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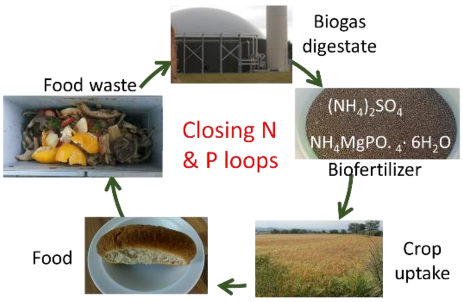
Graphical abstract



Abstract

Handling of digestate produced by anaerobic digestion impacts the environment through emission of greenhouse gases, reactive nitrogen and phosphorus. Previous life cycle assessments (LCA) evaluating the extraction of nutrients from digestate using struvite precipitation and ammonia stripping did not relate synthetic fertilizer substitution (SFS) to nutrient use efficiency consequences. We applied an expanded LCA to compare the conventional management of 1 m^3 of liquid digestate (LD) from food waste against the production and use of digestate biofertilizer (DBF) extracted from LD, accounting for SFS efficacy. Avoidance of CH_4, N_2O and NH_3 emissions from LD handling and enhanced SFS via more targeted use of nutrients in the versatile DBF product could generate environmental savings of up to 0.129 kg Sb eq., 4.16 kg SO_2 eq., 1.22 kg PO_4 eq., 33 kg CO_2 eq. and 20.6 MJ eq. per m^3 LD, for abiotic resource depletion, acidification, eutrophication, global warming and cumulative energy demand burdens, respectively. However, under worst-case assumptions, DBF extraction could increase global warming and cumulative energy demand by 7.5 kg CO_2e and 251 MJ eq. per m^3 LD owing to processing inputs. Normalizing these results against per capita environmental loadings, we conclude that DBF extraction is environmentally beneficial.

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

1. Introduction

Leaky nutrient cycles undermine the environmental sustainability of global food chains. The nitrogen (N) cycle is the second most critically impacted planetary system[1]. Pollution arising from N losses to air and water costs up to 320 billion euros annually across Europe[2,3] and manufacturing synthetic N fertilizer via the Haber-Bosch process is energy-intensive and expensive. Meanwhile, phosphorus (P) use efficiency is low, leading to eutrophication impacts in water bodies and depletion of poorly-quantified but essentially finite global phosphate reserves[4,5]. Closing nutrient cycles and minimising losses is therefore an imperative for sustainable food production. Anaerobic digestion (AD) is an increasingly popular option for the treatment of organic wastes, such as manures and food waste, that facilitates nutrient recycling whilst producing bio-energy[6]. The digestate co-product of AD is a valuable bio-fertilizer, rich in readily available macro- and micro-nutrients[7]. However, storage and application of digestate gives rise to fugitive emissions of methane (CH_4) and ammonia (NH_3), contributing towards global warming, acidification and eutrophication[8], whilst digestates from some feedstocks have been linked with increased risk of soil contamination with Cu, Zn and Mn[9]. Economies of scale favour large AD plants to treat food waste, whilst a high water content makes long-term storage and long-distance transport of digestate uneconomic[10]. Digestate certification schemes[11] have not yet overcome farmer suspicion about the agronomic value and safety of digestates which vary considerably in composition and deviate from ideal ratios for crop nutrition[9]. Consequently, there is concern that digestate is not distributed widely enough, nor applied at the right times, to achieve efficient nutrient use, i.e. digestate may be over-applied in areas adjacent to large AD plants[12] and in autumn when crop-uptake and N use efficiency is low [9,13]. A recent life cycle assessment (LCA) study[14] found that, even when digestate from food waste is applied at agronomically-appropriate times, field emissions outweigh fertilizer substitution credits, leading to net acidification and eutrophication burdens. Mechanical separation of digestate into solid fractions containing more of the P, and liquid fractions containing more of the N and K, could help to improve nutrient use efficiency, as demonstrated for separated pig slurry[15]. However, it may also increase N_2O emissions from the solid fraction[16]. Handling separated liquid digestate (LD) still gives rise to distribution challenges and ammonia emissions[8,9]. Upgrading digestate into a concentrated, easy-to-handle biofertilizer is a potential solution that could improve nutrient use efficiency and reduce emissions by avoiding prolonged storage of digestate, and by concentrating nutrients into a compact, convenient and familiar powder fertilizer format that can be applied in accordance with crop requirements[5]. A range of technologies have been developed to upcycle digestate, including struvite precipitation, ammonia stripping and capture (absorption/crystallisation), acidification and alkaline stabilisation[17], algal nutrient-stripping[18] and others. In this paper, we focus on struvite precipitation with ammonia stripping to produce a digestate biofertilizer (DBF) product, the most established technologies[17]. These technologies could also be applied to address problems associated with nutrient over-concentration in regions with high livestock densities and constrained landbanks for manure spreading, e.g. peri-urban livestock systems in Asia.

