IDENTIFYING IMPACTS FROM FOOD AND FARM DIGESTATES

FINAL REPORT

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About WRAP

WRAP is not-for-profit, working with governments, businesses and citizens to create a world in which we use resources sustainably. Our experts generate the evidence-based solutions we need to protect the environment, build stronger economies and support more sustainable societies. Our impact spans the entire life-cycle of the food we eat, the clothes we wear and the products we buy, from production to consumption and beyond.

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Executive Summary

The work reported here was commissioned by the Department for Energy Security & Net Zero to inform the mid-scheme review for the Green Gas Support Scheme (GGSS). The scheme has been in operation for less than a year, but at its launch the Department for Energy Security and Net Zero and Defra gave an undertaking to consider the potential environmental impacts from the digestate from Anaerobic Digestion (AD), particularly with respect to the potential effects on air quality, and the risk of plastic contamination of soils following the use of digestate. This final report sets out the evidence gathered for options to mitigate: ammonia emissions from digestate during storage and use; methane emissions during digestate storage; plastic contamination of digestates; lack of value associated with digestates. Initial evidence assessment failed to identify realised impacts from nitrate leaching following digestate applications that conformed to good practice (Spring application). In-scope digestates include those derived from food wastes only ('commercial') and those derived from a combination of crop residues and livestock manures / slurries ('farm'). Three different size AD plants were considered for each category of digestate, based on energy thresholds set out in the GGSS.

Whilst not seeking to undertake *de novo* risk assessment a number of further potential impacts were identified for farm and commercial digestates under some conditions. Following stakeholder discussions these were not taken forward for mitigation modelling: N_2O from stored digestate; CH_4 and N_2O (fugitive) emissions during AD; Earthworm mortality; Plant pathogens; Combined biological, physical and chemical hazards; Veterinary medicines; Organic compound contaminants; Antibiotic resistance genes; Bacteria of relevance to human health; Potentially Toxic Elements; Soil microbial activity; Weed seeds; Botulinum toxin; N_2O from digestate amended soils; P transformation in soils; Salinity.

Subsequent project tasks were sequenced to allow the team to:

1. identify mitigation options for shortlisted impacts, which were discussed with a group of industry and government stakeholders in a workshop;
2. identify opportunities to add value to digestates, or reduce the costs associated with their management;
3. identify, collate and model key data for each option using a technoeconomic assessment;
4. Report modelled outputs and inform recommendations for future consideration by the Department for Energy Security & Net Zero under the GGSS.

A Rapid Evidence Assessment was undertaken, screening more than 8,500 resources to deliver a sub-set of ~350 that informed the optioneering and modelling described in this report. An extensive programme of supplier engagement was integrated into the evidence gathering to sense-check and supplement published data. The focus of the evidence assessment was techniques that are at or near market, since they (potentially) need to be deployable within the timescale of the GGSS. For convenience techniques at Technology

Readiness Level (TRL) 7+ were prioritised. In-scope digestates were also prioritised, with techniques demonstrated on these materials categorised as Tier 1 options. Where techniques had been demonstrated on similar substrates such as livestock slurries or digested sewage sludges these were categorised as Tier 2 options. In some cases TRL <7 options were identified; these were catalogued for future reference but not taken forward for technoeconomic assessment. The following mitigation options were identified and assessed:

Option	Fraction*	Demonstrated on which digestate(s)?	TRL
Stripping / scrubbing	WD, SLD	Commercial and farm	9+
Nitrification / Denitrification	SLD	Commercial and farm	9+
Acidification in-field	WD, SLD	Farm	9+
Acidification in-store (Tier 2)	WD, SLD, SFD		9+
Gas-tight storage	WD, SLD, SFD	Commercial and farm	9+
Injection application	WD, SLD	Commercial and farm	9+
Screening	WD	Commercial	9+
***WD = Whole Digestate; SLD = Separated Liquor Digestate; SFD = Separated Fibre Digestate**			

The following valorisation end points were identified:

Option	Fraction	Demonstrated on which digestate(s)?	TRL
Acidified digestates	WD, SLD	Farm	9+
Ammonia solution	SLD	Food and farm	9
Ammonium nitrate solution	WD, SLD	Farm	9+
Ammonium sulphate solution	WD, SLD	Food and farm	9+
Animal bedding	SFD	Farm	9+
Calcium carbonate (+ ammonium sulphate)	WD	Farm	9
Composting	SFD	Food and farm	9+
Discharge quality water	SLD	Food and farm	9+
Dried digestate	SFD	Farm	9+
Fertigation solution	SLD	Farm	7
Fertiliser pellets	SFD	Farm	9+
Fuel pellets	SFD	Farm	9
Fulvic acids	SLD, SFD	Farm	9+
Growing medium	SFD	Food and farm	9+
High-P fibre (+ low P liquor)	SLD, SFD	Farm	9+
Low-N fibre (+ ammonium sulphate)	SFD	Farm	7
Low-P fibre (+ calcium phosphate)	SFD	Farm	7
Mushroom cultivation	SFD	Farm	7
N-enhanced digestate	SLD	Farm	8
Nutrient concentrates	SLD	Food and farm	9+

Option	Fraction	Demonstrated on which digestate(s)?	TRL
Struvite	WD, SLD	Farm	7
Vermicomposting	SFD	Farm	7

Since opportunities to add value to or reduce costs of digestate are business and process-specific, and since the evidence suggests that any digestate processing system should be piloted on site before full-scale implementation, it was not considered possible to develop models that would inform generally applicable valorisation recommendations. Instead, and following discussions with the Department for Energy Security & Net Zero and Defra, a series of valorisation 'archetypes' were developed. These drew from the library of mitigation technologies and added the following:

- Microfiltration
- Ultrafiltration
- Reverse Osmosis
- Centrifuge dewatering
- DAF
- Evaporation and condensation

These were developed into a series of costed process blocks that could be integrated in various ways to explore and highlight different points – such as the absence of landbank or opportunities arising from changing the regulatory status of specific digestate fractions. The archetypes are as follows:

Farm digestates – no specific landbank constraints		
A	Acidification of whole digestate in-field to improve nutrient use efficiency	Improved nutrient use efficiency
Farm digestates – particular landbank constraints		
B	P capture and export	P-rich fibre sales
C	N capture and export as ammonium sulphate	Ammonium sulphate sales
D	Nutrient concentrate for export	Concentrate sales
E	Fibre for export	Fibre sales
F	Nutrient concentrate and fibre export	Reduced logistics
Commercial digestates – no or limited landbank		
G	Nutrient concentrate for export	Concentrate sales
H	Liquor part-treated and disposed to sewer; clean fibre sold for amenity use	Fibre sales and reduced logistics

