

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

121

122

123   ## 2. Methodology
124   *2.1. Goal and scope*

125   The aim of this study is to evaluate the environmental performance of AD against the most
126   promising circular biowaste management, GHG mitigation and renewable energy generation
127   options, now and under future contexts of decarbonisation across critical interlinked systems.
128   Particular emphasis is placed on prevention and management of food waste, categorised along five
129   stages of the food supply chain associated with different prevention and management options:
130   primary production (PP); manufacturing (M); Retail (R); Catering (C); Household (HH). Other
131   dominant AD feedstocks are evaluated, namely, industrial biowastes, manures (pig, poultry and

132   cattle) and purpose-grown crops (maize and grass) (Table 1). An LCA approach is applied with a focus
133   on two core impact categories pertinent to the climate-energy-food nexus: global warming potential
134   (GWP), measured as kg CO_2 eq. (CO_2, CH_4 and N_2O = 1, 25 and 298, respectively: IPCC, 2007) and land
135   occupation (LO) measured as m^2.year. Additional results are expressed for relevant (avoided)
136   processes in terms of eutrophication potential (kg PO_4 eq.), acidification potential (kg SO_2 eq.) and
137   fossil resource depletion potential (MJ eq.) (CML - Department of Industrial Ecology, 2010) to
138   indicate outcomes for important impacts relating to nutrient leakage and energy security. Flows of
139   land, food and energy are balanced within the life cycle inventories of two main scenarios
140   representing higher and lower prioritisation of AD (Tables S2-2a-f), to elucidate relationships in the
141   food-energy-climate nexus (Fig. 1). System boundaries start at the point of waste collection, and are
142   expanded to account for displaced *(inter alia)* marginal separated food waste management (in-vessel
143   composting), energy generation, and food and animal feed production as environmental credits (Fig.
144   1), with a consequential LCA framework similar to Styles et al. (2016) and (Bishop et al., 2021).

145   A factorial approach is taken to enable efficient exploration of pertinent factors, based on two
146   scenarios (testing the comparative GHG mitigation efficacy of AD against alternative options) and
147   three contexts (testing the influence of wider decarbonisation on comparative GHG mitigation
148   efficiency). Two national scenarios represent maximum industry projections of AD deployment
149   (AD_{max}) or maximum circularity (*Circular*) – based on the waste hierarchy and findings from recent
150   studies that indicate higher-value, more circular uses of prospective AD feedstocks (Albizzati et al.,
151   2021b; Bishop et al., 2021; Moult et al., 2018; Salemdeeb et al., 2017). These scenarios are stylised
152   and assume future modification of health & safety constraints around use of waste-derived animal
153   feeds as per (Salemdeeb et al., 2017; Van Zanten et al., 2015; zu Ermgassen et al., 2016).

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

162   National quantities of the five aforementioned food waste categories are used to estimate specific
163   fractions of food waste that can be prevented or diverted (next section). Results are calculated
164   separately per Mg of fresh matter for all waste and crop flows, and for all fates, across the three
165   decarbonisation contexts, before aggregated results are calculated for total flows at national level in
166   the two indicative scenarios. Avoided food, feed and AD-crop production result in land sparing.
167   Spared land is assigned to indicative best-case uses in line with climate neutrality, energy- and food-
168   security objectives: afforestation of spared grassland to sequester CO_2, generation of solar
169   photovoltaic (PV) electricity on cropland spared from purpose-grown AD crops, and indigenous food
170   production on cropland spared from food and animal feed production (Fig. 1). The geographic scope

171 of analysis is the UK for foreground data (though background data for incurred or avoided activities,

172 including food and feed production, also represent overseas activities). The temporal scope ranges

173 from today up to circa 2050, in line with decarbonisation projections (UK CCC, 2019).

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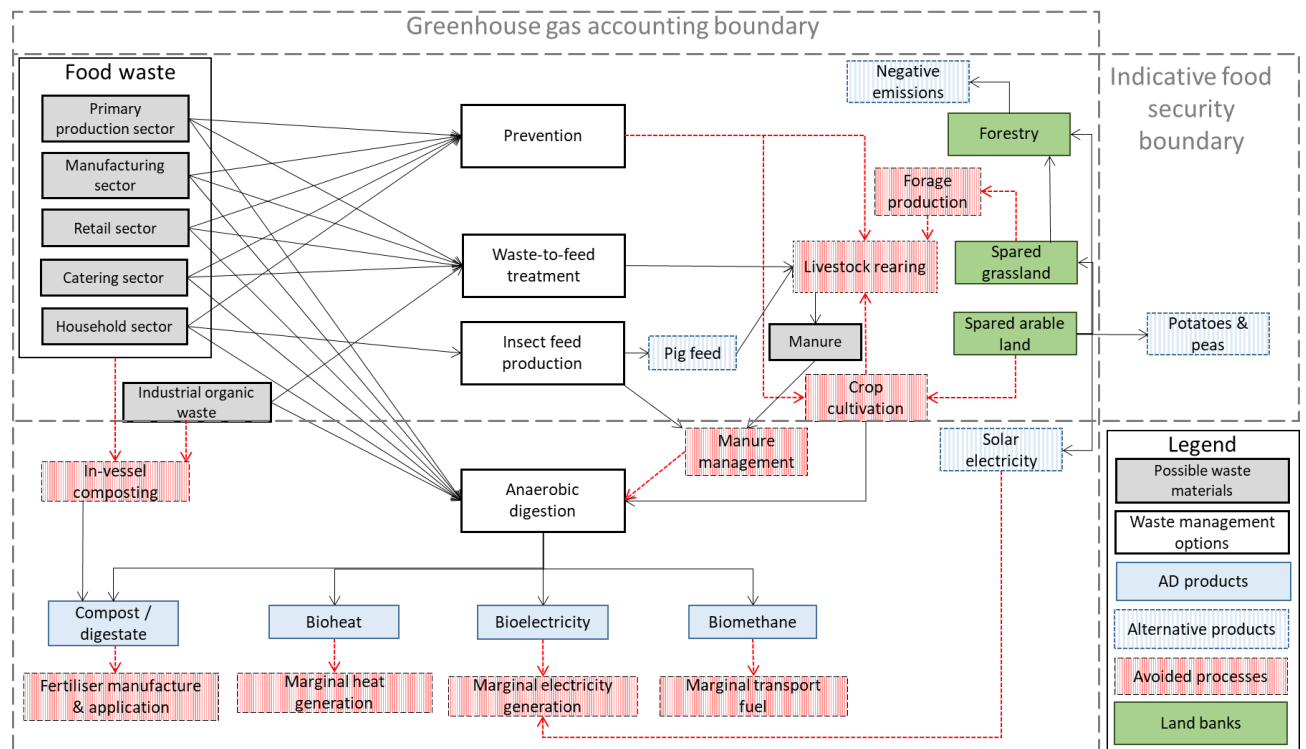
Figure 1. Major incurred and potentially avoided (dashed boxes) processes accounted for within the
life cycle assessment boundary. Potato and pea cultivation not included within GWP calculations, but
used to present alternative energy and food security implications of land sparing within scenarios.