Despite promising field trials valorising the crop nutrient value of such biofertilizers, legislative barriers have hitherto limited their development[9,19]. A recent LCA study highlighted environmental benefits and trade-offs associated with LD upcycling to DBF[20], but did not account for potential fertilizer substitution effects linked to more precise nutrient management, which could be particularly significant in the context of a rapidly expanding global AD sector. The common assumption of 1:1 substiution of synthetic fertilizer nutrients with organic nutrients frequently leads to overestimation of the environmental performance of conventional organic residue use in LCA studies[21]. For the first time, this study accounts for important nutrient use efficiency effects within an expanded boundary LCA to fully compare the environmental balance of conventional LD management with production and use of an upcycled DBF product. We build on recent LCA studies of digestate upcycling[8,20] with new detailed data on DBF processing obtained from bench and pre-commercial pilot trials undertaken by a Swedish company[22], and apply detailed accounting for emissions and fertilizer substitution arising from different management of LD based on appropriate models and emission factors[23–25].

2. Materials and Methods

2.1. Biofertilizer production process

Mechanical dewatering of whole digestate from food waste AD plants produces a solid digestate fraction, into which more of the P is partitioned, and a LD fraction, into which more of the N (especially NH_4-N) and K is partitioned[10]. Here, we focus on extraction and upcycling of a digestate biofertilizer (DBF) from the LD fraction, and benchmark the performance of the DBF life cycle with the baseline LD life cycle. Technical data on DBF production from LD produced at a centralized food waste AD plant was taken from bench- and pre-commercial pilot trials in Sweden[22]. The DBF is produced via the Ekobalans eco:P and eco:N processes. The eco:P process involves struvite (magnesium ammonium phosphate) precipitation via the addition of magnesium chloride and pH control by aeration, and crystallised precipitation of P. The eco:N process involves the air-stripping of ammonia from liquid digestate flowing down through a packed column, followed by crystallization recovery using sulphuric acid to produce solid ammonium sulphate ($(NH_4)_2SO_4$) at 21% N content. The efficiency of this technique is improved by increasing the temperature and the pH of the digestate using sodium hydroxide (NaOH)[22,26]. N and P extracted in struvite and ammonium sulphate are blended with potassium chloride (KCl) to produce the DBF product – a balanced NPK compound fertilizer.

2.2. Goal, scope and boundary definition

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

We undertook a "gate-to-grave" LCA in accordance with ISO[27] principles to benchmark the environmental performance of DBF production and use against typical handling of LD from centralised AD plants. The functional unit was the handling of 1 m^3 of LD from a food waste AD plant (Table S1). System boundaries for conventional LD and DBF management begin immediately following separation, representing the point of divergent management from existing best practice, and capturing major post-digestion environmental burdens of LD management (Fig. 1). Management of the solid digestate fraction is unaffected by DBF extraction and excluded from the analyses. To reflect important implications for synthetic fertilizer substitution, system boundaries were expanded to account for synthetic fertilizer replacement achieved by field-application of LD and DBF in terms of avoided field emissions and fertilizer manufacture. Capital equipment such as farm machinery and upgrading facilities are outside the system boundary[28]. Operational flows of digestate are expected to be thousands of m^3 a month over twenty or more years, leading to small burden contributions from construction and maintenance. The effects of varying transport distances, digestate storage infrastructure, field application methods and nutrient management planning (NMP) were explored using scenarios. Life cycle inventories are described below. Five impact categories pertinent to AD and agricultural systems were selected from the CML baseline method[29] to represent environmental impact and resource efficiency: abiotic resource depletion potential (ARDP), expressed as kg Sb eq.; acidification potential (AP), expressed as SO_2 eq.; cumulative energy demand (CED), expressed as MJ eq.; eutrophication potential (EP), expressed as PO_4 eq.; global warming potential (GWP), expressed as CO_2 eq.