Separate mitigation and valorisation models were developed to understand the costs of different interventions. The main outputs of the mitigation model are the costs per kg abatement, cost per tonne of digestate, and cost per MWh of energy produced. The valorisation model focuses on the valorisation of digestate, modelling the revenue derived from valorisation processes and associated costs of multiple valorisation archetypes. The main outputs of the valorisation model are the net revenue per tonne of digestate treated and net revenue per MWh of energy generated. Outputs from mitigation models are summarised for 'small' AD plants below for illustrative purposes:

Ammonia mitigation									
Plant type	Cost per tonne of:			Cost per Mwh of:			Cost per kg of ammonia abated for:		
	WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
Stripping / scrubbing									
90% abatement									
Commercial	£10.04	£10.39	-	£7.09	£5.14	-	£11.11	£12.28	-
Farm	£7.31	£4.06	-	£13.93	£5.42	-	£10.79	£11.36	-
Side-stream stripping / scrubbing									
40% abatement									
Commercial	£3.98	-	-	£2.81	-	-	£11.02	-	-
Farm	£2.93	-	-	£5.59	-	-	£10.82	-	-
Nitrification									
64% abatement									
Commercial	-	£5.30	-	-	£2.62	-	-	£6.98	-
Farm	-	£5.30	-	-	£7.07	-	-	£16.53	-
Nitrification / Denitrification									
90% abatement									
Commercial	-	£7.09	-	-	£3.51	-	-	£6.64	-
Farm	-	£7.09	-	-	£9.47	-	-	£15.72	-
Alum treatment									
98% abatement									
Commercial	-	-	£61.50	-	-	£13.04	-	-	£27.98
Farm	-	-	£61.50	-	-	£35.17	-	-	£44.47
In field acidification									
25% abatement									
Commercial	£2.91	£2.87	-	£2.05	£1.42	-	£10.62	£11.19	-
Farm	£2.77	£2.57	-	£5.27	£3.43	-	£13.47	£23.68	-
In store acidification									
82% abatement in store and 67% during subsequent application									
Commercial	£15.28	£15.41	-	£10.80	£7.62	-	£17.04	£18.32	-

Ammonia mitigation									
Plant type	Cost per tonne of:			Cost per Mwh of:			Cost per kg of ammonia abated for:		
	WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
Farm	£15.11	£15.15	-	£28.79	£20.21	-	£22.46	£42.68	-
Gas-tight storage									
100% abatement									
Commercial	£0.20	£0.20	-	£0.14	£0.10	-	£1.44	£1.54	-
Farm	£0.20	£0.20	-	£0.38	£0.27	-	£1.92	£3.64	-
Injection application									
70% abatement									
Commercial	£1.40	£1.40	-	£0.99	£0.69	-	£2.24	£2.39	-
Farm	£1.40	£0.22	-	£2.67	£0.30	-	£2.98	£0.90	-

Methane mitigation									
Plant type	Cost per tonne of:			Cost per Mwh of:			Cost per m^3 of methane abated for:		
	WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
In store acidification									
78% abatement									
Commercial	£1.18	£1.31	-	£0.84	£0.65	-	£0.09	£2.16	-
Farm	£1.01	£1.05	-	£1.92	£1.40	-	£0.21	£1.73	-
Gas-tight storage									
100% abatement									
Commercial	£0.20	£0.20	-	£0.14	£0.10	-	£0.01	£0.26	-
Farm	£0.20	£0.20	-	£0.38	£0.27	-	£0.03	£0.26	-

Plastics' mitigation									
Plant type	Cost per tonne of:			Cost per Mwh of:			Cost per kg of plastic abated for:		
	WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
Screening									
72% abatement									
Commercial	£0.28	-	-	£0.19	-	-	£0.15	-	-

Sensitivity analyses were performed for both mitigation and valorisation scenarios. In most cases significant model impacts were linked to the nutrient contents of digestates and to the volumes of digestate processed (which varies according to the mix of farm materials processed in AD). Many of the mitigation scenarios are OPEX-dominated and consequently sensitive to the costs of consumables such as sulphuric acid and alum. Mitigations are also very sensitive to the % abatement allocated, and in some cases (for example, stripping and scrubbing, nitrification, nitrification / denitrification) evidence for abatement was extremely variable. Fertiliser prices impacted several valorisation scenarios where revenue is associated with nutrients – particularly nitrogen. However, even very high fertiliser prices (March 2022) were insufficient in most cases to transform negative valorisation business cases in positive cases.

Evidence was also collected (and in some cases, modelled) for the pollution swapping potential of the mitigation techniques. Assessments of the regulatory complexity of each option were also made, as were assessment of the quality of data used within the modelling.

Eight valorisation archetypes were modelled, revealing that several techniques might be commercially attractive. In particular where digestates could be transformed into a nutrient concentrate for retail sale or where separated fibre could be supplied for landscaping / horticultural uses. In both cases the potential revenue for each stream was estimated to be many millions of £. Perhaps more realistically the use of DAF to capture fine solids and increase the phosphorus value of fibre digestate was also attractive purely from a nutrient management perspective. Regulatory barriers currently prevent the use of digestate concentrates or soil improvers for landscaping / amenity purposes as products. The physical characteristics of commercial digestates make phase separation challenging, but their conversion to nutrient concentrates is feasible via several process routes. Revenues for valorisation models are summarised below:

Valorisation archetypes	Revenue per tonne digestate treated (£/t)	Revenue per MWh generated (£/t)
Archetype 1. In field acidification and increased nutrient use efficiency – farm plant	-1.65	-3.15
Archetype 2. Capture of phosphorus for export	1.31	2.49
Archetype 3. N capture for export as ammonium sulphate	-3.96	-7.55
Archetype 4. Nutrient concentrate for export	-0.84	-1.60
Archetype 5. Fibre for export - farm plant	5.14	9.79
Archetype 6. Nutrient concentrate and fibre for export - farm plant	8.49	16.18
Archetype 7. Nutrient concentrate for export, commercial plant	-10.72	-7.58
Archetype 8. Discharge to sewer, commercial plant*	1.96	1.39
***Option 1B in which biological sludges and treated liquor are returned to the AD process rather than exported from the site**		

Overall it is possible to conclude that cost-effective mitigation options are available for ammonia, methane and plastics – and that a number of valorisation approaches are available that may return positive value to AD businesses. The financial status of several valorisation approaches would be very significantly improved if end of waste positions could be developed or clarified for the supply of nutrient concentrates and separated fibre digestates to amenity / landscape markets.

