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1 **Life cycle assessment of biofertilizer production and use compared with**
2 **conventional liquid digestate management**

3

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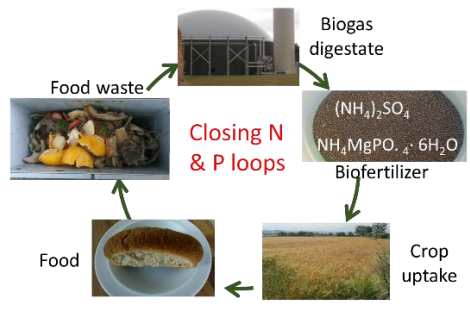
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15

16 **Graphical abstract**



17

18 **Abstract**

19 Handling of digestate produced by anaerobic digestion impacts the environment through emission
20 of greenhouse gases, reactive nitrogen and phosphorus. Previous life cycle assessments (LCA)
21 evaluating the extraction of nutrients from digestate using struvite precipitation and ammonia
22 stripping did not relate synthetic fertilizer substitution (SFS) to nutrient use efficiency consequences.
23 We applied an expanded LCA to compare the conventional management of 1 m³ of liquid digestate
24 (LD) from food waste against the production and use of digestate biofertilizer (DBF) extracted from
25 LD, accounting for SFS efficacy. Avoidance of CH₄, N₂O and NH₃ emissions from LD handling and
26 enhanced SFS via more targeted use of nutrients in the versatile DBF product could generate
27 environmental savings of up to 0.129 kg Sb eq., 4.16 kg SO₂ eq., 1.22 kg PO₄ eq., 33 kg CO₂ eq. and
28 20.6 MJ eq. per m³ LD, for abiotic resource depletion, acidification, eutrophication, global warming
29 and cumulative energy demand burdens, respectively. However, under worst-case assumptions, DBF
30 extraction could increase global warming and cumulative energy demand by 7.5 kg CO₂e and 251 MJ
31 eq. per m³ LD owing to processing inputs. Normalizing these results against per capita environmental
32 loadings, we conclude that DBF extraction is environmentally beneficial.

33

34 **Keywords:** digestate; expanded life cycle assessment; struvite; anaerobic digestion; greenhouse
35 gases; ammonia; environmental burdens

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41 1. Introduction

42 Leaky nutrient cycles undermine the environmental sustainability of global food chains. The nitrogen
43 (N) cycle is the second most critically impacted planetary system¹. Pollution arising from N losses to
44 air and water costs up to 320 billion euros annually across Europe^{2,3} and manufacturing synthetic N
45 fertilizer via the Haber-Bosch process is energy-intensive and expensive. Meanwhile, phosphorus (P)
46 use efficiency is low, leading to eutrophication impacts in water bodies and depletion of poorly-
47 quantified but essentially finite global phosphate reserves^{4,5}. Closing nutrient cycles and minimising
48 losses is therefore an imperative for sustainable food production. Anaerobic digestion (AD) is an
49 increasingly popular option for the treatment of organic wastes, such as manures and food waste, that
50 facilitates nutrient recycling whilst producing bio-energy⁶. The digestate co-product of AD is a valuable
51 bio-fertilizer, rich in readily available macro- and micro-nutrients⁷. However, storage and application
52 of digestate gives rise to fugitive emissions of methane (CH₄) and ammonia (NH₃), contributing
53 towards global warming, acidification and eutrophication⁸, whilst digestates from some feedstocks
54 have been linked with increased risk of soil contamination with Cu, Zn and Mn⁹. Economies of scale
55 favour large AD plants to treat food waste, whilst a high water content makes long-term storage and
56 long-distance transport of digestate uneconomic¹⁰. Digestate certification schemes¹¹ have not yet
57 overcome farmer suspicion about the agronomic value and safety of digestates which vary
58 considerably in composition and deviate from ideal ratios for crop nutrition⁹. Consequently, there is
59 concern that digestate is not distributed widely enough, nor applied at the right times, to achieve
60 efficient nutrient use, i.e. digestate may be over-applied in areas adjacent to large AD plants¹² and in
61 autumn when crop-uptake and N use efficiency is low^{9,13}. A recent life cycle assessment (LCA) study¹⁴
62 found that, even when digestate from food waste is applied at agronomically-appropriate times, field
63 emissions outweigh fertilizer substitution credits, leading to net acidification and eutrophication
64 burdens. Mechanical separation of digestate into solid fractions containing more of the P, and liquid
65 fractions containing more of the N and K, could help to improve nutrient use efficiency, as
66 demonstrated for separated pig slurry¹⁵. However, it may also increase N₂O emissions from the solid

67 fraction¹⁶. Handling separated liquid digestate (LD) still gives rise to distribution challenges and
68 ammonia emissions^{8,9}. Upgrading digestate into a concentrated, easy-to-handle biofertilizer is a
69 potential solution that could improve nutrient use efficiency and reduce emissions by avoiding
70 prolonged storage of digestate, and by concentrating nutrients into a compact, convenient and
71 familiar powder fertilizer format that can be applied in accordance with crop requirements⁵. A range
72 of technologies have been developed to upcycle digestate, including struvite precipitation, ammonia
73 stripping and capture (absorption/crystallisation), acidification and alkaline stabilisation¹⁷, algal
74 nutrient-stripping¹⁸ and others. In this paper, we focus on struvite precipitation with ammonia
75 stripping to produce a digestate biofertilizer (DBF) product, the most established technologies¹⁷. These
76 technologies could also be applied to address problems associated with nutrient over-concentration
77 in regions with high livestock densities and constrained landbanks for manure spreading, e.g. peri-
78 urban livestock systems in Asia.