179

2.2. Scenarios

181 Two stylised national scenarios are evaluated to assess the comparative GHG mitigation efficacy of

182 four categories of AD feedstock: food waste, industrial biowaste, purpose-grown crops and animal

183 manures. Food waste is studied in particular detail, considering three prospective circular

184 management options: (i) anaerobic digestion; (ii) preventing food waste arising via changes in

185 business practises and consumer behaviour; (iii) diversion to animal feed (following heat treatment

186 for retail and catering wastes, and following fly-egg larvae production for HH food waste in the *NZ-*

187 *GHG* context). Once food wastes are separated from packaging, there are few constraints to

188 treatment via AD. In contrast, prevention of food waste depends on the specific fraction (e.g. fruit

189 stones and meat bones are "unavoidable" waste) and diversion of food waste to animal feed is

190 governed by strict food safety legislation in Europe (REGULATION (EC) No 1069/2009, 2009; zu

191 Ermgassen et al., 2016). Thus, in order to estimate plausible levels of prevention and diversion to

192 animal feed, it is necessary to categorise food waste according to its origin and composition. We

193 evaluate waste from five stages of the food chain (Table 1) based on data from the UK Waste &

194 Resources Action Programme (WRAP, 2016, 2018b, 2018a, 2019). Compositions by stage are

195 displayed in Table S2-1. Aggregated food categories (e.g. "Meat", "Meat & fish", "Dairy & eggs",

196 "Produce", Ready meals") are disaggregated based on consumption data (detailed in Table S1-1).

197 Specific composition of each waste stream is used to calculate, *inter alia*, avoidable upstream

198 production burdens via prevention, feed-replacement value, biogas yield and fertiliser replacement

199 value of the digestate (or counterfactual compost).

200 Table 1 displays the quantities of food waste managed according to the possible options under the

201 AD_{max} and *Circular* scenarios. For the AD_{max} scenario, food waste composition and management data

202 are taken from WRAP (2016, 2018, 2019), reflecting targets for a reduction in annual post-farm-gate

203 food waste from 10.2 million tonnes in 2007 to 7.7 million tonnes by 2030 (WRAP, 2019, 2020). We

204 generate a stylised scenario of maximum AD deployment by assuming all waste that is not prevented

205 or diverted to animal feed goes to AD, alongside quantities of industrial biowastes, manures and

206 crops in line with AD industry projections for 80 TWh of biomethane to be produced by 2030 in the

207 UK (ADBA, 2018). For the *Circular* scenario, appropriate food waste streams are prevented or

208 diverted to animal feed in order to meet the UN Sustainable Development Goal target to halve food

209 waste, using a 2015 baseline – from 11.8 to 5.9 million tonnes yr^{-1}. Some regulatory change is

210 assumed to allow catering waste and some meat products to go into the non-ruminant animal feed

211 chain following heat treatment (Dou et al., 2018; zu Ermgassen et al., 2016). The volume of food

212 waste going to AD reduces by 36%-56% relative to the AD_{max} scenario (Table 1). The largest share of

213 food waste sent to AD is from households (Table 1), reflecting the dominance of post-consumer

214 waste generation in industrialised countries (Parfitt et al., 2010) and the difficulty diverting this

215 waste to alternative, higher-value uses owing to hygiene and regulatory constraints (Luyckx et al.,

216 2019).

217 ADBA (2018) projections of future biomethane production include circa 1 TWh yr^{-1} from "industrial

218 wastes", such as solid residues from alcohol production, and 13 TWh yr^{-1} from bioenergy crops. In

219 the absence of a detailed breakdown for industrial biowaste, we use aggregate food waste as a

220 proxy and infer a volume of 905,806 Mg FM going to AD in the AD_{max} scenario, half of which may be

221 diverted to animal feed in the *Circular* scenario (Table 1). We split bioenergy crops evenly between

222 maize and ryegrass, and assume zero use of bioenergy crops in the *Circular* scenario (Table 1).

223 Projections for up to 20 TWh of biomethane from farm animal wastes by 2030 (ADBA, 2018), equate

224 to 119,820,571 Mg FM (87% of the manure quantity collected in 2008: Table S1-3) based on the

225 upper end of specific biomethane yields (Styles et al., 2016). We use the total quantity of manure

226 inferred from ADBA and the composition reported by ADAS (2009) to determine manure quantities

227 by livestock type sent to AD (Table 1). For the *NZ-GHG* context, we assume that the volume of

228 handled manure declines by 50% to 68,689,350 Mg FM, representing a dietary shift away from meat

229 (CCC, 2019), but that all this manure is sent to AD, resulting in a net 43% reduction in digestion of

230 manures compared with *CURRENT* and *Low-GHG* contexts (Table 1). Insect manure is also sent to AD

231 in the *Circular* scenario, *NZ-GHG* context. Note that we do not model the upstream food system and

232 land sparing effects of the implied dietary shift, which is outside the scope of this study.

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 Mg fresh matter (FM) per year for the UK.