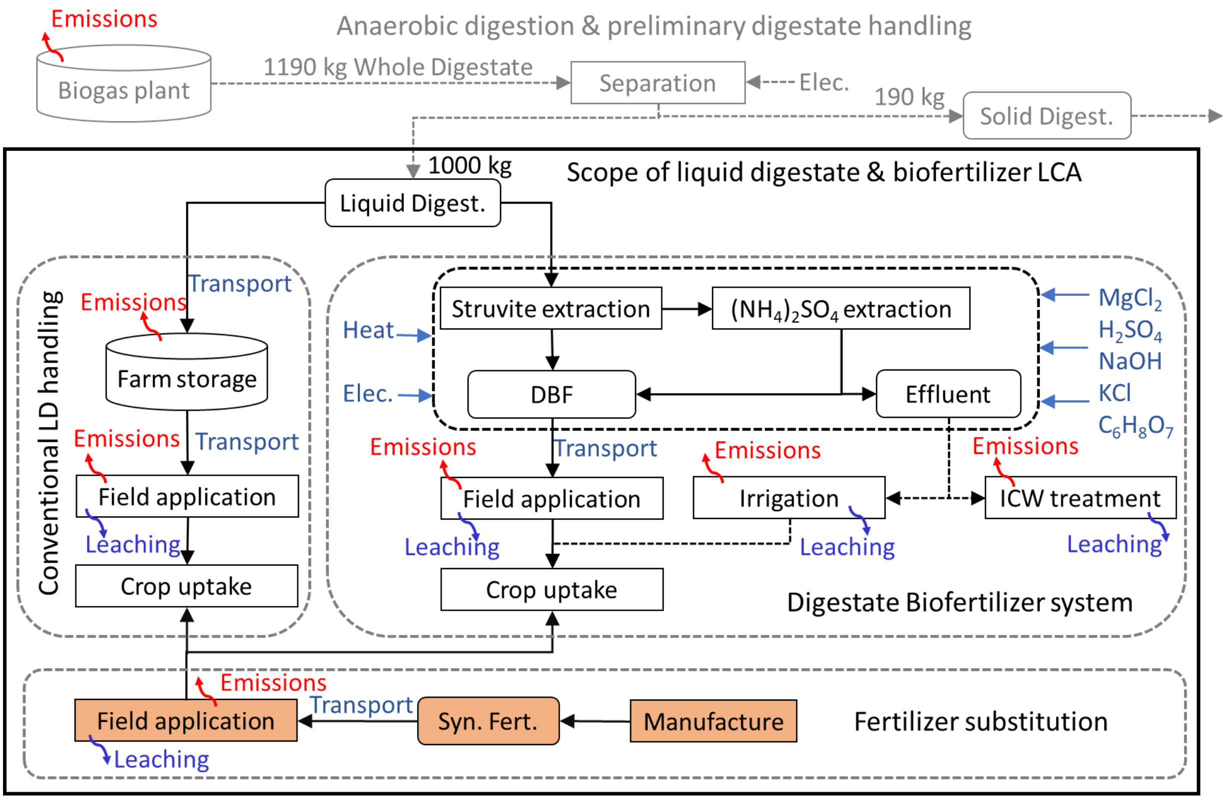


Figure 1. Main processes and inputs accounted for in this study, within system boundaries for (i) conventional liquid digestate (LD) handling and (ii) digestate biofertilizer (DBF) production and use, including synthetic fertilizer substitution, but excluding preliminary digestate management common to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

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

2.3. Conventional liquid digestate handling

Emission factors and fertilizer substitution rates associated with LD handling are highly dependent on the type of digestate storage and application[10,14,30,31]. Sensitivity analyses were therefore applied through scenarios to evaluate different storage and application options, and varying transport distances to farms (Table 1). A major challenge for efficient use of LD is convincing a sufficient number of farmers within an economic transport distance to spread it in accordance with good nutrient management planning. Therefore, sensitivity analyses were undertaken for actual NPK-fertilizer replacement achieved by field application of LD, by multiplying maximum potential fertilizer replacement values calculated in MANNER-NPK[23] by 25%, 50%, 75% and 100% (Table 1).

Table 1. Scenario permutations for liquid digestate (LD) and digestate biofertilizer (DBF) 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.

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

$$\text{kg } CH_4 = VS \times Bo \times 0.714 \times MCF$$

where volatile solids (VS) content of the LD fraction is 12.8 kg m^{-3} (Banks, 2011), CH_4 generating capacity (Bo) is 0.2 m^3 kg^{-1} [25,32], methane density is 0.714 kg m^{-3}, and methane conversion factor (MCF) is expressed in relation to the type of storage system[33], ranging from 1% (sealed tank), through 10% (covered tank) to 17% (open tank and lagoon). NH_3-N emission factors were applied to NH_4-N in the LD depending on the type of storage system, ranging from 2% (sealed tank), 5% (covered tank) through 10% (open tank) to 52% (lagoon)[24]. N_2O emissions from storage of LD in tanks and lagoon systems were assumed to be negligible, as reported in previous studies[25] and consistent with GHG accounting guidelines for liquid slurry systems[33]. Table 2 presents CH_4 and NH_3 emissions from the four scenarios of digestate storage.