79 Despite promising field trials valorising the crop nutrient value of such biofertilizers, legislative barriers
80 have hitherto limited their development^{9,19}. A recent LCA study highlighted environmental benefits
81 and trade-offs associated with LD upcycling to DBF²⁰, but did not account for potential fertilizer
82 substitution effects linked to more precise nutrient management, which could be particularly
83 significant in the context of a rapidly expanding global AD sector. The common assumption of 1:1
84 substitution of synthetic fertilizer nutrients with organic nutrients frequently leads to overestimation
85 of the environmental performance of conventional organic residue use in LCA studies²¹. For the first
86 time, this study accounts for important nutrient use efficiency effects within an expanded boundary
87 LCA to fully compare the environmental balance of conventional LD management with production and
88 use of an upcycled DBF product. We build on recent LCA studies of digestate upcycling^{8,20} with new
89 detailed data on DBF processing obtained from bench and pre-commercial pilot trials undertaken by
90 a Swedish company²², and apply detailed accounting for emissions and fertilizer substitution arising
91 from different management of LD based on appropriate models and emission factors²³⁻²⁵.

92 2. Materials and Methods

93 2.1. Biofertilizer production process

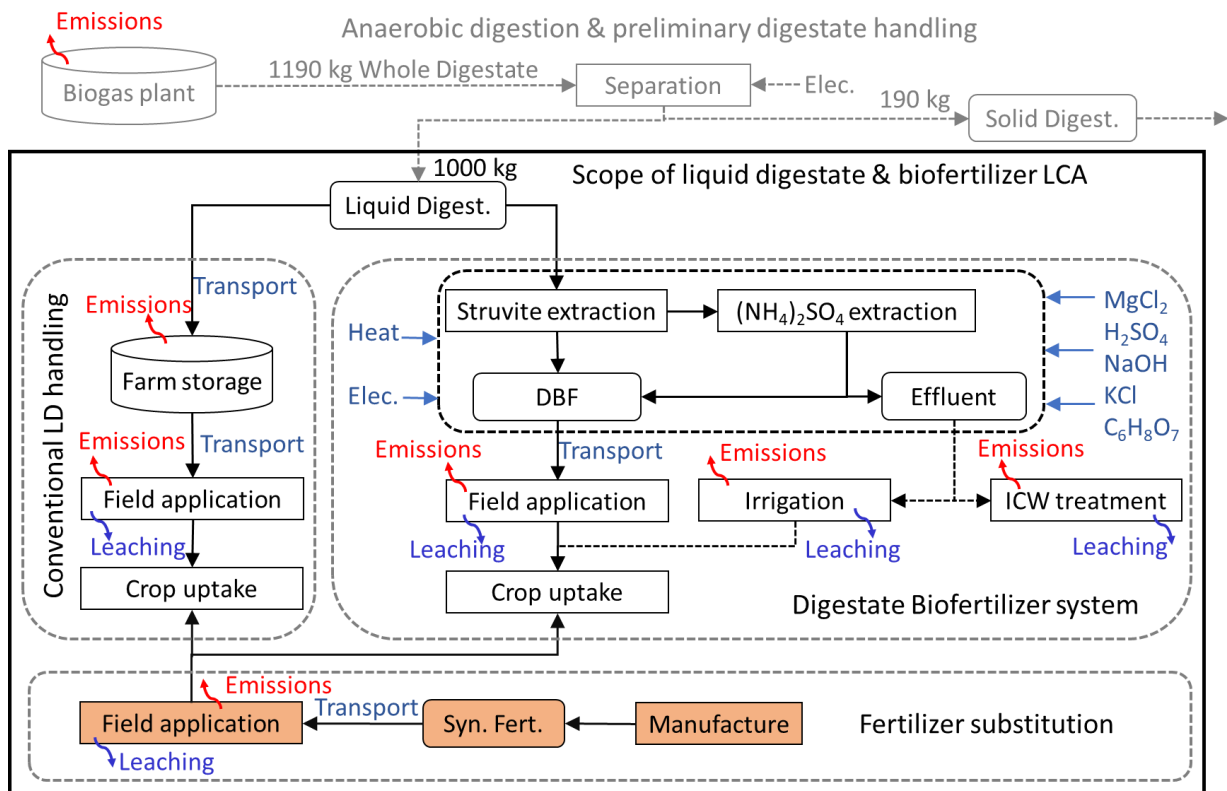
94 Mechanical dewatering of whole digestate from food waste AD plants produces a solid digestate
95 fraction, into which more of the P is partitioned, and a LD fraction, into which more of the N (especially
96 $\text{NH}_4\text{-N}$) and K is partitioned¹⁰. Here, we focus on extraction and upcycling of a digestate biofertilizer
97 (DBF) from the LD fraction, and benchmark the performance of the DBF life cycle with the baseline LD
98 life cycle. Technical data on DBF production from LD produced at a centralized food waste AD plant
99 was taken from bench- and pre-commercial pilot trials in Sweden²². The DBF is produced via the
100 Ekobalans eco:P and eco:N processes. The eco:P process involves struvite (magnesium ammonium
101 phosphate) precipitation via the addition of magnesium chloride and pH control by aeration, and
102 crystallised precipitation of P. The eco:N process involves the air-stripping of ammonia from liquid
103 digestate flowing down through a packed column, followed by crystallization recovery using sulphuric
104 acid to produce solid ammonium sulphate ($(\text{NH}_4)_2\text{SO}_4$) at 21% N content. The efficiency of this
105 technique is improved by increasing the temperature and the pH of the digestate using sodium
106 hydroxide (NaOH)^{22,26}. N and P extracted in struvite and ammonium sulphate are blended with
107 potassium chloride (KCl) to produce the DBF product – a balanced NPK compound fertilizer.

108 2.2. Goal, scope and boundary definition

109 The primary goal of the study was to compare conventional management of LD with the production
110 and use of DBF in terms of resource use efficiency and environmental impact. The primary research
111 question is: does the upcycling of LD into DBF lead to net environmental benefits and resource
112 savings? The answer to this question is pertinent to waste managers, farmers and policy makers.