Feedstock	Management	CURRENT		Low-GHG		NZ-GHG	
		AD_{max}	Circular	AD_{max}	Circular	AD_{max}	Circular
		Mg yr^{-1} FM					
Primary production food waste	Prevention	260,300	1,286,000	260,300	1,286,000	260,300	1,286,000
	Animal feed	1,994,000	1,511,000	1,994,000	1,511,000	1,994,000	1,511,000
	AD	1,345,700	803,000	1,345,700	803,000	1,345,700	803,000
Manufacturing food waste	Prevention	375,686	901,000	375,686	901,000	375,686	901,000
	Animal feed	865,933	731,000	865,933	731,000	865,933	731,000
	Animal feed-insects						
	AD	1,285,387	893,688	1,285,387	893,688	1,285,387	893,688
Retail food waste	Prevention	112,870	117,500	112,870	117,500	112,870	117,500
	Animal feed	45,330	45,000	45,330	45,000	45,330	45,000
	AD	134,195	130,500	134,195	130,500	134,195	130,500
Catering food waste	Prevention	141,000	357,000	141,000	357,000	141,000	357,000
	Animal feed		153,000		153,000		153,000
	AD	878,995	510,000	878,995	510,000	878,995	510,000
Household food waste	Prevention	1,491,110	3,551,000	1,491,110	3,551,000	1,491,110	3,551,000
	Animal feed						
	Animal feed-insects						1,776,860
	AD	5,608,570	3,551,000	5,608,570	3,551,000	5,608,570	1,776,860
Food waste total	**Prevention**	**2,380,966**	**6,212,500**	**2,380,966**	**6,212,500**	**2,380,966**	**6,212,500**
	Animal feed	**2,905,263**	**2,440,000**	**2,905,263**	**2,440,000**	**2,905,263**	**2,440,000**
	Animal feed-insects						**1,776,860**
	AD	**9,252,847**	**5,890,907**	**9,252,847**	**5,890,907**	**9,252,847**	**4,114,048**
Industrial waste	**Animal feed**	**0**	**452,543**	**0**	**452,543**	**0**	**452,543**
	AD	**905,086**	**452,543**	**905,086**	**452,543**	**905,086**	**452,543**
Maize	**AD**	**6,101,636**	**0**	**6,101,636**	**0**	**6,101,636**	**0**
Grass	**AD**	**7,321,964**	**0**	**7,321,964**	**0**	**7,321,964**	**0**
Pig slurry	**AD**	**19,149,40**	19,149,406	**19,149,40**	**19,149,40**	**10,977,75**	**10,977,75**
Cattle slurry	**AD**	**87,540,14**	**87,540,14**	**87,540,14**	**87,540,14**	**50,184,00**	**50,184,00**
Poultry manure	**AD**	**13,131,02**	**13,131,02**	**13,131,02**	**13,131,02**	**7,527,600**	**7,527,600**
Insect manure	**AD**	**0**	**0**			**0**	**1,143,926**

238   *2.3. Decarbonisation contexts*

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

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

279 combined with appropriate sensitivity analyses, allow for exploration of AD efficacy when interacting
280 with plausible, transparently-parameterised future systems.

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

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

293 *Table 2. Evolution of key parameters pertinent to calculating the GHG and land balance of biowaste management options (prevention, diversion to animal*
294 *feed and anaerobic digestion) within three decarbonisation (prevailing technology) contexts (CURRENT technology, LOW-GHG emissions and net zero (NZ-)*
295 *GHG emissions). Food waste is categorised as arising from primary production (PP), manufacturing (M), retailing (R), catering (C) and households (HH). Red*
296 *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.				

297

298   *2.4. Life cycle inventories*

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

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

317

318   *Table 3. Best-case biomethane uses, and indicative best case land uses attributed to land spared from*
319   *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

320

321

322   *2.5. Livestock feed production via insect larvae meal*

323   Conversion of HH food waste into animal feed via insects within the *Circular* scenario *(NZ-GHG*
324   context) is modelled based on an LCA study producing house fly (*Hermetia illucens*) meal from food
325   waste (van Zanten et al., 2015). One Mg of DM larvae meal requires 12.2 Mg waste, 378 kWh of
326   electricity and 183 kWh of natural gas for heating. We simplify the scenario by substituting the ca.

13

327   12% of feed as chicken manure considered in that study with food waste on a dry matter basis,

328   avoiding manure handling emissions. Energy is sourced from renewables in the *NZ-GHG* context

329   (Table 2). Based on data presented by van Zanten et al. (2015), one Mg of DM larvae meal can

330   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

331   nutrient concentrations of 12.46, 6.53 and 4.49 kg Mg^{-1}, respectively. This manure is sent to AD, in

332   line with the principle of circularity.

333

334   *2.6. Credits for avoided food & feed production*

335   Food waste prevention across all stages (Table 1) leads to avoided production of constituent food

336   groups, and thus environmental credits – directly (Table S2-3) and indirectly via alternative use of

337   spared land (Fig. 1). Food waste diverted to animal feed is first heat treated, with heat and electricity

338   inputs taken from De Menna et al. (2019). Context-specific marginal heat and electricity sources are

339   applied (Table 2). Aggregate energy and protein contents per Mg of food waste are used to calculate

340   quantities of marginal feed ingredients avoided using linear optimisation to balance out digestible

341   energy and crude protein against replaced maize grain as a marginal energy feed and soybean meal

342   as a marginal protein feed (Table S1-3). Avoided burdens and areas of land spared via animal feed

343   substitution are then calculated using context-specific burdens for soybean meal and maize listed in

344   Table S2-3, scaled (Table 2) according to current burdens from Ecoinvent v3.6 (Wernet et al., 2016).

345   Land requirements for food and feed production in the *NZ-GHG* context are based on technical

346   potential yields for cereals, oil seeds, potatoes, sugar beet, fruit & vegetables and grass summarised

347   in Table 1 of Lamb et al. (2016). For beef, dairy and lamb production, land area requirement is

348   reduced through multiplication by the ratio of feed conversion factor improvement (MJ feed per kg

349   output in 2050 divided by MJ feed per kg output in 2010) reported in Lamb et al. (2016). GWP

350   reductions for crop-derived products are set at twice the yield improvement, reflecting concurrent

351   decarbonisation of energy (Table 2 & Table S2-3) required for fertiliser manufacture, field

352   operations, processing and transport. Following land (feed) efficiency scaling, pork and poultry GWP

353   burdens are scaled down by a further 25% to represent potential advancements in housing and

354   manure management technologies to reduce animal-related emissions. Beef, dairy and sheep

355   production GHG emissions are not scaled down beyond feed conversion ratio and grassland use

356   efficiency, reflecting constraints to mitigation of enteric methane emissions that dominate carbon

357   footprints from cattle and sheep systems (FAO, 2018). Nonetheless, the GWP footprint of beef

358   reduces by 63% between *CURRENT* and *NZ-GHG* contexts (Table S2-3). Optimistic reductions in the

359   *NZ-GHG* context reflect outcomes associated with widespread and deep "sustainable intensification"

14

360   (Lamb et al., 2016). Food and feed footprints in the *LOW-GHG* context are fixed as intermediate

361   between *CURRENT* and *NZ-GHG* contexts.