Table 2. Inventory of inputs and direct emissions for a reference flow of 1m^3 of liquid digestate (LD) exiting an anaerobic digestion plant and either sent 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) 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_2O	0	0	0	0	–	Kg	[25,33]
Struvite extraction	$MgCl_2.6H_2O$	–	–	–	–	0.85	Kg	[22]
	Electricity	–	–	–	–	0.70	kWh	[22]
Ammonium sulfate extraction	NaOH 50%	–	–	–	–	10.00	Kg	[22]
	H_2SO_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_2O	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_2O	–	–	–	–	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_2O	–	–	–	–	0.016	Kg	[23]
	Avoided fert-N	–	–	–	–	0.40	Kg	[23]
	Avoided fert-K	–	–	–	–	0.675	Kg	[23]

Following 3-6 months of storage, LD is applied to land using either shallow injection (LD-1 and LD-2) or trailing hose (LD-3 and LD-4) application. Emissions of NH_3, NO_3 leaching and maximum NPK-fertilizer replacement values were calculated using MANNER NPK[23] for spring and autumn LD applications in good conditions (calm weather, moist soils, no rain immediately after application), on a medium textured soil prior to a spring cereal crop (see SI2). LD nutrient concentrations inputted into MANNER-NPK were corrected for storage losses of N. Direct and indirect N_2O emissions were calculated based on IPCC Tier 1[43]. Varying levels of NMP were represented by equating actual fertilizer replacement from 25 to 100% of replacement potential calculated using MANNER-NPK (Table 1). To reflect considerable uncertainty over emission factors, gaseous emissions and leaching losses were varied by ±50% for each scenario.

Credits for avoided fertilizer use comprised avoided manufacture taken from the Ecoinvent database[44] and avoided field emissions post-application based on emission factors of 0.017 NH_3-N[24], 0.1 NO_3-N[36] and 0.01 for P following N- and P-fertilizer application[38]. Nitrogen, phosphorus and potassium fertilizers were assumed to be in the forms of ammonium nitrate, triple superphosphate and potassium chloride. Diesel consumption for trailing hose and shallow injection application[34,35]was multiplied by relevant tractor emissions[38] and upstream production and supply burdens[44]. Uncertainty in transport and upstream burdens was reflected by varying these burdens by ±20%.

2.4. Upcycled digestate biofertilizer production and use

Digestate upcycling into DBF occurs in four stages: flocculation of suspended solids, struvite extraction, ammonium sulfate cystalisation and final fertilizer blending, with various heat, electricity and chemical inputs (Table 2). Three permutations of DBF production and use were considered (Table 1). Indirect emissions from heat, electricity and chemical production were taken from Ecoinvent[44], with sensitivity analyses undertaken by varying electricity and heat sources. The default electricity source was natural gas combined cycle turbine (NG-CCT) power stations, representing typical marginal electricity generation[45]. Best- and worst-case permutations were based on a grid mix of 90% nuclear and renewable sources (current Swedish grid), and coal generation. The source of heat was varied between a natural gas condensing boiler (default) and waste heat from biogas combined heat and power generators (zero burden on assumption otherwise dumped). It was assumed that fugitive emissions from the upgrading process were negligible because the stripping air is circulated in a closed loop between the crystallizer and the ammonia stripping column. The DBF product was transported 50 km in a 16-32 t EURO V lorry[44] for field application where needed, and in accordance with good NMP, resulting in 1:1 substitution of fertilizer NPK. Field emissions were calculated as per synthetic fertilizer (section 2.3), accounting for diesel consumption[34]. Uncertainty analyses were undertaken by varying the rate of fertilizer-P substitution by struvite-P from 100% down to 50%, reflecting the findings of recent research on struvite as a slow-release fertilizer[46], and varying heating, electricity and chemical requirements by ± 20%.

Effluent water contains significant quantities of N and K (see SI3), and was assumed to be treated in a constructed wetland (default option) or returned to land as irrigation water (best case option). Field emissions and fertilizer replacement value for irrigation water were calculated using MANNER-NPK, assuming 1% residual dry matter content, "trailing hose" type irrigation, and taking the average of January, April, July and October applications to represent year-round irrigation (Table 2). Electricity requirements for pumping effluent to irrigation pipes and through a constructed wetland were taken from Plapally et al. (2012)[39]. Nutrients contained in effluent sent to a constructed wetland will be retained in biomass and denitrified, giving rise to N_2O emissions[40–42] (Table 2). Effluent water treatment burdens were varied by ± 50%.