113 We undertook a “gate-to-grave” LCA in accordance with ISO²⁷ principles to benchmark the
114 environmental performance of DBF production and use against typical handling of LD from centralised
115 AD plants. The functional unit was the handling of 1 m³ of LD from a food waste AD plant (Table S1).
116 System boundaries for conventional LD and DBF management begin immediately following

117 separation, representing the point of divergent management from existing best practice, and
118 capturing major post-digestion environmental burdens of LD management (Fig. 1). Management of
119 the solid digestate fraction is unaffected by DBF extraction and excluded from the analyses. To reflect
120 important implications for synthetic fertilizer substitution, system boundaries were expanded to
121 account for synthetic fertilizer replacement achieved by field-application of LD and DBF in terms of
122 avoided field emissions and fertilizer manufacture. Capital equipment such as farm machinery and
123 upgrading facilities are outside the system boundary²⁸. Operational flows of digestate are expected to
124 be thousands of m³ a month over twenty or more years, leading to small burden contributions from
125 construction and maintenance. The effects of varying transport distances, digestate storage
126 infrastructure, field application methods and nutrient management planning (NMP) were explored
127 using scenarios. Life cycle inventories are described below. Five impact categories pertinent to AD and
128 agricultural systems were selected from the CML baseline method²⁹ to represent environmental
129 impact and resource efficiency: abiotic resource depletion potential (ARDP), expressed as kg Sb eq.;
130 acidification potential (AP), expressed as SO₂ eq.; cumulative energy demand (CED), expressed as MJ
131 eq.; eutrophication potential (EP), expressed as PO₄ eq.; global warming potential (GWP), expressed
132 as CO₂ eq.



133
 134 **Figure 1. Main processes and inputs accounted for in this study, within system boundaries for (i)**
 135 **conventional liquid digestate (LD) handling and (ii) digestate biofertilizer (DBF) production and use,**
 136 **including synthetic fertilizer substitution, but excluding preliminary digestate management**
 137 **common to both systems.**

138
 139 Results were calculated for different management practices and contexts through consideration of
 140 four scenarios of conventional LD management and three scenarios of DBF production and use (Table
 141 1). Uncertainty ranges for each scenario were calculated by propagating specific methodological
 142 uncertainties detailed in sections 2.3 and 2.4 in quadrature (square root of summed squared errors),
 143 expressed as error bars on results.

144 2.3. Conventional liquid digestate handling

145 Emission factors and fertilizer substitution rates associated with LD handling are highly dependent on
 146 the type of digestate storage and application^{10,14,30,31}. Sensitivity analyses were therefore applied
 147 through scenarios to evaluate different storage and application options, and varying transport
 148 distances to farms (Table 1). A major challenge for efficient use of LD is convincing a sufficient number
 149 of farmers within an economic transport distance to spread it in accordance with good nutrient

150 management planning. Therefore, sensitivity analyses were undertaken for actual NPK-fertilizer
 151 replacement achieved by field application of LD, by multiplying maximum potential fertilizer
 152 replacement values calculated in MANNER-NPK²³ by 25%, 50%, 75% and 100% (Table 1).

153 **Table 1. Scenario permutations for liquid digestate (LD) and digestate biofertilizer (DBF)**
 154 **management**

Liquid digestate scenario	Transport distance (km)	Storage location and infrastructure	Field application technique	Fertilizer replacement (% available NPK*)
LD-1 (optimum)	5	Biogas plant, sealed tank	Shallow injection	100%
LD-2 (good case)	10	Farm, covered tank	Shallow injection	75%
LD-3 (default)	10	Farm, open tank	Trailing hose	50%
LD-4 (worst case)	20	Farm, lagoon	Trailing hose	25%
Digestate biofertilizer scenario	Transport distance (km)	Electricity source	Heat source	Effluent management
DBF-1 (optimum)	20	Nuclear/renewable	Biogas-CHP waste heat	Crop-irrigation
DBF-2 (default)	50	NG-CCT	Gas boiler	Constructed wetland
DBF-3 (worst case)	200	Coal	Gas boiler	Constructed wetland
*Potentially plant-available NPK (fertilizer replacement potential) calculated using MANNER-NPK ²³ . NG-CCT = Natural gas combined cycle turbine marginal electricity generation.				

155
 156 Life cycle inventories were compiled to account for all inputs and outputs from processes arising
 157 within the respective system boundaries. The first stage of conventional LD handling is transport to
 158 the farm using a bulk liquid tanker over 10 km, varied from 5 to 20km (Table 2). In the default scenario,
 159 LD is stored in an open tank on the farm. Alternative scenarios involve a tank with a natural crust or
 160 floating cover, a lagoon storage system, or longer storage of separated liquid digestate at the
 161 centralised digester plant in a sealed tank prior to direct field-application (Table 1). Methane emissions
 162 were calculated using the following equation:

163 $\text{kg CH}_4 = \text{VS} \times \text{Bo} \times 0.714 \times \text{MCF}$

164 where volatile solids (VS) content of the LD fraction is 12.8 kg m^{-3} (Banks, 2011), CH_4 generating
165 capacity (B_o) is $0.2 \text{ m}^3 \text{ kg}^{-1}$ ^{25,32}, methane density is 0.714 kg m^{-3} , and methane conversion factor (MCF)
166 is expressed in relation to the type of storage system³³, ranging from 1% (sealed tank), through 10%
167 (covered tank) to 17% (open tank and lagoon). $\text{NH}_3\text{-N}$ emission factors were applied to $\text{NH}_4\text{-N}$ in the
168 LD depending on the type of storage system, ranging from 2% (sealed tank), 5% (covered tank) through
169 10% (open tank) to 52% (lagoon)²⁴. N_2O emissions from storage of LD in tanks and lagoon systems
170 were assumed to be negligible, as reported in previous studies²⁵ and consistent with GHG accounting
171 guidelines for liquid slurry systems³³. Table 2 presents CH_4 and NH_3 emissions from the four scenarios
172 of digestate storage.