362   *2.7.<u>Utilisation of spared land</u>*

363   Land areas spared from waste prevention, substitution of animal feeds and avoided AD-crop

364   cultivation are calculated based on context-specific land footprints listed in Table S2-3. Land

365   occupation is categorised as "arable" or "grassland" based on the following approximations: all

366   crops, 100% arable; fruit & veg., 50% arable; dairy derived products, 20% arable; meat derived

367   products, 5% arable. Afforestation of spared land (grassland plus arable land spared from food and

368   feed production) results in annual C sequestration of 3600 kg C ha^{-1} based on average values for

369   temperate forest regeneration provided in Searchinger et al. (2018). Solar PV electricity generation

370   on land spared from AD-maize cultivation is calculated based on annual electricity output of 44 kWh

371   m^{-2} yr^{-1} (Westmill Solar park, 2020), generating a GWP credit based on substitution of an equivalent

372   quantity of marginal electricity generation (Table 2) minus the current GWP footprint for electricity

373   generated by a 570 kWp open ground installation listed in Table S2-3 (Wernet et al., 2016).

374   Emissions associated with additional electricity storage requirements for solar PV vs bioelectricity

375   (Vandepaer, Cloutier, et al., 2019) are not explicitly considered, but are implicitly accommodated by

376   conservatively holding the GWP footprint of solar PV electricity at current levels through the *LOW-*

377   *GHG* and *NZ-GHG* contexts. As a proxy for food security implications attributable to waste diversion,

378   potatoes and peas are harvested at average UK yields (2013-2017) of 41.6 Mg ha^{-1} yr^{-1} and 4.4 Mg

379   ha^{-1} yr^{-1}, respectively (UN FAO Stat, 2019) on spared arable land (50/50 area split): these yields

380   increase in line with aforementioned crop productivity improvements based on Lamb et al. (2016)

381   across the *LOW-GHG* and *NZ-GHG* contexts. Calculation of GHG emissions incurred and avoided

382   (through import substitution) from this simple food security measure are outside the scope of this

383   study.
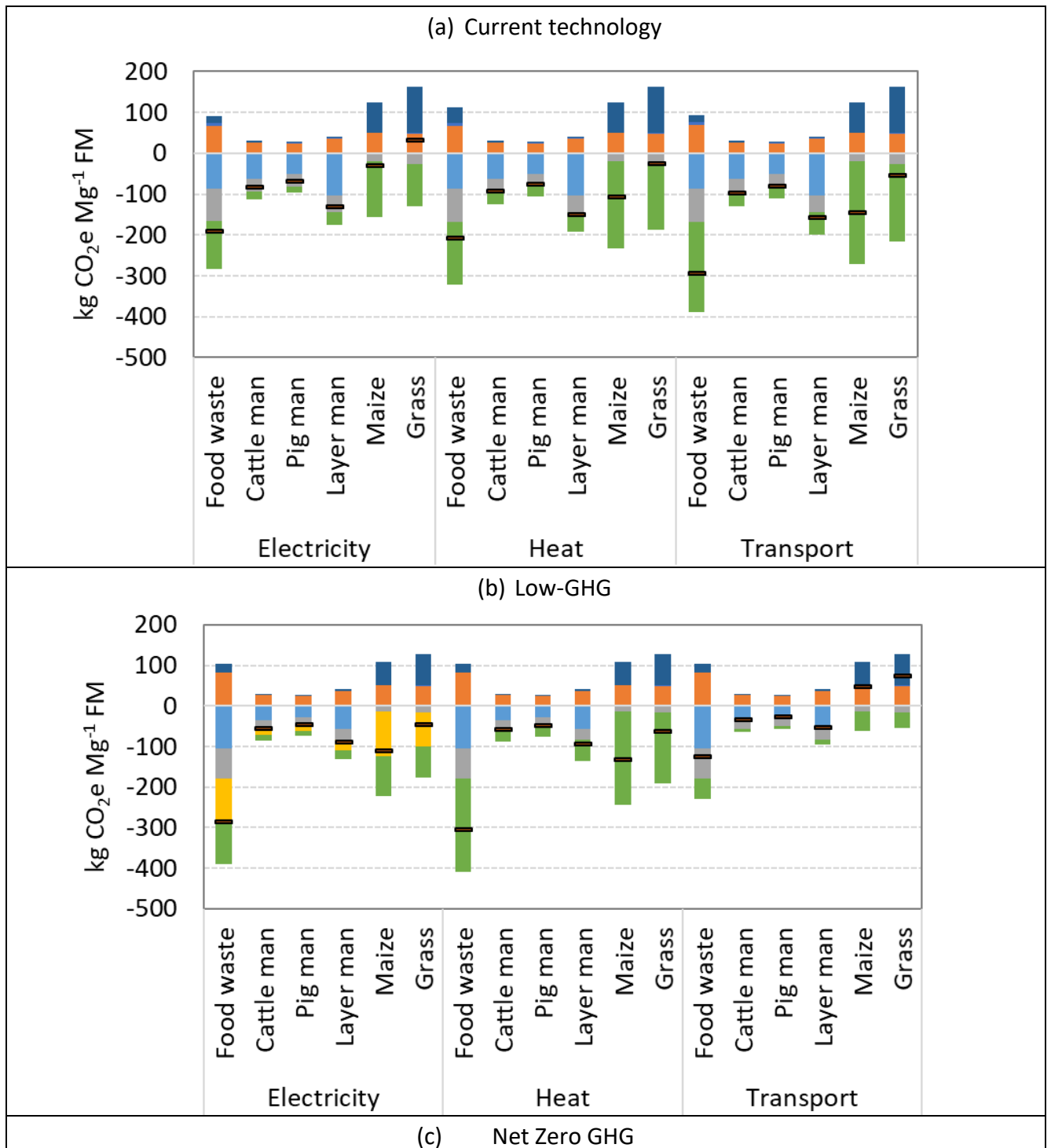
384

385   **3. RESULTS**

386   *3.1.<u>GHG mitigation efficacy of anaerobic digestion</u>*

387   Per Mg fresh matter (FM) digested, food waste and poultry manure generate the largest net GWP

388   credits, owing to a combination of avoided waste management, soil C sequestration and fertiliser