The following recommendations are made for further work:

1. Implement a strategic approach to the surveillance and understanding of emerging hazards of concern in food and farm digestates
2. Determine the potential methane emissions from commercial and farm digestates during / after application within the context of undigested manures and slurries. Where relevant, investigate the potential for acidification and/or precision application techniques to mitigate such emissions
3. Develop a dataset for plastic contamination in UK commercial digestates. Consider collecting data for farm digestates to confirm research assumptions that these materials are not a relevant vector for plastics in soils
4. Engage with the research community to develop understanding of the potential of lower TRL and under-represented potential mitigation options such as gas-permeable membrane recovery of ammonia and hot microbubble ammonia stripping
5. Determine the potential for methane emissions and abatement for separated fibre digestates in storage. Options for mitigation could include alum treatment and covering with plastic sheeting
6. Develop a mechanism for information exchange between GB users of digestate mitigation and valorisation techniques to facilitate understanding of costs, performance and applicability across different types of digestate
7. Engage with suppliers and operators to understand the true costs and implications of using gas-tight store covers to mitigate ammonia and methane emissions during storage of whole and separated liquor digestates
8. Investigate the costs and benefits of combining mitigation techniques during storage and use of whole and separated liquor digestates, as compared with techniques that may confer benefit at both process points
9. Engage with suppliers and operators to understand the potential for acidification of separated liquor digestates alongside options for mitigation of ammonia and methane emissions from separated fibre digestates

10. Engage with suppliers, operators and the research community to understand and develop options for improved depackaging techniques which recover contaminants for recycling and obviate the need for downstream digestate screening
11. Engage with regulators and operators to develop end of waste positions for specific digestate-derived materials, particularly for farm digestates. These include nutrient concentrates and soil improvers.

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AD	Anaerobic Digestion
AOB	Ammonia Oxidising Bacteria
ARG	Antibiotic Resistant Gene
As	Arsenic
BOD	Biochemical Oxygen Demand
BoNT	Botulinum Neurotoxin
CMC	Component Material Category
Cr	Chromium
Cu	Copper
DAF	Dissolved Air Flotation
DEET	N, N-Diethyl-meta-toluamide
DM	Dry Matter
DS	Dry Solids
EU-FPR	EU Fertilising Products Regulation
FIB	Faecal Indicator Bacteria
FOG	Fats, Oils and Greases
FYM	Farmyard manure
GGSS	Green Gas Support Scheme
K	Potassium
LCA	Life-cycle analysis
NH_4-N	Ammoniacal nitrogen
NO_3-N	Nitrate nitrogen
NO_2-N	Nitrite nitrogen
Nm^3	Normal cubic metre
NMR	Nuclear magnetic resonance
NUE	Nutrient use efficiency
P	Phosphorus
PAH	Polycyclic aromatic hydrocarbon
PAO	Potential ammonia oxidation
PAS110	Publicly Available Specification 110
PBB	Polybrominated biphenyl
PCB	Polychlorinated biphenyl
PFC	Product Function Category
PPCP	Pharmaceuticals and Personal Care Products
PTE	Potentially toxic element
QMRA	Quantitative microbial risk assessment
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RENURE	REcovered Nitrogen from manURE
RTE	Ready to eat
S	Sulphur

LOD	Limit of detection
MAD	Mesophilic anaerobic digestion
MGE	Mobile genetic elements
N	Nitrogen
N_2O	Nitrous oxide
Na	Sodium
NH_3	Ammonia
NH_4^+	Ammonium
SFD	Separated fibre fraction of digestate
SLD	Separated liquor fraction of digestate
TAD	Thermophilic anaerobic digestion
TCPP	Tris (2-chloroisopropyl) phosphate
TRL	Technology Readiness Level
WD	Whole digestate
Zn	Zinc

1.0 Introduction

Project rationale

The work reported here was commissioned by the Department for Energy Security & Net Zero to inform the mid-scheme review of the Green Gas Support Scheme (GGSS). At the time of writing the scheme has been in operation for less than a year. However, at its launch the Department for Energy Security & Net Zero and Defra gave an undertaking to consider the potential environmental impact of the generation and use of the digestate from AD, particularly with respect to potential effects on air and soil quality from components such as ammonia and plastic. The drivers for this work are summarised below:

1. The UK anaerobic digestion industry has seen significant growth over the past two decades and represents a flexible source of bioenergy that will be increasingly important in meeting the UK's net zero targets. Digestate is the inevitable residue from anaerobic digestion and although it is a useful biofertiliser it has a number of properties that can have negative impacts unless appropriately managed. Digestate handling is also (in most cases) a cost centre for AD businesses, and it is increasingly important that digestate impacts are mitigated in a cost-effective way if the industry is to continue to grow in a sustainable manner. Understanding the gap between the costs of current digestate handling practices and future 'sustainable' digestate handling practices forms a key element of this project.
2. At present, the majority of digestate (regardless of the feedstock that it is derived from) is used as a biofertiliser on agricultural land (WRAP 2021). However, increasing scrutiny around the environmental impact of digestate spreading activities is suggesting an urgent need to diversify processing techniques and markets for digestate derivatives.
3. The fertiliser value of the materials is well proven and well researched. Previous research undertaken by WRAP illustrated the fertiliser potential of digestates while highlighting the importance of using the right timing and application techniques to maximise effective nutrient use, minimising potential ammonia and nitrate losses.
4. Since the original WRAP work was published, the regulatory landscape around the use of digestates and manures in agriculture have been changing. The introduction of the Farming Rules for Water (FRfW) in England in 2018 and the implementation of equivalent regulatory instruments in Scotland and Wales mean that the application windows for the spreading of digestates are now narrower than under previous regulatory controls. The restrictions are intended to ensure that nutrient applications in digestate (and other materials) better match crop demands and are not applied in excess – which could lead to diffuse pollution. This in turn means that digestate

producers must have sufficient storage for digestate during those times when land application is not allowed – the 'closed periods'. Such storage must be designed to minimise or prevent atmospheric losses. Digestate users must also deploy appropriate equipment that allows digestates to be applied accurately and without ammonia losses during available spreading windows.