173 **Table 2. Inventory of inputs and direct emissions for a reference flow of 1m³ of liquid digestate (LD) exiting an anaerobic digestion plant and either sent**
 174 **to nearby farms where it may be managed along a spectrum of best to worst practices (LD-1 to LD-4; Table 1), or upcycled to digestate biofertilizer (DBF)**
 175 **for use on farms further away (DBF-1 to DBF-3; Table 1).**

Stage	Process	LD-1	LD-2	LD-3	LD-4	DBF	Units	References
LD transport & storage	Trans. to farm	5.00	10.00	10.00	20.00	0.69	Tkm	
	Storage CH ₄	0.02	0.18	0.31	0.31	–	Kg	25,32,33
	Storage NH ₃	0.03	0.08	0.41	2.12	–	Kg	24
	Storage N ₂ O	0	0	0	0	–	Kg	25,33
Struvite extraction	MgCl ₂ .6H ₂ O	–	–	–	–	0.85	Kg	22
	Electricity	–	–	–	–	0.70	kWh	22
Ammonium sulfate extraction	NaOH 50%	–	–	–	–	10.00	Kg	22
	H ₂ SO ₄ 96%	–	–	–	–	11.00	Kg	22
	Electricity	–	–	–	–	1.10	kWh	22
	Heat	–	–	–	–	16.00	kWh	22
	Citric acid	–	–	–	–	0.28	Kg	22
Fertilizer production	KCl	–	–	–	–	0.019	Kg	22
	Electricity	–	–	–	–	0.002	kWh	22
	Heat	–	–	–	–	0.014	kWh	22
Field application	Diesel consum.	0.75	0.75	0.50	0.50	0.004	Kg	34,35
	NH ₃	0.38	0.38	0.81	0.54	0.003	Kg	23,24
	N ₂ O	0.087	0.085	0.085	0.056	0.053	Kg	33
	N leaching	0.92	0.91	0.77	0.51	0.31	Kg	36
	P leaching	0.0012	0.0012	0.0012	0.0012	0.0012	Kg	37,38
Fertilizer substitution	Avoided fert-N	2.16	1.60	0.88	0.29	3.14	Kg	²³ x replacement factor (Table 1)
	Avoided fert-P	0.060	0.045	0.030	0.015	0.12	Kg	²³ x replacement factor (Table 1)
	Avoided fert-K	1.27	0.95	0.64	0.32	1.00	Kg	²³ x replacement factor (Table 1)
DBF effluent in ICW	Electricity	–	–	–	–	0.12	kWh	39
	N ₂ O	–	–	–	–	0.016	Kg	40–42

DBF effluent irrigation use (DBF-1 only)	Electricity	-	-	-	-	0.25	kWh	³⁹
	N leaching	-	-	-	-	0.025	Kg	²³
	NH ₃	-	-	-	-	0.030	Kg	²³
	N ₂ O	-	-	-	-	0.016	Kg	²³
	Avoided fert-N	-	-	-	-	0.40	Kg	²³
	Avoided fert-K	-	-	-	-	0.675	Kg	²³

176

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179

180 Following 3-6 months of storage, LD is applied to land using either shallow injection (LD-1 and LD-2)
181 or trailing hose (LD-3 and LD-4) application. Emissions of NH_3 , NO_3 leaching and maximum NPK-
182 fertilizer replacement values were calculated using MANNER NPK²³ for spring and autumn LD
183 applications in good conditions (calm weather, moist soils, no rain immediately after application), on
184 a medium textured soil prior to a spring cereal crop (see SI2). LD nutrient concentrations inputted into
185 MANNER-NPK were corrected for storage losses of N. Direct and indirect N_2O emissions were
186 calculated based on IPCC Tier 1⁴³. Varying levels of NMP were represented by equating actual fertilizer
187 replacement from 25 to 100% of replacement potential calculated using MANNER-NPK (Table 1). To
188 reflect considerable uncertainty over emission factors, gaseous emissions and leaching losses were
189 varied by $\pm 50\%$ for each scenario.

190 Credits for avoided fertilizer use comprised avoided manufacture taken from the Ecoinvent database⁴⁴
191 and avoided field emissions post-application based on emission factors of $0.017 \text{ NH}_3\text{-N}^{24}$, $0.1 \text{ NO}_3\text{-N}^{36}$
192 and 0.01 for P following N- and P-fertilizer application³⁸. Nitrogen, phosphorus and potassium
193 fertilizers were assumed to be in the forms of ammonium nitrate, triple superphosphate and
194 potassium chloride. Diesel consumption for trailing hose and shallow injection application^{34,35} was
195 multiplied by relevant tractor emissions³⁸ and upstream production and supply burdens⁴⁴. Uncertainty
196 in transport and upstream burdens was reflected by varying these burdens by $\pm 20\%$.