389   substitution, in addition to energy substitution (Fig. 2a & Table S2-4). Cattle and pig manures

390   generate smaller credits owing to lower avoided counterfactual storage emissions and lower

391   biomethane yield (reflecting low dry matter content, just 4% in the case of pig manure). Meanwhile,

392   maize and grass generate relatively large energy credits per Mg FM but also considerable emissions

393   during cultivation (fertiliser manufacture and soil nitrous oxide emission) and digestion (methane

394   leakage). Thus, even in the *CURRENT* context with high GHG-intensities from counterfactual energy,

395   grass bioelectricity generation does not result in a net GWP saving (Fig. 2a). Energy credits are larger

396   where biomethane replaces natural gas heating or diesel transport fuel, with net GWP credits from

15

397   biomethane transport fuel ranging from 56 kg CO_2 eq Mg^{-1} FM grass to 295 kg CO_2 eq Mg^{-1} FM food

398   waste under the *CURRENT* context (Fig. 2a).

399   As decarbonisation progresses along the *LOW-GHG* and *NZ-GHG* contexts (Fig. 2b&c), the efficiency

400   of AD (biomethane yield, electrical conversion) increases, leading to larger credits, whilst emissions

401   from crop cultivation decrease (Table S2-3). Credits from avoided manure storage also decrease, but

402   credits from avoided waste management (via composting) remain relatively constant owing to

403   counteracting effects (lower energy burdens but also smaller fertiliser credits from composting). For

404   electricity generation, CCS contributes substantially to net emission avoidance (though also curtails

405   emissions credits from avoided natural gas electricity generation). Biomethane generation of

406   electricity and heat achieves larger GWP savings in the *LOW-GHG* context compared with the

407   *CURRENT* context, on the assumption that natural gas remains the marginal energy source replaced

408   by biomethane (UK CCC, 2019). Net GWP credits from AD when biomethane is used to replace

409   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).

410   However, transport electrification in the *LOW-GHG* context means that avoided transport credits are

411   much smaller, and growing maize or grass to produce transport biomethane leads to a net increase

412   in GWP burden (Fig. 2b). The GHG mitigation efficacy of AD diminishes dramatically under the *NZ-*

413   *GHG* context owing to extensive decarbonisation of energy carriers and reduced credits from

414   avoided manure management emissions (Fig. 2c). Food waste is the only feedstock to generate a

415   significant credit when biomethane is used for heating or transport fuel. However, using biogas to

416   generate electricity results in substantial GHG mitigation, ranging from 30 kg CO_2 eq Mg^{-1} FM pig

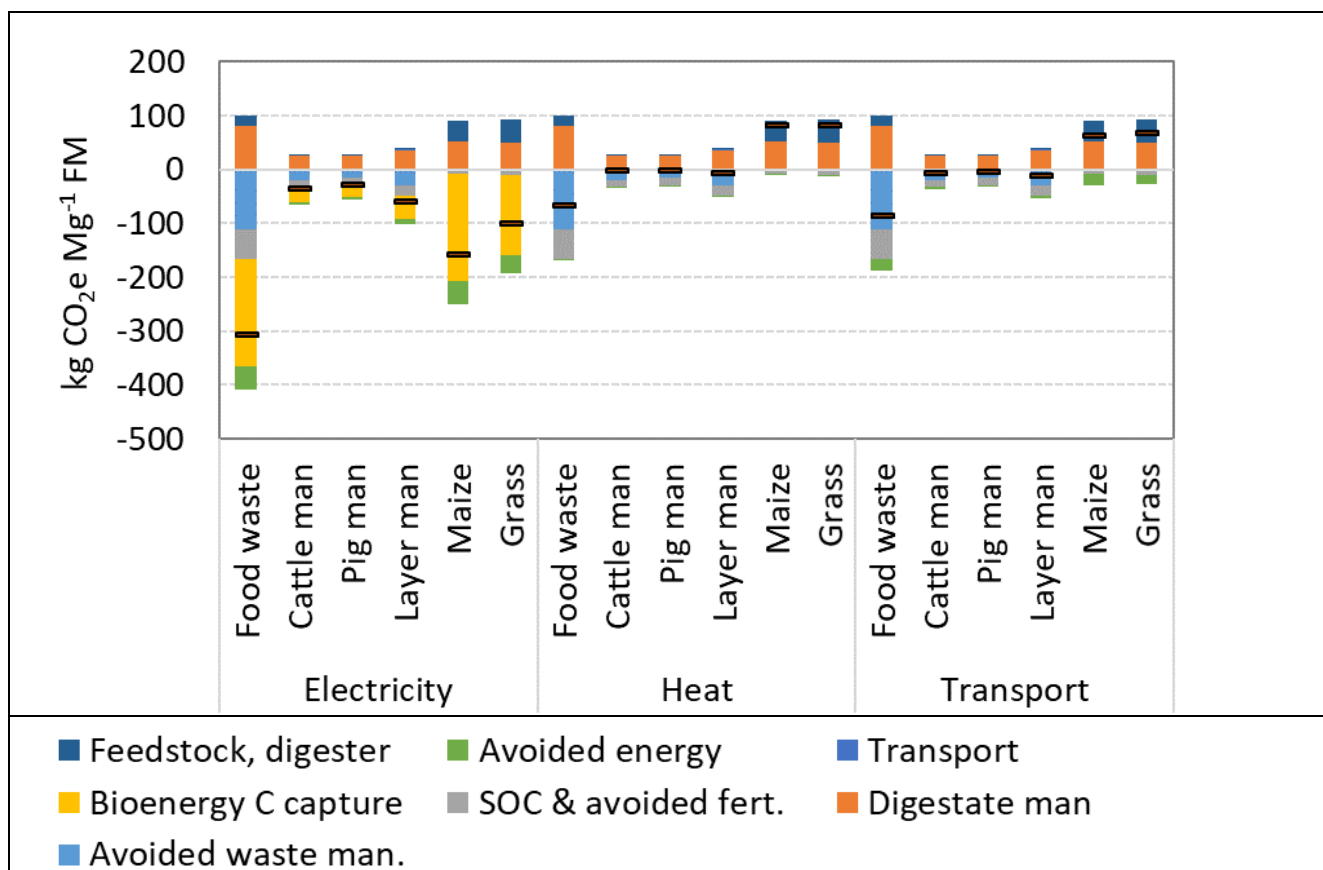417   manure to 308 kg CO_2 eq Mg^{-1} FM food waste (Fig. 2c).