5. Recent work and modelling of the implications of the FRfW published by AHDB in June 2021 highlights the increasing requirement for farmers to manage the application of organic materials to their soils carefully. Based on the findings of the modelling, this paper proposes a matrix which aims to guide the industry on when and where organic materials can be used most effectively to reduce the risks that applications pose to diffuse water and air pollution, and soil compaction. If adopted, the matrix approach will mean a significant change to current digestate management practice – and will not guarantee the absence of environmental risk when the material is used, since nitrogen and phosphorus (in particular) behave in different ways in soil and have different principal polluting mechanisms.
6. If the UK AD industry continues to produce and deploy high volumes of low strength liquid digestates, the scale of storage and spreading issues will only increase.
7. UK environmental regulators have become increasingly concerned about plastic contamination of digestates, particularly in those that have been produced from household or commercial waste sources. In Scotland, SEPA have already introduced significantly lower plastic contamination levels in their requirements for digestates; the Environment Agency is similarly keen to see reductions in plastic contamination.
8. Irrespective of the regulatory mechanism by which digestates are applied to agricultural land, protection of soil quality will require that there are reductions in the levels of plastics in digestates.

In its modelling for the Green Gas Support Scheme, the Department for Energy Security & Net Zero assumed zero value for digestate (the Department for Energy Security & Net Zero). In discussions with Defra, the Department for Energy Security & Net Zero have also identified a number of potential impacts associated with digestate:

(1) Ammonia emissions to land, air and water

(2) Nitrate leaching following digestate use

(3) Plastic contamination

This final report sets out the evidence gathered for options to mitigate these impacts – as well as options to add value to or reduce the costs of digestate handling. This evidence forms the basis of a Techno-Economic Assessment (TEA).

The project was sequenced to allow the team to:

(1) refine the project scope by identifying additional impacts that could be abated and discussing these with an Advisory Panel in an initial workshop;

(2) identify mitigation options for agreed impacts, which were discussed with a group of stakeholders in a subsequent workshop;

(3) identify opportunities to add value to digestates, or reduce the costs associated with their management;

(4) identify, collate and model key data for each technology option using a technoeconomic modelling procedure;

(5) report modelled outputs and inform recommendations for future consideration by the Department for Energy Security & Net Zero under the GGSS.

An extensive programme of supplier engagement was woven through the evidence gathering to sense-check and supplement literature data. This engagement activity, when combined with our wider evidence gathering and modelling has highlighted a number of commercial or semi-commercial mitigation and valorisation techniques that can be successfully applied to food and farm digestates.

Types of digestate in scope

The project has focussed on agricultural and commercial/municipal digestates – rather than industrial, sewage sludge or other digestates. The reasons for this are that:

There will be future growth in anaerobic digestion of food wastes, following introduction of household and business food waste collections from 2023 onwards. WRAP models for the impact of the introduction of the new measures outlined in the Resources and Waste Strategy indicate that combined household and non-household food waste could increase as much as 300% above current levels. AD will be the priority recycling route for this material so measures to improve the quality and decrease the impact of digestate will be vital.

There will be future growth in anaerobic digestion on farms – principally of livestock manures and slurries, but potentially also of crop processing residues. The key drivers behind this trend are climate change (mitigation of emissions from handling raw livestock manures and slurries) and business diversification (renewable energy and future farm business resilience).

Although the majority of sewage sludges are processed via anaerobic digestion in GB, the resulting digestates are typically dewatered to produce a phosphorus-rich stackable cake. Nitrogen-rich liquors are either returned directly to wastewater treatment works for processing or first processed via nitrogen removal systems that include nitrification and denitrification. Although there will be some process changes in this sector in future (for example, to accommodate chemical phosphorus sludges from final effluent polishing), there is unlikely to be significant growth.

Industrial digestates (such as those from breweries or dairies) are normally further processed in associated effluent treatment activities, and then discharged to sewer (or surface water). They are not stored, hauled or applied to land in the same way as other types of digestate.

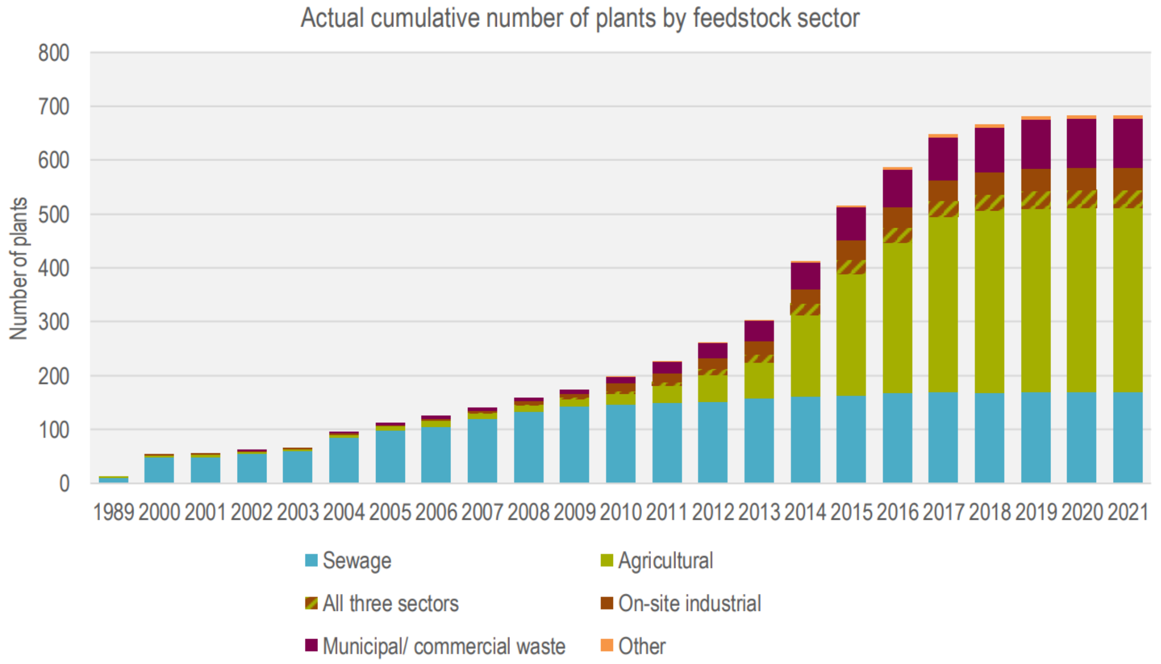


Figure 1 Showing historic growth of AD in the UK, and the main process classifications (based on feedstocks used). From: https://adbioresources.org/newsroom/adba-policy-report-april-2021/