197 **2.4. Upcycled digestate biofertilizer production and use**

198 Digestate upcycling into DBF occurs in four stages: flocculation of suspended solids, struvite
199 extraction, ammonium sulfate crystallisation and final fertilizer blending, with various heat, electricity
200 and chemical inputs (Table 2). Three permutations of DBF production and use were considered (Table
201 1). Indirect emissions from heat, electricity and chemical production were taken from Ecoinvent⁴⁴,
202 with sensitivity analyses undertaken by varying electricity and heat sources. The default electricity
203 source was natural gas combined cycle turbine (NG-CCT) power stations, representing typical marginal
204 electricity generation⁴⁵. Best- and worst-case permutations were based on a grid mix of 90% nuclear

205 and renewable sources (current Swedish grid), and coal generation. The source of heat was varied
206 between a natural gas condensing boiler (default) and waste heat from biogas combined heat and
207 power generators (zero burden on assumption otherwise dumped). It was assumed that fugitive
208 emissions from the upgrading process were negligible because the stripping air is circulated in a closed
209 loop between the crystallizer and the ammonia stripping column. The DBF product was transported
210 50 km in a 16-32 t EURO V lorry⁴⁴ for field application where needed, and in accordance with good
211 NMP, resulting in 1:1 substitution of fertilizer NPK. Field emissions were calculated as per synthetic
212 fertilizer (section 2.3), accounting for diesel consumption³⁴. Uncertainty analyses were undertaken by
213 varying the rate of fertilizer-P substitution by struvite-P from 100% down to 50%, reflecting the
214 findings of recent research on struvite as a slow-release fertilizer⁴⁶, and varying heating, electricity and
215 chemical requirements by $\pm 20\%$.

216 Effluent water contains significant quantities of N and K (see SI3), and was assumed to be treated in a
217 constructed wetland (default option) or returned to land as irrigation water (best case option). Field
218 emissions and fertilizer replacement value for irrigation water were calculated using MANNER-NPK,
219 assuming 1% residual dry matter content, “trailing hose” type irrigation, and taking the average of
220 January, April, July and October applications to represent year-round irrigation (Table 2). Electricity
221 requirements for pumping effluent to irrigation pipes and through a constructed wetland were taken
222 from Plapally et al. (2012)³⁹. Nutrients contained in effluent sent to a constructed wetland will be
223 retained in biomass and denitrified, giving rise to N₂O emissions⁴⁰⁻⁴² (Table 2). Effluent water
224 treatment burdens were varied by $\pm 50\%$.

225

226 **3. Results and discussion**

227 **3.1. Resource depletion and global warming**

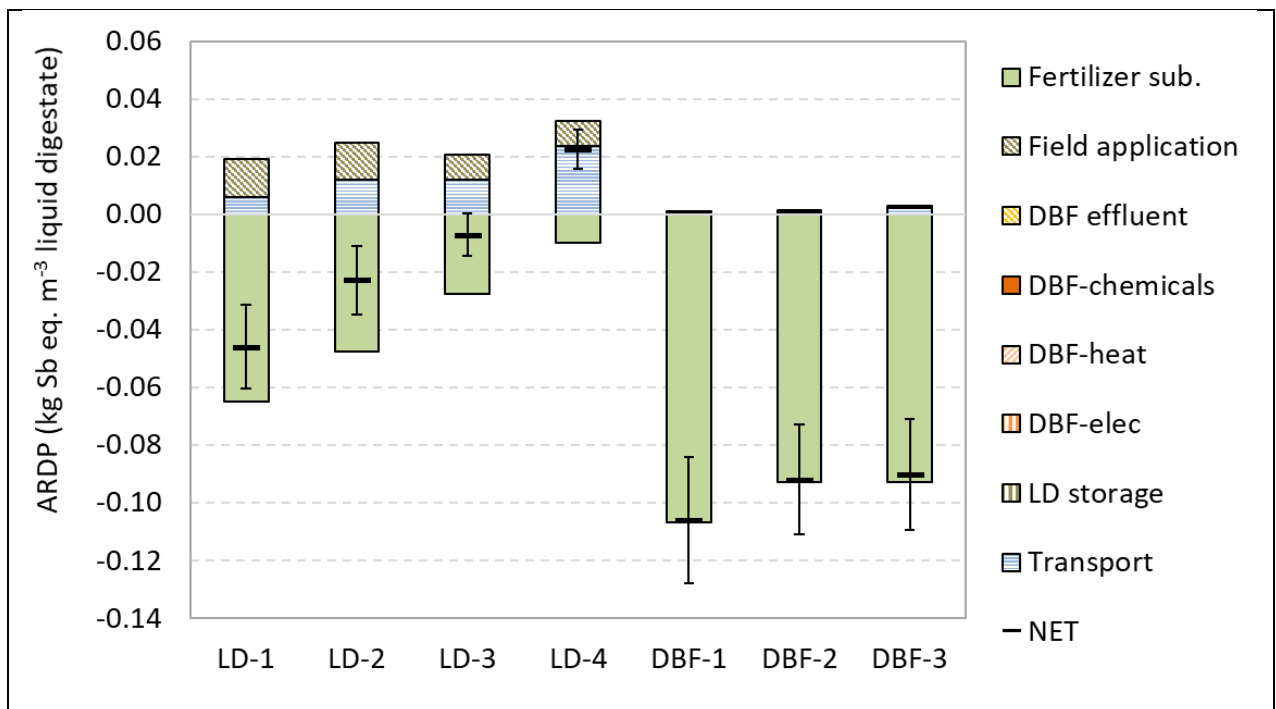
228 Avoided fertilizer manufacture dominates ARDP and CED balances, which are negative for default LD
229 management (LD-3) and good (LD-2) or optimum (LD-1) LD management options, reflecting a net