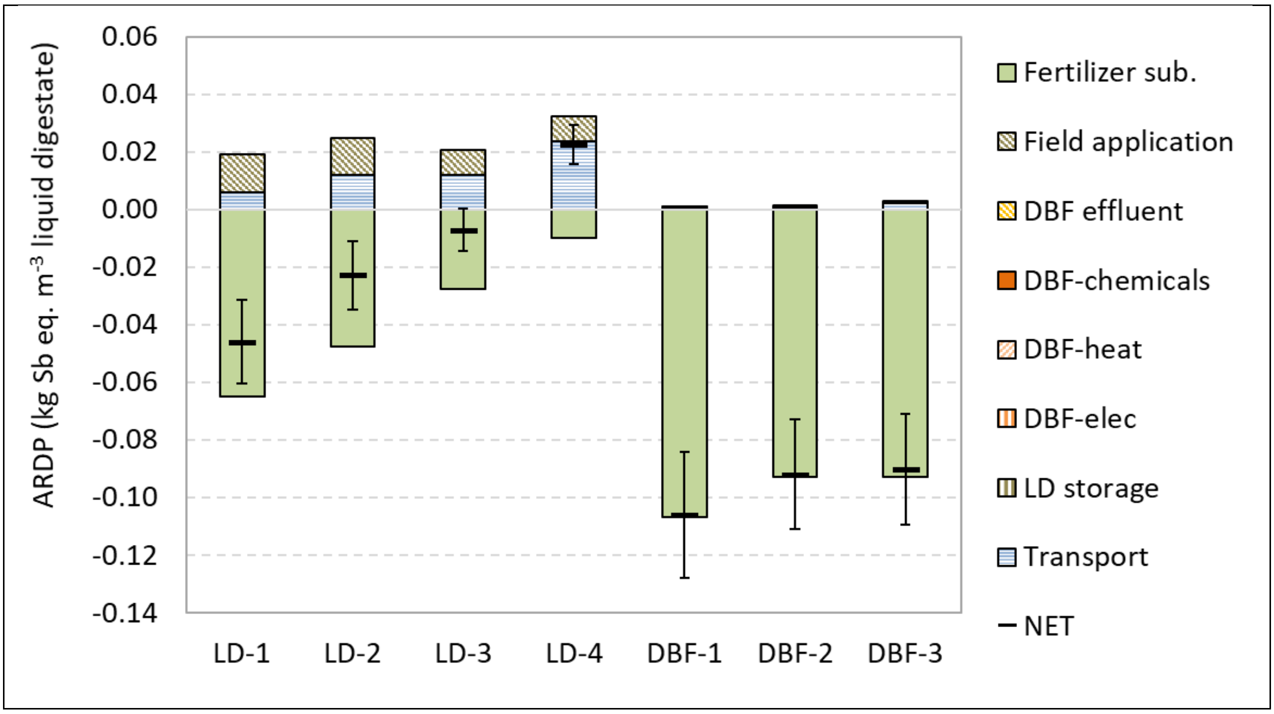
3. Results and discussion

3.1. Resource depletion and global warming

Avoided fertilizer manufacture dominates ARDP and CED balances, which are negative for default LD management (LD-3) and good (LD-2) or optimum (LD-1) LD management options, reflecting a net environmental benefit arising from good agronomic use of LD via synthetic fertilizer substitution (Fig. 2 and Table S3). However, if LD is poorly managed so that synthetic fertilizer substitution is just 25% of the potential (LD-4), then ARDP and CED burdens arising from the transport and spreading of LD are greater than the fertilizer substitution credits. The latter situation represents inefficient agronomic use of LD, not applied in accordance with good NMP, at wrong time of year and/or to land and cropping systems that do not require the nutrients. Whilst it is assumed that most digestate from crop-fed AD is returned to nearby cropping fields[38,47,48], there is a lack of information on the management of digestate produced in food waste AD plants. Food waste AD plant operators may need to pay farmers to take digestate away, and there is evidence that digestate is being over-applied to land close to food waste AD plants[12] so that conventional LD management could generate net ARDP and CED burdens. These outcomes are not reflected in LCA studies that typically assume either all, or all plant-available, nutrients in digestate substitute synthetic fertilizers[31,47,49,50], confirming the need to improve the transparency and accuracy of fertilizer substitution in agronomic LCA studies.[21]