16

(a) Current technology

(b) Low-GHG

(c) Net Zero GHG

427   *3.2. Comparative mitigation efficiency of alternative options*

428   Table 4 displays the main environmental credits generated by AD of food wastes and crops

429   compared with alternative food waste and land use options, based on environmental balance of: (i)

430   the most favourable biomethane uses in each context; (ii) avoided food production (waste

431   prevention); (iii) avoided animal feed production (waste diversion); (iv) afforestation or solar PV

432   electricity generation as alternative land use options. Results for individual food waste categories are

433   shown in Table S2-5, whilst full LCA results are displayed for GWP in Figs. S1-1 to S1-3 (net credits

434   include avoided waste management and sterilisation burdens, but are similar to gross credits

435   displayed in Table 4). Notably, animal feed diversion or waste prevention credits are at least 1.5 to 3

436   times larger than AD credits for food waste in the *CURRENT* context, concurring with results of

437   recent studies (Albizzati et al., 2021a; Moult et al., 2018; Salemdeeb et al., 2017). Waste prevention

438   credits are highly sensitive to the waste composition, ranging from 1079 kg CO_2 eq. Mg^{-1} FM for PP

439   waste in the AD_{max} scenario to 16,524 kg CO_2 eq. Mg^{-1} FM for M waste in the *Circular* scenario, under

440   the *CURRENT* context (Table S2-5) – reflecting a high share of meat, poultry, fish and dairy products

441   in the M waste stream (Table S2-1). Including potential afforestation of land spared from food and

442   feed production increases GWP credits by up to a factor of four, to 9,617 kg CO_2 eq. Mg^{-1} FM food

443   waste prevented (Table 4). Despite declining prevention and animal feed credits through time owing

444   to reduced carbon and land footprints of crop and animal production(Table S2-3), food waste

445   prevention and animal feed diversion remain considerably more effective than AD for GHG

446   mitigation in the *NZ-GHG* context, but the differential is considerably reduced compared with

447   *CURRENT* and *LOW-GHG* contexts (Table 4).

448   Food waste also carries high embodied eutrophication, acidification and fossil resource depletion

449   burdens, in particular the M & HH categories containing higher shares of animal-derived products

450   (Table S2-5) owing to high rates of reactive nitrogen leakage from livestock systems (Balmford et al.,

451   2018; Pinder et al., 2012). Thus, average eutrophication and acidification burden savings are

452   approximately 10 times higher for waste prevention than for AD, and avoided fossil resource

453   depletion is relatively similar for food waste prevention as for AD (Table 4) owing to avoided fossil

454   fuel use in food value chains, including for fertiliser manufacture. Diversion of food waste to animal

455   feed avoids crop cultivation, resulting in intermediate savings (Table 4 and Table S2-5). Growing

456   crops for AD is not environmentally advantageous overall, generating relatively small GWP credits

457   per Mg, and incurring additional eutrophication and acidification burdens, across all contexts (Table

458   4). Alternative land uses (afforestation or solar PV electricity generation) are far more effective at

459   mitigating GHG emissions and displacing fossil fuels. Solar PV electricity generation avoids 16 times

460   more fossil energy and between four and 23 times more GHG mitigation compared with AD-maize

461   grown on the same area of land, in the *CURRENT* and *LOW-GHG* contexts (Table 4). In the NZ-GHG

462   context, solar-PV is the marginal electricity generating technology, so there would be no need for,

463   and no credit associated with, solar PV generation on land spared from AD-maize cultivation. The

464   GHG credits from afforestation of such land in this context remain larger than credits achievable

465   with AD-BECCS (Table 4).

Table 4. Environmental credits generated by anaerobic digestion of food waste, maize and grass
compared, and 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	GWP & LUC	EP	AP	FRDP	LO
			kg CO_2 eq. Mg^{-1}	kg CO_2 eq. Mg^{-1}	kg PO_4 eq. Mg^{-1}	kg SO_2 eq. Mg^{-1}	MJ eq. Mg^{-1}	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				

473

3.3. National mitigation potential of deployment scenarios

Figure 3 and Table 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

478 and kcal production potential for the *Circular* vs the AD_{max} scenario, assuming best-case biomethane
479 use. Despite considerable uncertainty around GHG mitigation achievable from alternative land use in
480 particular, *Circular* scenarios clearly outperform AD_{max} scenarios for all metrics except direct GHG
481 mitigation in the *NZ-GHG* context (owing to the strong mitigation potential of AD coupled with
482 BECCS). Nonetheless, when alternative land use is factored in, the *Circular* scenario mitigates an
483 additional 15% of projected gross UK GHG emissions in 2050 (CCC, 2019), in the *NZ-GHG* context
484 (Table 5). Increasing crop yields through time translate into smaller areas of spared land as
485 decarbonisation progresses, from 17% and 34% of arable and grassland areas in the *CURRENT*
486 context, down to 8% and 14% of (current) arable and grassland areas in the *NZ-GHG* context (Table
487 5). These percentages may be misleading because approximately half of UK food demand is
488 imported (DEFRA, 2020), so that some of the land sparing realised by waste prevention (and indeed
489 animal feed diversion) will occur outside of the UK. Despite producing less biomethane, *Circular*
490 scenarios generate 118 to 237 PJ more energy than AD_{max} scenarios owing to solar PV generation. In
491 terms of food security effects, yield increases in energy and protein crops counter the declining land
492 areas spared by enhanced circularity as decarbonisation progresses, so that additional arable land
493 sparing in the *Circular* scenario is able to provide 20-23% of national protein and kcal requirements
494 irrespective of the level of decarbonisation (Table 5).