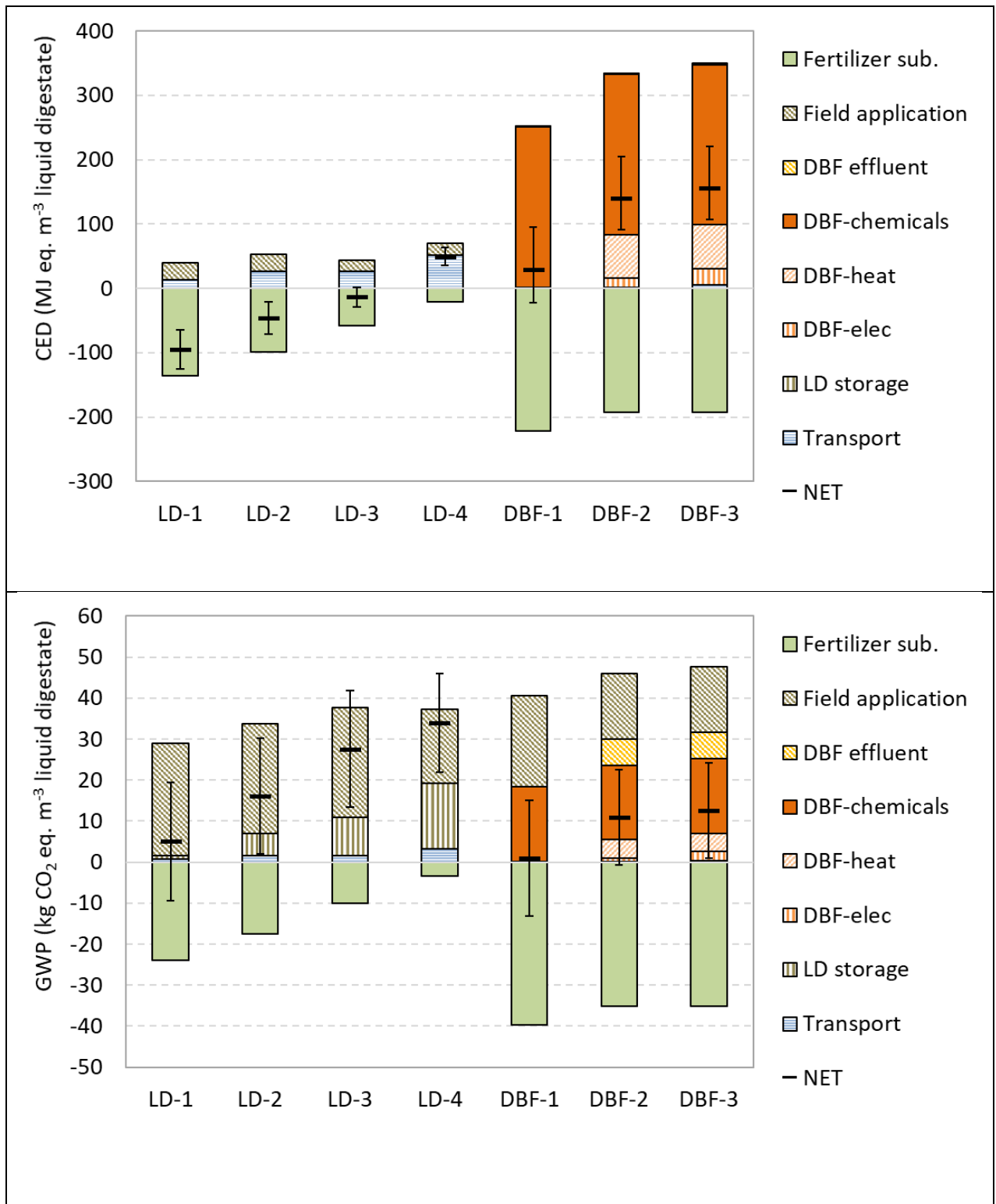
230 environmental benefit arising from good agronomic use of LD via synthetic fertilizer substitution (Fig.
231 2 and Table S3). However, if LD is poorly managed so that synthetic fertilizer substitution is just 25%
232 of the potential (LD-4), then ARDP and CED burdens arising from the transport and spreading of LD
233 are greater than the fertilizer substitution credits. The latter situation represents inefficient agronomic
234 use of LD, not applied in accordance with good NMP, at wrong time of year and/or to land and
235 cropping systems that do not require the nutrients. Whilst it is assumed that most digestate from
236 crop-fed AD is returned to nearby cropping fields^{38,47,48}, there is a lack of information on the
237 management of digestate produced in food waste AD plants. Food waste AD plant operators may need
238 to pay farmers to take digestate away, and there is evidence that digestate is being over-applied to
239 land close to food waste AD plants¹² so that conventional LD management could generate net ARDP
240 and CED burdens. These outcomes are not reflected in LCA studies that typically assume either all, or
241 all plant-available, nutrients in digestate substitute synthetic fertilizers^{31,47,49,50}, confirming the need
242 to improve the transparency and accuracy of fertilizer substitution in agronomic LCA studies.²¹

243 Extracted DBF performs almost twice as well as LD, even when LD is managed optimally (LD-1) in terms
244 of ARDP, owing to more effective synthetic fertilizer substitution, but leads to a CED burden for DBF-
245 2 and DBF-3 almost three times greater than even poorly-managed LD (LD-4). This is partly because of
246 high embodied energy in the chemicals required in the production process (Fig. 2), especially NaOH
247 (Table 2). Heat and electricity used during DBF production give rise to significant energy demand that
248 can be mitigated through use of non-fossil electricity and waste heat from biogas-fed combined heat
249 and power plants, resulting in a net energy demand of below 30 MJ m⁻³ LD treated for best case DBF
250 extraction, and possibly even resulting in a net credit for CED at the low end of the uncertainty range
251 (Fig. 2). For context, the net CED burden in the DBF-2 scenario would offset 4% of the net CED benefit
252 arising from the digestion of the 1.2 Mg of food waste substrate producing 1 m³ of LD (Fig. S1)¹⁴.