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

Production and use of DBF leads to a net GHG emission of less than 1 (DBF-1) up to 12.5 (DBF-3) kg CO_2 eq. per m^3 of LD processed, compared with emissions of 5 to 34 kg CO_2 eq. m^{-3} arising from conventional management of LD (Fig. 2). For DBF, embodied GWP in chemical inputs, N_2O emissions from field application and effluent management in a constructed wetland, and CO_2 emissions from natural gas heating, are cumulatively greater than GWP avoidance achieved through fertilizer substitution. However, if non-fossil electricity and heat sources are used (DBF-3), DBF production and use becomes close to carbon neutral. For LD, N_2O emissions from field application are the main source of GWP, and these emissions are higher for the better case scenarios (LD-1 and LD-2) than the worse scenarios (LD-3 and LD-4) owing to less loss of N during storage in the former scenarios. However, overall GWP burdens are significantly greater for LD-3 and LD-4 overall owing to high CH_4 losses, and indirect N_2O following NH_3 losses, during open tank and lagoon storage of LD, respectively. Thus, despite significant emissions in the production process, DBF can mitigate GHG emissions arising from LD management by avoiding direct and indirect N_2O and CH_4 emissions from digestate storage and field-application, and by increasing fertilizer substitution. For context, under default assumptions DBF can enhance the overall GHG abatement potential of food waste digestion by 8% (Fig. S1), but under the most pessimistic assumptions for DBF it could reduce the overall GHG abatement potential of food waste digestion by 4%.



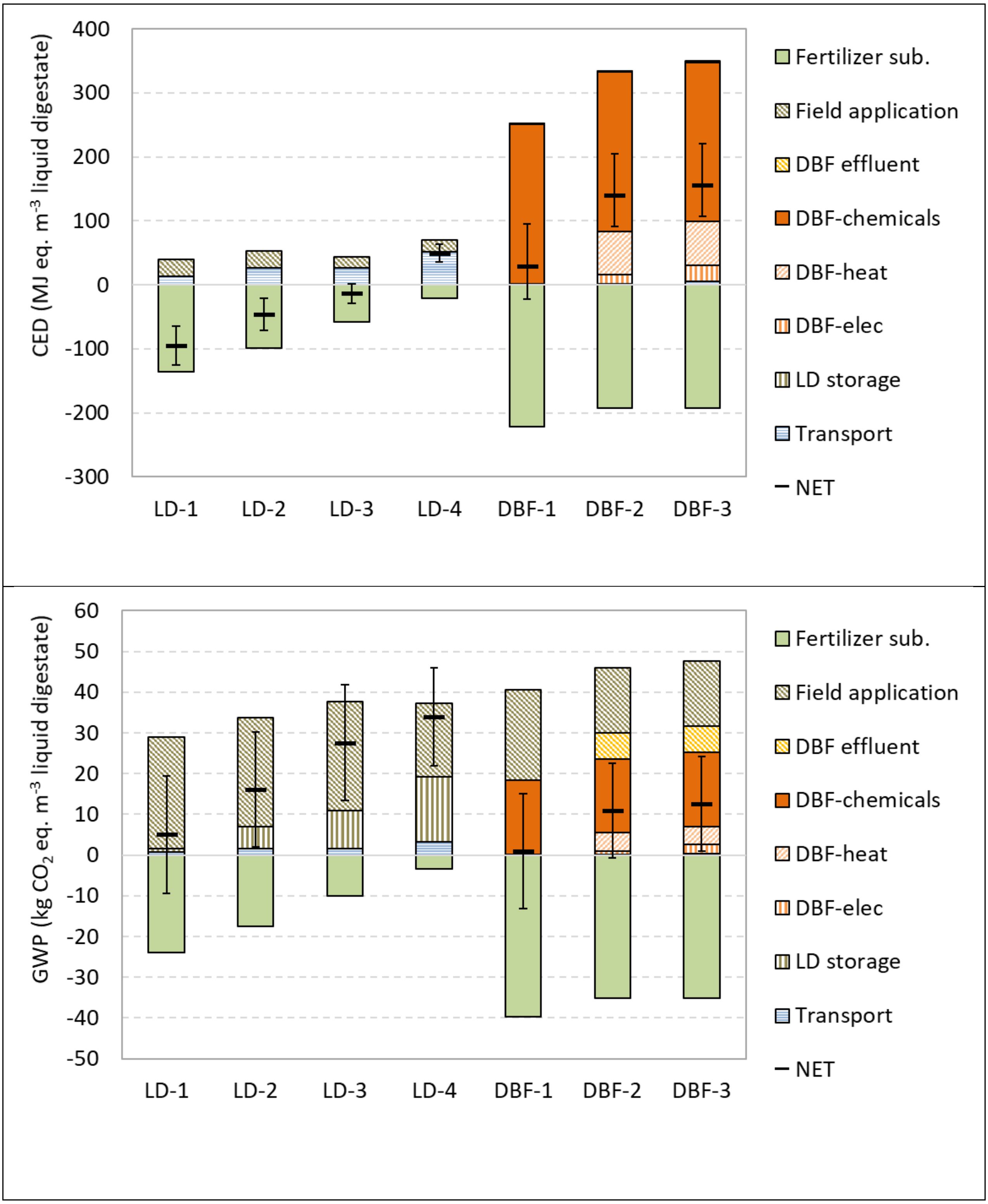


Figure 2. Environmental balance per m^3 of liquid digestate (LD) managed along a spectrum of best (LD-1) to worst (LD-4) practice, and upcycled digestate biofertilizer managed along a spectrum of best (DBF-1) to worst (DBF-3) practice. Results displayed for abiotic resource depletion (ARD, top), cumulative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