Key objectives

1. To identify the key environmental impacts associated with digestate during its production, storage and use.
2. To identify commercial and near-commercial technologies for mitigation of the significant impacts.
3. To investigate techniques for valorisation of digestates, to determine which offer the best potential for adding value or reducing costs associated with digestate management.
4. To develop, verify and apply a techno-economic assessment model that allows the exploration of the cost effectiveness of each technology in terms of impact abatement and/or valorisation.
5. To draw on the modelling outputs and collected contextual data to develop a set of recommendations for the Department for Energy Security & Net Zero.

2.0 Data collection

Approach to evidence gathering

The general approach to evidence gathering has been based on the principles of Rapid Evidence Assessment (REA)[1]. An REA is not intended to be a comprehensive literature review but is more targeted and allows the researcher to access resources such as grey literature, statutes and websites that might not be included in conventional searches, but in a very structured and traceable way. This approach allows researchers to quickly identify key themes without having to review every publication linked to any specific topic. The search databases, applied strings of search terms, numbers of hits and numbers of resources examined before saving for use in this report are listed in Appendix 1 REA Search . More than 8,500 resources were reviewed and a sub-set of ~350 were ultimately selected as key sources for the production of this report. The research databases included:

- AHDB knowledge library (project reports from the Agriculture & Horticulture Development Board)
- American Chemical Society publications (scientific papers)
- Biorefine Cluster Europe (platform for bio-based projects)
- British Library EThOS (e-theses online service: hosts >500,000 doctoral theses from 148 participating UK institutions)
- CORDIS (European / EC-funded projects)
- Defra Science Search (information on Defra-funded projects, including outputs)
- Engineering Village (engineering literature and patents)
- Google scholar (scientific papers)
- Google.com (general searches to identify grey literature)
- IEMA (publications from the Institute of Environmental Management & Assessment)
- IWA publishing (scientific books, papers and conference proceedings from the International Water Association)
- keep.eu (Projects and beneficiaries of EU-funded cross-border, transnational and inter-regional cooperation programmes)
- Keep.EU (outputs from regional ERDF-funded research projects)

[1] https://www.gov.uk/government/collections/rapid-evidence-assessments

- Knovel (engineering reference materials)
- LIFE (outputs from EC-funded research projects)
- NARCIS (publications from the Netherlands)
- OpenGrey (now closed service with >700,000 grey literature sources from across the EU)
- ResearchGate (scientific papers, conference proceedings and other resources, direct engagement with active researchers)
- Royal Society of Chemistry publications (scientific papers)
- Science Direct (scientific papers)
- Springer Link (scientific literature, including papers and books)
- VCM (Flemish Centre for Manure processing – partner in numerous slurry and digestate valorisation initiatives)
- Wageningen University (publications from this renowned agricultural and life sciences' institution in The Netherlands)
- Wiley online library (scientific literature, including papers and books)

In a small number of cases, citations of specific papers were also followed-up. This was particularly useful for topics where few relevant resources could be identified, such as the performance of food waste depackaging equipment – and where specific authors are particularly active in the field of digestate management / processing / valorisation. Having identified mitigation and valorisation options, targeted searches were used to identify specific aspects such as cost, mitigation performance and potential for pollution swaps. The focus throughout this project was to identify options that were commercial or near commercial, and a common Technology Readiness Level approach was used to facilitate classification (Table 1).

Table 1: Technology Readiness Levels, as defined by The Department for Energy Security & Net Zero[2]

Real world	TRL 9	Technology proven in operational environment
	TRL 8	Technology qualified through test and demonstration
	TRL 7	Prototype demonstration in operational environment
Simulated world	TRL 6	Technology demonstrated in relevant environment
	TRL 5	Technology validated in relevant environment
Research laboratory	TRL 4	Technology validated in lab
	TRL 3	Experimental proof of concept
	TRL 2	Technology concept formulated
	TRL 1	Basic principles observed

[2] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1019066/ietf-phase-2-autumn-guidance.pdf

3.0 Refining project scope

Using the structured evidence assessment methods described above, evidence for indications that there may be other significant digestate-related impacts were explored. It was not the intention to undertake risk assessment – rather to seek evidence of harms from digestate use (and not *potential* for harm). The research focus was on impacts associated with commercial and/or farm digestates.

More than 2,500 abstracts were reviewed, identifying 78 resources of potential interest. 21 of these being found to be more applicable to later project tasks. The remainder could be categorised as follows:

- 40 peer-reviewed scientific papers
- 16 pieces of 'grey literature' including technical reports, trade body documents and opinion pieces
- 1 conference paper

Each of these is summarised in Appendix 2 (Evidence for additional impacts), which also indicates those impacts which were subsequently discussed with the Department for Energy Security & Net Zero and other stakeholders during an initial project workshop. The impacts were broadly grouped according to various 'categories', with summary metrics provided in Table 2. Several papers explore multiple impacts and have been allocated to each that is relevant. Note that n ≠ 57 due to this double-counting and due to some sources not considering digestate impacts.

Table 2 Summary metrics for impacts identified and whether they should be discussed for potential inclusion (highlighted in blue).

Digestate impact	**Number of sources**	**Discussed at workshop?**
CH_4 from stored digestate	7	Yes
N_2O from stored digestate	4	Yes
CH_4 and N_2O (fugitive) emissions during AD	1	Yes
Earthworm mortality	3	Yes
Plant pathogens	1	Yes
Combined biological, physical and chemical hazards	7	No

Digestate impact	Number of sources	Discussed at workshop?
Veterinary medicines	6	No
Organic compound contaminants	4	No
Antibiotic resistance genes	3	No
Bacteria of relevance to human health	9	No
Potentially Toxic Elements	2	No
Soil microbial activity	2	No
Weed seeds	2	No
Botulinum toxin	1	No
N_2O from digestate amended soils	1	No
P transformation in soils	1	No
Salinity	1	No

3.1 Initial workshop

The following topics were synthesised from the evidence assessment for discussion in the workshop events. The aim of the first workshop was to agree the finalised list of impacts to be included in the REA. A summarised report of the workshop is included at Appendix 3 (Workshop summary).