253 Production and use of DBF leads to a net GHG emission of less than 1 (DBF-1) up to 12.5 (DBF-3) kg
254 CO₂ eq. per m³ of LD processed, compared with emissions of 5 to 34 kg CO₂ eq. m⁻³ arising from

255 conventional management of LD (Fig. 2). For DBF, embodied GWP in chemical inputs, N₂O emissions
 256 from field application and effluent management in a constructed wetland, and CO₂ emissions from
 257 natural gas heating, are cumulatively greater than GWP avoidance achieved through fertilizer
 258 substitution. However, if non-fossil electricity and heat sources are used (DBF-3), DBF production and
 259 use becomes close to carbon neutral. For LD, N₂O emissions from field application are the main source
 260 of GWP, and these emissions are higher for the better case scenarios (LD-1 and LD-2) than the worse
 261 scenarios (LD-3 and LD-4) owing to less loss of N during storage in the former scenarios. However,
 262 overall GWP burdens are significantly greater for LD-3 and LD-4 overall owing to high CH₄ losses, and
 263 indirect N₂O following NH₃ losses, during open tank and lagoon storage of LD, respectively. Thus,
 264 despite significant emissions in the production process, DBF can mitigate GHG emissions arising from
 265 LD management by avoiding direct and indirect N₂O and CH₄ emissions from digestate storage and
 266 field-application, and by increasing fertilizer substitution. For context, under default assumptions DBF
 267 can enhance the overall GHG abatement potential of food waste digestion by 8% (Fig. S1), but under
 268 the most pessimistic assumptions for DBF it could reduce the overall GHG abatement potential of food
 269 waste digestion by 4%.





270 **Figure 2. Environmental balance per m³ of liquid digestate (LD) managed along a spectrum of best**
 271 **(LD-1) to worst (LD-4) practice, and upcycled digestate biofertilizer managed along a spectrum of**
 272 **best (DBF-1) to worst (DBF-3) practice. Results displayed for abiotic resource depletion (ARD, top),**
 273 **cumulative energy demand (CED, middle) and global warming potential (GWP, bottom)**