3.2. Air and water quality

Results in Fig. 3 and Table S3 confirm those of previous studies indicating high acidification and eutrophication burdens from digestate storage and field application[8,14,31,47]. Acidification burdens are driven by NH_3 emissions, which are related to methods of digestate storage and application, and range from 0.7 to 4.3 kg SO_2 eq. per m^3 LD for optimum management (LD-1) and worst-case management (LD-4), respectively (Fig. 3). Upgrading LD into DBF avoids these emissions, and reduces the net acidification burden of food waste digestion by up to 73% (Fig. S1), representing a potentially important mitigation option for perhaps the most significant environmental hotspot of AD systems[14,50,51]. Eutrophication burdens follow a similar though less pronounced pattern to acidification, increasing from 0.4 to 1.1 kg PO_4 eq. per m^3 of LD for optimum management (LD-1) and worst-case management (LD-4), respectively (Fig. 3). The production and use of DBF achieves a net reduction in eutrophication owing to the avoidance of upstream extraction and processing of nutrients for synthetic fertilizers (field emissions are assumed to be the same for synthetic fertilizers and DBF). Under default assumptions, DBF extraction reduces the net eutrophication burden of food waste digestion by 85% (Fig. S1). Thus, upgrading LD to DBF largey mitigates a second environmental hotspot of digestate use specifically, and AD systems in general[14,50,51].