495   *3.4. Sensitivity analyses*

496 Combining *CURRENT* (avoided) energy burdens with *NZ-GHG* (avoided) food production and waste
497 management burdens (S1) increases GHG mitigation achieved by AD_{max} scenarios between 32% (AD-
498 electricity) to 173% (AD-heat generation), relative to the straight *NZ-GHG* context (Table 6). *Circular*
499 scenario mitigation increases by just 1% (AD-electricity) to 14% (AD-transport), but remains at least
500 36% higher than AD_{max} mitigation (Fig. 3; S2-8). Meanwhile, combining *CURRENT* (avoided) food
501 production and waste management burdens with *NZ-GHG* (avoided) energy burdens (S2) increases
502 AD_{max} mitigation by between 100% (AD-electricity) and 282% (AD-heat), and *Circular* mitigation by
503 193% (AD-electricity) to 229% (AD-heat) (Table 6). *Circular* mitigation remains approximately 2.7
504 greater than AD_{max} mitigation (Fig. 3). Finally, failure to successfully deploy BECCS on AD electricity
505 generation in the *NZ-GHG* context would reduce GHG mitigation by 41% for the AD_{max} scenario, and
506 7% for the *Circular* scenario (Table 6). Nonetheless, AD-electricity remains the best performing
507 energy conversion pathway in the NZ-GHG context (S2-8) owing to the significant embodied
508 emissions in substituted solar PV generation (S2-3), from Ecoinvent (Wernet et al., 2016).

509

510

511 *Table 5. Additional annual GHG mitigation and land sparing for the UK national CIRCULAR scenario*

512 *compared with the AD$_{max}$ scenario. Indicative alternative land uses (ALU) support further GHG*

513 *mitigation (via afforestation of spared grassland), solar PV electricity generation (on land spared*

514 *from AD-maize), and food protein and kcal production (on arable land spared from food and feed*

515 *production). Negative values (red shading) indicate additional mitigation is achieved in the AD$_{max}$*

516 *scenario. Annual differences are also expressed as a percentages of UK GHG emissions under the*

517 *different contexts* (Brown et al., 2019; CCC, 2019)*, and as a percentage of current primary energy*

518 (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%)

519

520

521 *Table 6. Sensitivity of net GHG mitigation results to mixed combinations of NZ-GHG and CURRENT*

522 *context process assumptions, expressed as percentage change in mitigation vis-à-vis NZ-GHG results*

523 *(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%

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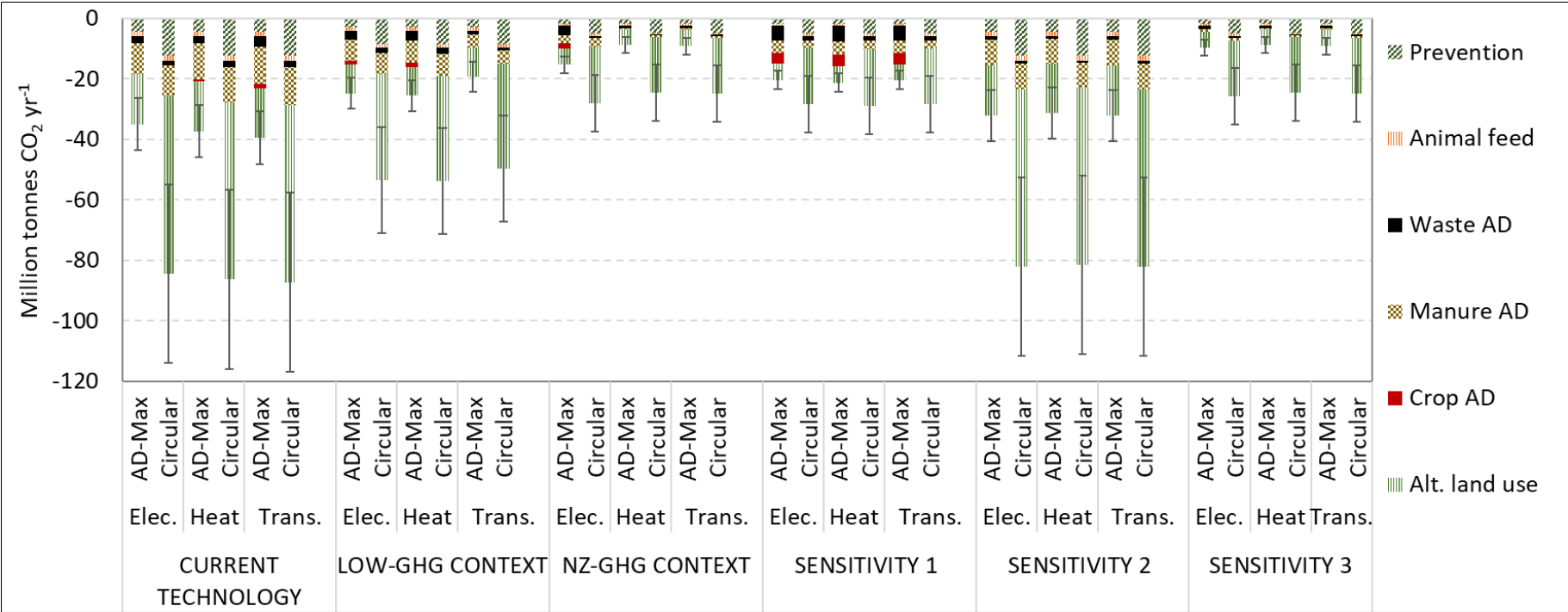
528 **Fig. 3. Net GHG emission mitigation for the UK assuming maximum deployment of anaerobic digestion (*AD_max* scenario) or enhanced circularity (*Circular***

529 **scenario) under different contexts, from *CURRENT* technology, through *LOW-GHG* emissions to *Net Zero (NZ-)GHG* emissions. Sensitivity analyses**

530 **systematically mix context assumptions (see S2-8). Contribution of waste prevention, waste conversion to animal feed, anaerobic digestion and**

531 **potential alternative land uses are displayed, along with error bars representing uncertainty propagation across the aforementioned categories (see S2-**

532 **6).**

4. Discussion

534 *4.1. Waste management*

535 Anaerobic digestion is promoted as a green circular economy technology that supports energy

536 generation and nutrient recycling (ADBA, 2018) whilst avoiding emissions from alternative biowaste

537 management options such as landfilling, incineration, composting or conventional manure handling

538 (Boulamanti et al., 2013a; Fusi et al., 2016; Lijó et al., 2014; Slorach et al., 2019). This study confirms

539 that role, but also defines boundaries around the sustainable operating space for AD in the future as

540 the waste management, energy and land sectors it straddles decarbonise at differential rates.