3.1.1 CH_4, N_2O, NH_3 and NO_3^-

Evidence assessment highlighted the potential for fugitive CH_4 and N_2O emissions during anaerobic digestion. The magnitude and impact of these emissions were not explored. Point source limits are in place for some emissions at AD facilities operating under Environmental Permits – but not for these gases. Fugitive emissions are not limited, and Leak Detection and Repair (LDAR) programmes are only required at Installations, rather than smaller permitted operations. LDAR programmes cover volatile organic compounds (VOCs) – including methane – but do not cover N_2O or NH_3. There are no specific point source limits for emissions during storage of digestates, although stores must be covered.

The REA did not examine the magnitude or impact of fugitive CH_4 and N_2O emissions from AD processes and digestate stores. If impacts were deemed to be sufficient, mitigation options could be established during the next stage of the project. However, baselines would be required against which to model any mitigation approach.

Baselines would also be required for NH_3 and NO_3^-, and it is possible that these had already been developed by the Department for Energy Security & Net Zero, Defra or the EA. This was discussed during the workshop, recognising that current obligations do not (for example) specify the type of cover that must be used for digestate stores, merely that those stores be covered.

3.1.2 Earthworm mortality

Several papers have highlighted the impact of digestates on earthworms – with both short- and long-term implications for soil health and resilience. The research is not always conclusive, since the impacts may be confounded by other factors such as soil wetness and compaction. Nonetheless it is clear that exposure to ammonia can negatively impact earthworms in the short-term, and that digestate is a source of ammonia. Nevertheless, in some studies long-term positive impacts on earthwork abundance are reported, despite the initial mortalities.

Rather than specifically investigate options to mitigate digestate impacts on earthworms, the team recommended that the focus remained the mitigation of ammonia losses from digestate – but that mitigation solutions which could have a positive or negative impact on earthworms be highlighted.

3.1.3 Plant pathogens

One source highlighted the potential for a quarantine potato pathogen (*Synchytrium endobioticum*) to survive both pasteurisation and anaerobic digestion. There was no indication as to the magnitude of risk, but guidance was recommended around the use of digestates derived from potatoes on land where potato crops are grown. This echoed similar earlier advice. Since this issue was not expected to be common across the AD industry, The team recommended that it was excluded from the scope of this project – but that consideration be given to future research on this topic.

3.1.4 Organic compound contaminants

A number of organic compounds have been identified in digestates. Research highlighting that PAH limits in digestate have been introduced in a number of countries, but not the UK. The absence of direct control in the UK does not indicate a risk, but future research may be required to demonstrate the absence of risk.

A similar approach might also be adopted for veterinary medicines and other organic compound contaminants. Even where these compounds are not removed, no magnification of the underlying risks is expected via AD, when digestates are applied to land that might otherwise have received un-processed materials. If digestates are applied to other land or used in other ways, then the risk profiles may be different. Investigation of these is beyond the scope of this project but might be deemed suitable for future research activity.

The final agreed list of impacts requiring investigation and (potentially) mitigation was agree as:

- Ammonia emissions during digestate storage and use
- Nitrate leaching following digestate use
- Methane emissions during digestate storage and use
- Plastics in digestates

4.0 Identifying mitigation options

Using the structured evidence assessment methods described above, available information for impact mitigation options applicable to agricultural and commercial/municipal digestates was collected.

More than 3,000 abstracts were reviewed, identifying 208 resources of potential interest which – when combined with relevant Task 1 resources and filtered – provided a set of 129 resources that could be categorised as follows:

- 88 peer-reviewed scientific papers
- 1 PhD thesis
- 3 MSc theses
- 36 pieces of 'grey literature' including technical reports, trade body documents, web pages and opinion pieces
- 1 conference paper

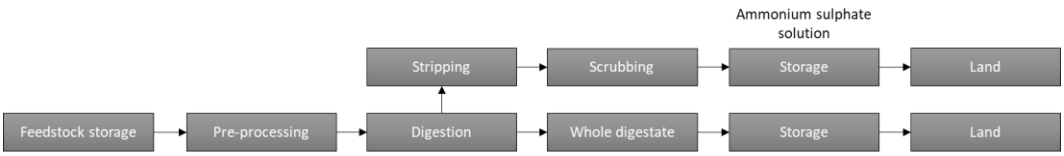
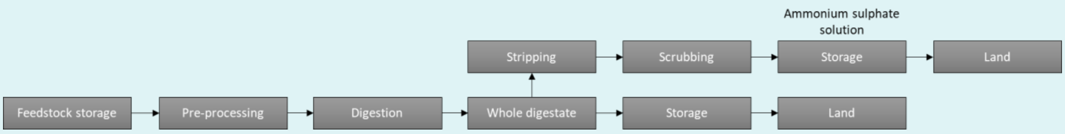
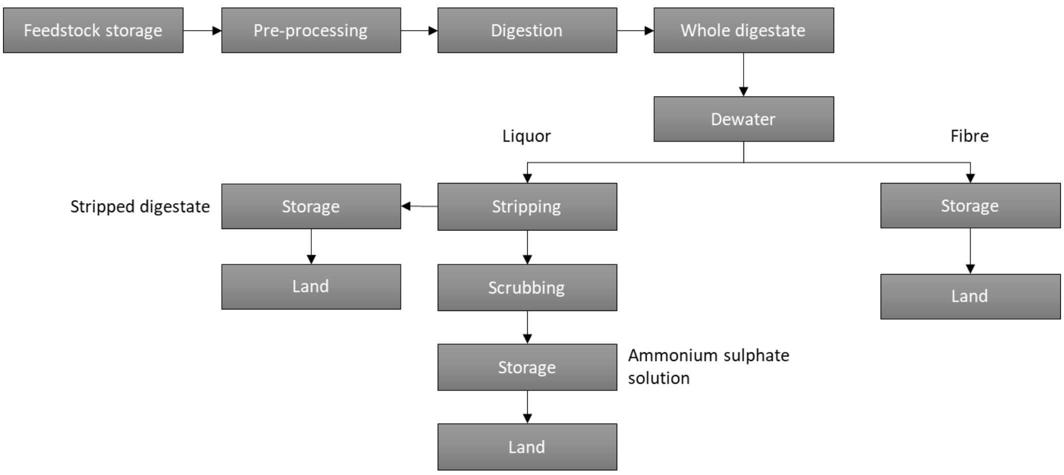
Where mitigation options had been demonstrated at Technology Readiness Level (TRL) 7+ on substrates that are similar to agricultural or commercial digestates, then these were also captured in the evidence assessment as 'Tier 2' options. Such substrates include livestock slurries and sewage sludges. Short descriptions of each mitigation technique at TRL 7+ are provided in the following sections. Mitigation techniques at lower TRLs are summarised in Appendix 4:.