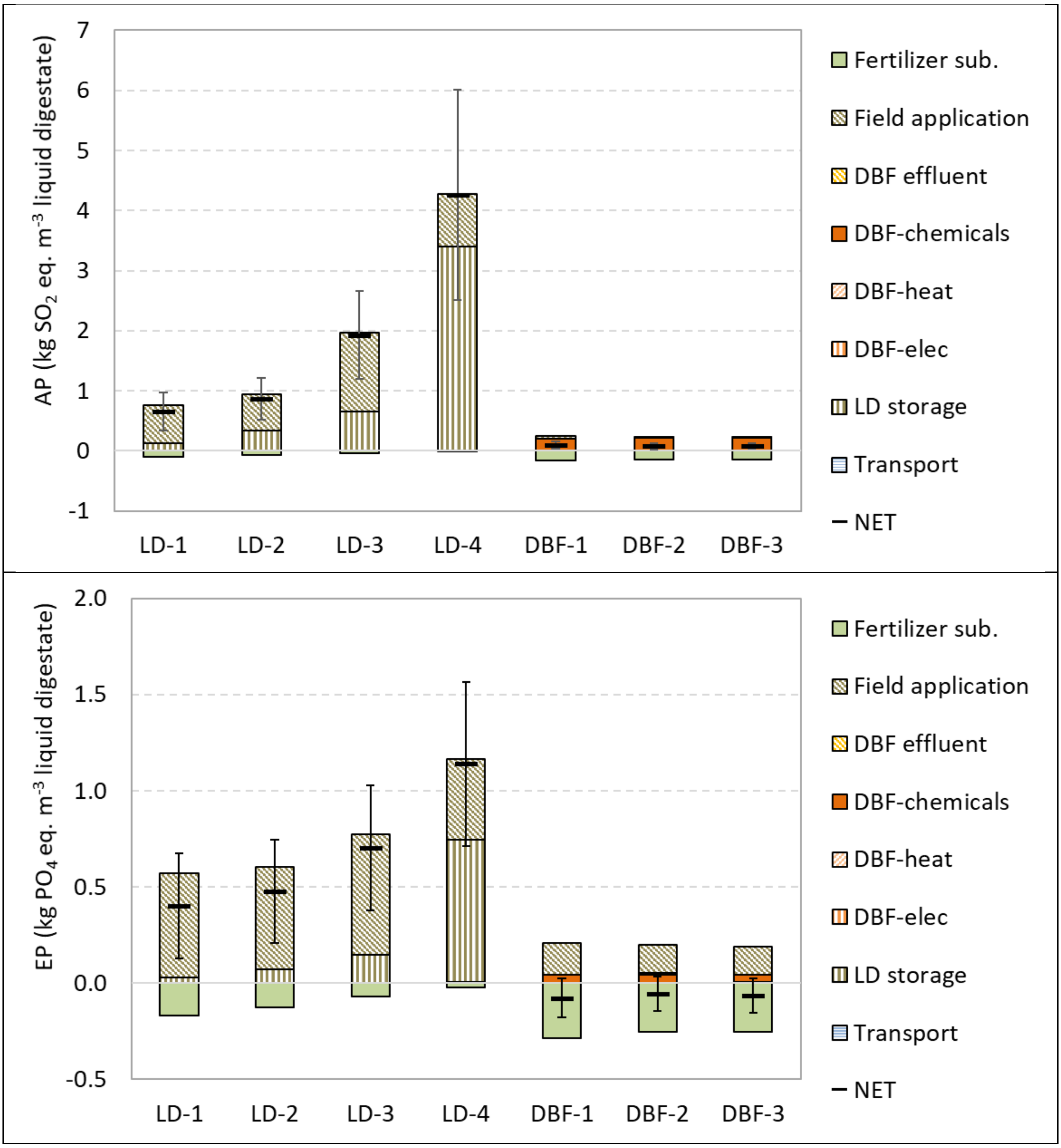


Figure 3. Environmental balance per m³ of liquid digestate (LD) managed along a spectrum of best (LD-1) to worst (LD-4) practice or upcycled into digestate biofertilizer (DBF), for acidification potential (AP, top) and eutrophication potential (EP, bottom).

3.3. Abatement potential

A recent survey of AD operators indicated that open tank and lagoon storage systems predominate[14].

Although almost one third of large AD plants were found to have sealed digestate storage tanks[14], digestate sent to farms is likely to be stored in open tanks if it is not spread immediately, supporting our default assumption of open-tank storage (LD-3). Producing DBF at medium efficiency (DBF-2) from LD that would otherwise be handled in such a way would give rise to savings of 0.085 kg Sb eq., 1.85 kg SO_2 eq., 0.76 kg PO_4 eq. and 16.8 kg CO_2 eq. per m^3 of LD upcycled to DBF, though cumulative energy demand would increase by 154 MJ eq. (Table S4). It is worth noting that a shift towards best practice in LD handling (LD-1) from default practice (LD-3) would also lead to significant environmental savings, and outperform DBF in terms of cumulative energy demand and global warming potential, though fall short of DBF in terms of the abatement of acidification, eutrophication and resource depletion hotspots (Table S4; Fig. S1; Fig. S2). Achieving environmental savings from best practice in digestate management would require all biogas plants to install sealed tank storage of digestate, all LD to be transported to land producing crops requiring all the nutrients in the LD, and all LD to be spread via shallow injection at the optimum time for crop uptake. There would be significant technical and logistical barriers to implementing such practices universally, and costs could exceed the projected costs of commercial DBF extraction which are estimated to be €5-10 per m^3 LD.

Extrapolated to an ambitious future scenario in which 25% of global food waste is treated by AD (detailed in S6), the annual mitigation potential of upgrading all LD would equate to approximately 439 Gg SO_2 eq., 22.6 Gg Sb eq. and 4465 Gg CO_2 eq. under default assumptions (Table S5). Normalisation of these theoretical abatement potentials (Fig. S2) indicates that abiotic resource depletion and acidification potential would be the impact categories most benefitted, with global burdens reduced by up to 1% and 0.2%, respectively, under default assumptions, with a minor trade-off in cumulative energy demand which would increase by 0.01%.

Recommendations

In summary, expanded boundary LCA highlights the relative importance of environmental credits attributed to differential rates of fertilizer substitution when comparing the overall environmental balance of liquid digestate handling and use with the production and use of biofertilizer extracted from liquid digestate via struvite precipitation and ammonia stripping. Avoided gaseous emissions during storage and spreading of liquid digestate, and enhanced fertilizer substitution arising from more targeted application of the versatile biofertilizer product, mean that extraction of biofertilizer from liquid digestate can achieve significant environmental savings. Normalization indicates that the identified trade-off of higher cumulative energy demand is comparatively minor, and could be mitigated by use of renewable energy or surplus biogas heat. The avoidance of NH_3 emissions and conservation of elemental resources appear to be the most significant advantages of biofertilizer production and use, which can help to close nutrient loops. External damage costs of NH_3 emissions are estimated at approximately €3000 per tonne[52], suggesting that the considerable NH_3 abatement achieved by upgrading LD to DBF could be of significant public good benefit, and potentially worthy of subsidy support or regulatory push via tighter emission standards for digestate (and slurry) management. On the basis of these results, we would recommend:

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

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

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