274

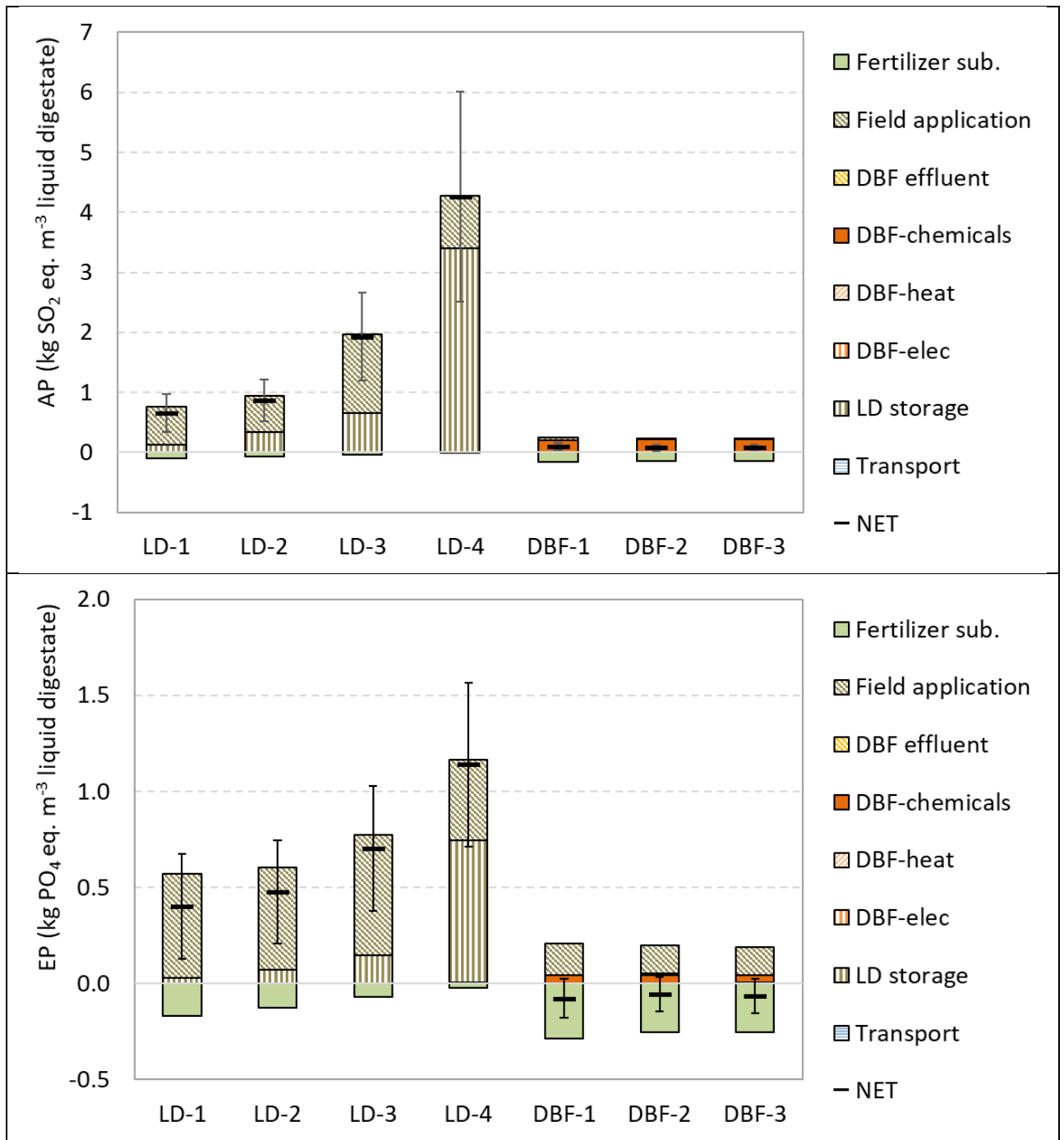
275

276 **3.2. Air and water quality**

277 Results in Fig. 3 and Table S3 confirm those of previous studies indicating high acidification and
278 eutrophication burdens from digestate storage and field application^{8,14,31,47}. Acidification burdens are
279 driven by NH₃ emissions, which are related to methods of digestate storage and application, and range
280 from 0.7 to 4.3 kg SO₂ eq. per m³ LD for optimum management (LD-1) and worst-case management
281 (LD-4), respectively (Fig. 3). Upgrading LD into DBF avoids these emissions, and reduces the net
282 acidification burden of food waste digestion by up to 73% (Fig. S1), representing a potentially
283 important mitigation option for perhaps the most significant environmental hotspot of AD
284 systems^{14,50,51}. Eutrophication burdens follow a similar though less pronounced pattern to
285 acidification, increasing from 0.4 to 1.1 kg PO₄ eq. per m³ of LD for optimum management (LD-1) and
286 worst-case management (LD-4), respectively (Fig. 3). The production and use of DBF achieves a net
287 reduction in eutrophication owing to the avoidance of upstream extraction and processing of nutrients
288 for synthetic fertilizers (field emissions are assumed to be the same for synthetic fertilizers and DBF).
289 Under default assumptions, DBF extraction reduces the net eutrophication burden of food waste
290 digestion by 85% (Fig. S1). Thus, upgrading LD to DBF largely mitigates a second environmental hotspot
291 of digestate use specifically, and AD systems in general^{14,50,51}.

292

293



294 **Figure 3. Environmental balance per m³ of liquid digestate (LD) managed along a spectrum of best**
 295 **(LD-1) to worst (LD-4) practice or upcycled into digestate biofertilizer (DBF), for acidification**
 296 **potential (AP, top) and eutrophication potential (EP, bottom).**

297

298 **3.3. Abatement potential**

299 A recent survey of AD operators indicated that open tank and lagoon storage systems predominate¹⁴.

300 Although almost one third of large AD plants were found to have sealed digestate storage tanks¹⁴,

301 digestate sent to farms is likely to be stored in open tanks if it is not spread immediately, supporting
302 our default assumption of open-tank storage (LD-3). Producing DBF at medium efficiency (DBF-2) from
303 LD that would otherwise be handled in such a way would give rise to savings of 0.085 kg Sb eq., 1.85
304 kg SO₂ eq., 0.76 kg PO₄ eq. and 16.8 kg CO₂ eq. per m³ of LD upcycled to DBF, though cumulative energy
305 demand would increase by 154 MJ eq. (Table S4). It is worth noting that a shift towards best practice
306 in LD handling (LD-1) from default practice (LD-3) would also lead to significant environmental savings,
307 and outperform DBF in terms of cumulative energy demand and global warming potential, though fall
308 short of DBF in terms of the abatement of acidification, eutrophication and resource depletion
309 hotspots (Table S4; Fig. S1; Fig. S2). Achieving environmental savings from best practice in digestate
310 management would require all biogas plants to install sealed tank storage of digestate, all LD to be
311 transported to land producing crops requiring all the nutrients in the LD, and all LD to be spread via
312 shallow injection at the optimum time for crop uptake. There would be significant technical and
313 logistical barriers to implementing such practices universally, and costs could exceed the projected
314 costs of commercial DBF extraction which are estimated to be €5-10 per m³ LD.

315 Extrapolated to an ambitious future scenario in which 25% of global food waste is treated by AD
316 (detailed in S6), the annual mitigation potential of upgrading all LD would equate to approximately
317 439 Gg SO₂ eq., 22.6 Gg Sb eq. and 4465 Gg CO₂ eq. under default assumptions (Table S5).
318 Normalisation of these theoretical abatement potentials (Fig. S2) indicates that abiotic resource
319 depletion and acidification potential would be the impact categories most benefitted, with global
320 burdens reduced by up to 1% and 0.2%, respectively, under default assumptions, with a minor trade-
321 off in cumulative energy demand which would increase by 0.01%.

322

323 **Recommendations**

324 In summary, expanded boundary LCA highlights the relative importance of environmental credits
325 attributed to differential rates of fertilizer substitution when comparing the overall environmental

326 balance of liquid digestate handling and use with the production and use of biofertilizer extracted
327 from liquid digestate via struvite precipitation and ammonia stripping. Avoided gaseous emissions
328 during storage and spreading of liquid digestate, and enhanced fertilizer substitution arising from
329 more targeted application of the versatile biofertilizer product, mean that extraction of biofertilizer
330 from liquid digestate can achieve significant environmental savings. Normalization indicates that the
331 identified trade-off of higher cumulative energy demand is comparatively minor, and could be
332 mitigated by use of renewable energy or surplus biogas heat. The avoidance of NH₃ emissions and
333 conservation of elemental resources appear to be the most significant advantages of biofertilizer
334 production and use, which can help to close nutrient loops. External damage costs of NH₃ emissions
335 are estimated at approximately €3000 per tonne⁵², suggesting that the considerable NH₃ abatement
336 achieved by upgrading LD to DBF could be of significant public good benefit, and potentially worthy of
337 subsidy support or regulatory push via tighter emission standards for digestate (and slurry)
338 management. On the basis of these results, we would recommend:

- 339 • Further research into digestate management practices by farmers to better estimate
340 associated emissions and actual, rather than theoretical, fertilizer substitution
- 341 • Detailed techno-economic assessment of DBF versus better management practices for
342 digestate to identify potential contexts for cost-effective deployment of DBF production
- 343 • Investment into commercial development of struvite extraction and ammonia stripping from
344 digestate, to optimise process efficiency and reduce costs
- 345 • Policies to drive pollution mitigating technologies such as biofertilizer extraction from
346 digestate and other nutrient-rich residues, such as pollution taxes and/or tighter controls on
347 residue storage and (rates, methods and timings of) application

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353 **Supporting Information.** Five tables containing information on liquid digestate characteristics,
354 emission factors, detailed results and extrapolated biofertilizer scenarios, and two figures showing
355 normalized environmental loading changes.

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