Performance, cost and other relevant data for each option are included in Appendix 5:

4.1 Ammonia and methane mitigation options

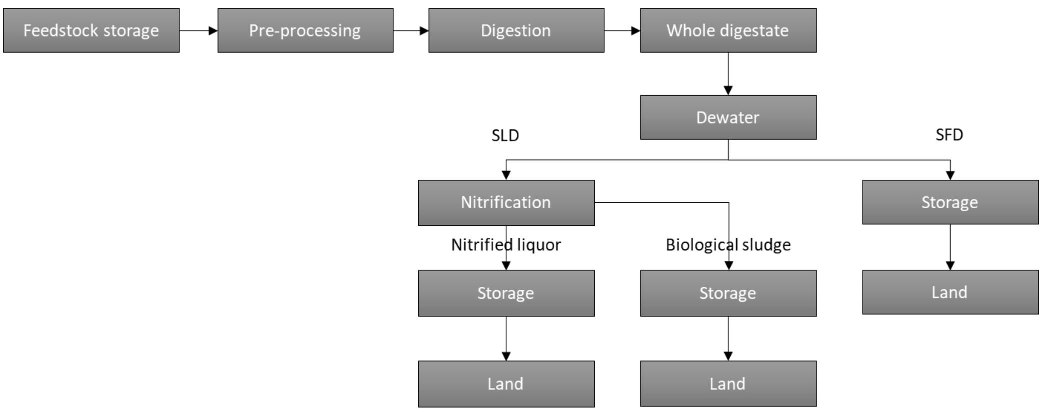
4.1.1 Stripping / Scrubbing

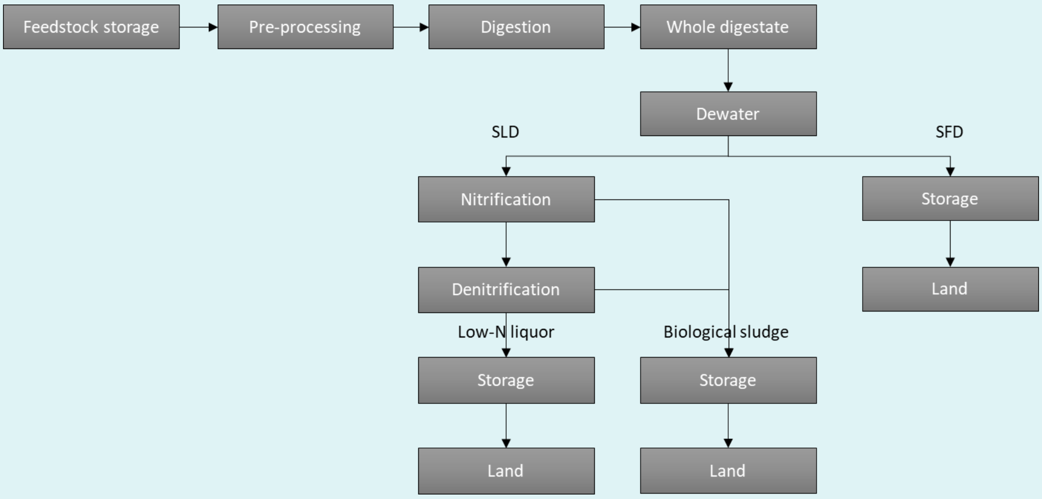
TRL	**Commercial (TRL 9+)**
Digestate type	Food and farm
Digestate fraction(s)	Whole / Separated liquor
Descriptio n	Ammonia is stripped from liquid digestates into a carrier gas from which it is then scrubbed with a strong acid (typically concentrated sulphuric acid) to create an ammonium sulphate solution. The equilibrium between dissolved ammonia and ammonium depends on solution temperature and pH.

	Increasing either will push the equilibrium in favour of ammonia, but the use of heat is only practicable under some circumstances. This technology is fully commercialised and can be deployed in various configurations - whether on whole or separated liquor digestates, or as a side-stream process to manage ammonia loadings during anaerobic digestion. The commonest stripping approach involves passing the liquid down a column against a counter-current of the stripping gas. Physical media within the column (used to increase surface area of the liquid being stripped) are prone to clogging unless solids are handled appropriately. Nitric acid can be used for the scrubbing phase, but is more expensive than sulphuric acid. One full-scale trial (of the ANA-strip or Fiber-plus process) is scrubbing with a gypsum solution, which creates a calcium carbonate suspension in an ammonium sulphate solution. The gypsum in this case derives from a flue gas desulphurisation unit. Stripping from stored digestates may deliver better results, compared with fresh digestates. There is at least one commercial supplier that uses heat-assisted stripping, but then combusts the ammonia-rich carrier gas in a 'thermal oxidising unit'. We have not included this specific approach in our library of mitigation techniques
Side-stream	
Whole digestate	
Liquor digestate	
References	(Adriaens *et al.*, 2020); (D. Bolzonella *et al.*, 2018); (Brienza et al., 2020); (Brienza et al., 2021); (Hutchings *et al.*, 2013); (NUTRIMAN, 2020a); (NUTRIMAN, 2020b); (NUTRIMAN, 2020c); (Serna-Maza, Heaven and Banks,

	2015); (Sigurnjak *et al.*, 2019); (SYSTEMIC, 2020b); (SYSTEMIC, 2021); (Vaneeckhaute *et al.*, 2017); (Verbeke, Van Dijk and Brienza, 2021)