541 Overall, the boundaries for sustainable AD deployment in future contexts are similar to those

542 identified in the current context vis-à-vis biowaste management (Albizzati et al., 2021a; Styles et al.,

543 2016; Tonini et al., 2018; Tufvesson et al., 2013). However, a key finding of this study is the

544 magnitude of GHG mitigation, alternative renewable energy generation and food security that could

545 be achieved through alternative uses of land spared from waste prevention or diversion to animal

546 feed, and from cultivation of AD-crops. Agriculture continues to expand into native habitats globally

547 (Persson et al., 2014), and nature based solutions enabled by land sparing will be central to climate

548 stabilisation (IPCC, 2019). Yet we are not aware of previous studies that have explicitly quantified

549 these potential trade-offs in relation to food waste management and crop bioenergy via AD. Land

550 opportunity costs help to maintain a clear GHG mitigation advantage for biowaste prevention and

551 diversion to animal feed over AD under a *NZ-GHG* context where food production emissions are

552 dramatically reduced. Wider LCA results presented here show that food waste prevention and

553 animal feed diversion also confer environmental sustainability advantages compared with AD

554 treatment in terms of nutrient cycling (avoided nutrient leakage), addressing key planetary boundary

555 exceedances (Steffen et al., 2015). Perhaps counter-intuitively, waste prevention performs as well as

556 AD in terms of (avoided) fossil resource depletion, reflecting the large amounts of fossil energy

557 embodied in food and feed supply chains. National GHG mitigation estimates from indicative

558 scenarios in this study are large compared with estimated mitigation of 10 Tg CO_2 eq. annually from

559 a halving of meat consumption in the UK (CCC, 2020), confirming that waste management has a

560 critical role to play alongside diet change in delivering climate neutrality. Nonetheless, even under

561 optimistic projections for food waste prevention and diet change within the *NZ-GHG Circular*

562 scenario presented here, over 74 million tonnes per year of residual wastes and manures remain

563 available for sustainable management by AD in the UK.

564

565 *4.2. Energy generation*

566 This study provides new insight into the "sustainable niche" for AD in relation to decarbonising

567 energy sectors, pertinent to policy and investment decisions in support of technological and

568 behavioural transitions towards circularity and climate neutrality. The shift in optimal use of

569 biomethane from transport fuel to large scale combustion as decarbonisation progresses is

570 predicated on two important assumptions: (i) electrification (or hydrogen fuelling) of transport,

571 including HGVs (Ainalis et al., 2020); (ii) widespread deployment of BECCS across large-scale
572 biomethane combustion by 2050. Although commercially uncertain (Muri, 2018), BECCS features
573 prominently in global scenario modelling for climate stabilisation (Huppmann et al., 2019), and is
574 likely to be commercially viable at high carbon process over the medium to long term. If this
575 happens, AD will be transformed into a negative emission technology able to contribute towards
576 maintaining climate neutrality (emissions balance), gaining a comparative advantage over otherwise
577 more land- and cost- efficient renewable energy sources such as wind and solar PV. Nonetheless,
578 results presented here confirm that cultivation of crops specifically for AD should be avoided where
579 possible, and confined to balance seasonal operation of AD plants fed primarily by manures or
580 wastes, confirming conclusions from previous studies (Adams & McManus, 2019; Styles et al., 2015).
581 Meanwhile, it has recently been shown that forestry value chains provide an effective way to lock up
582 carbon in biomass until BECCS becomes commercially viable (Forster et al., 2021), further supporting
583 the important role of forestry identified in this study (here, we did not account for additional
584 mitigation downstream in commercial forestry value chains). Thus, investment in alternative
585 renewable energy technologies such as solar PV and wind combined with electricity storage, and
586 afforestation, should be priorities for the transition to a circular, climate neutral future. Nonetheless,
587 AD has an important role to play in providing a clean transport fuel (Ullah Khan et al., 2017) in the
588 short-term, and a negative emission technology supplying dispatchable renewable electricity or heat
589 in the long term. Establishing flexible infrastructure and value chains for biomethane use in
590 transport and industrial combustion could leverage maximum GHG mitigation over different time
591 scales.

592

593   *4.3. Limitations and wider applicability*

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

610 feed made up by chicken manure with food waste. This simplification is not expected to
611 meaningfully influence results because upstream land and GHG burdens of both these waste inputs
612 are negligible (Van Zanten et al., 2015).

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

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

640

641   **5. Conclusions**

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

646   Many recent conclusions on sustainable AD deployment remain valid even with strong
647   decarbonisation in the wider economy. Growing crops specifically for AD is an inefficient GHG
648   mitigation option compared with alternative uses of land, such as solar PV electricity generation or
649   afforestation, irrespective of wider decarbonisation context. But AD can leverage substantial
650   environmental credits from avoidance of counterfactual food waste and manure management,
651   though the latter credits are likely to decline as improved manure management is deployed. Net
652   GHG mitigation from food waste AD is remarkably resilient to decarbonisation context, varying from
653   334 kg CO_2 eq. Mg^{-1} food waste in the current technology context to 303 kg CO_2 eq. Mg^{-1} food waste
654   in the net zero GHG context – assuming optimal deployment and large-scale combustion of
655   biomethane coupled with BECCS in future (transforming AD into a negative emissions technology).
656   Adding to previous studies, we show that land sparing from waste prevention and diversion to
657   animal feed (instead of AD treatment) can dramatically increase GHG mitigation, by up to 9.6 Mg
658   CO_2 eq. per Mg food waste, though these counterfactual credits will decline with sustainable
659   intensification. Compared with AD, biowaste prevention is also much more effective at reducing
660   reactive nitrogen pollution, and saves similar amounts of fossil energy whilst sparing land to support
661   energy and food security objectives. Nonetheless, even with optimistic projections of food waste
662   reduction and diet change, large quantities of residual wastes and manures will remain available for
663   sustainable treatment by AD in the future.

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

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