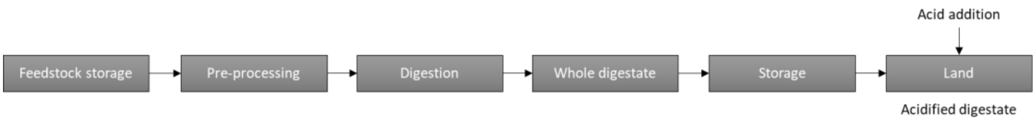
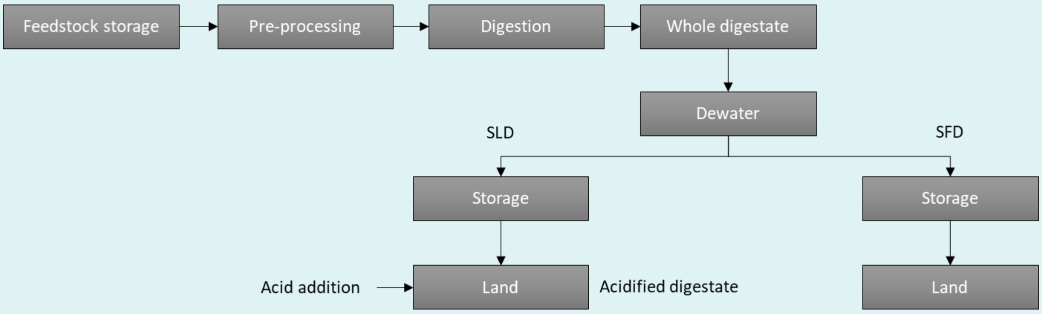
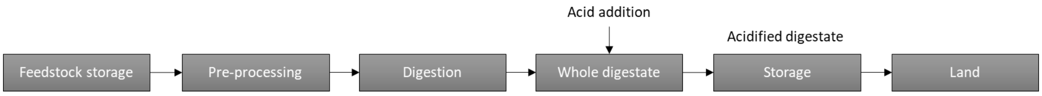
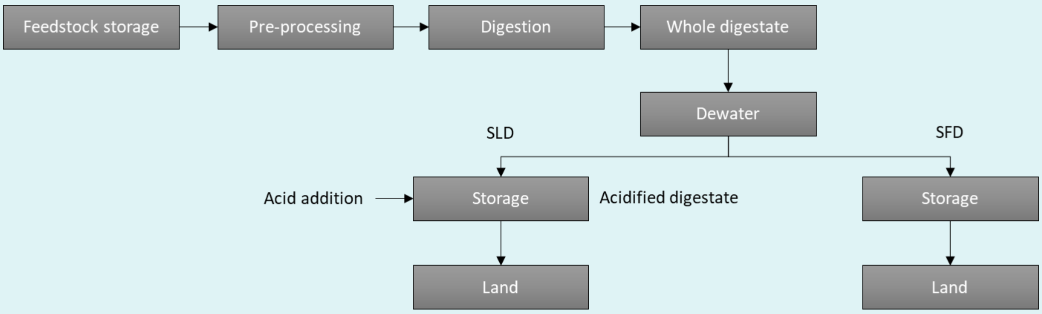
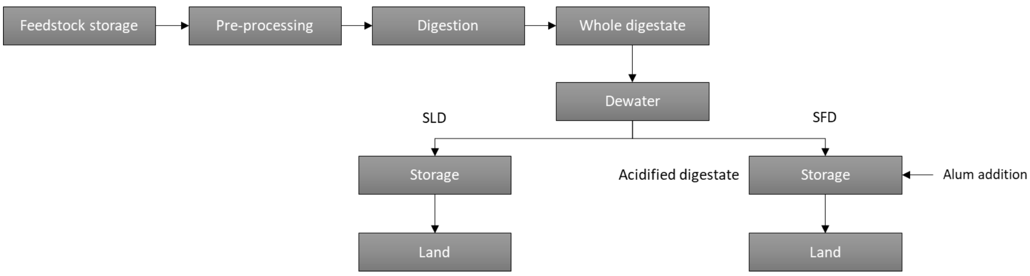
4.1.2 Nitrification / Denitrification

TRL	**Commercial (TRL 9+)**
Digestate type	Food and farm
Digestate fraction(s)	Separated liquor
Description	Nitrification and denitrification are biological processes that (under aerobic and anoxic conditions, respectively) convert ammoniacal nitrogen to nitrate and thence to dinitrogen gas. This technique is very commonly applied in wastewater treatment and is also widely used in strategies to address regional nitrogen surpluses from livestock manures in the Netherlands. The reduced-nitrogen liquors can be further processed (in various valorisation flow sheets) or land-applied. In principle the process can be configured to deliver nitrification only, which would mitigate the ammonia impact. This is not done in practice as the requirement is normally to remove nitrogen from a system. Nitrification / Denitrification is also commonly applied to the liquor fraction of livestock slurries in The Netherlands, but examples of its application in AD plants are infrequent in the literature. The overall removal efficiency of a nitrification / denitrification system can range from 70 to 97% of total nitrogen removed from treated substrate.
Nitrification	

Nitrification / Denitrification	
References	(Hou *et al.*, 2018); (Finzi *et al.*, 2020a); (Gorissen and Snauwert, 2019); (vcm, 2020); (Foged, Flotats, Bonmati Blasi, *et al.*, 2011)

4.1.3 Acidification of digestate (in field and in store)

TRL	**TRL 9**
Digestate type	Farm
Digestate fraction(s)	Whole digestate / Separated liquor (Tier 2 for Separated fibre)
Description	In Denmark, pig slurries are commonly acidified through addition of concentrated sulphuric acid. This pushes the ammonia-ammonium equilibrium in favour of the latter. The approach is not commonly used in other countries as different ammonia mitigation strategies have been deployed (for example, in the Netherlands a requirement to cover slurry stores means that there is no additional benefit from acidification). Various trials with acidification of farm digestates have taken place - both in storage and at the point of application in the field - but the technology does not appear to be commercialised for digestates. There are limited data for trials (TRL5) with acidification of food waste digestates. In-situ acidification of livestock slurries is also advertised as resulting from plasma treatment of this material, with similar benefits with respect to reduced ammonia volatilisation. We have not included plasma treatment in our library of mitigation options since (unlike standard acid-dosing) it also introduces nitrate into the treated material and is largely proven on livestock slurries. Although we could not find evidence of their commercial use in UK/Europe, there are data from the USA on the use of alum to treat poultry litter. This

<table>
<tr><td></td><td>also acidifies the substrate, reducing the NH_3 volatilisation potential. This technique has been demonstrated on whole pig slurry digestates.</td></tr>
<tr><td>In field (whole digestate)</td><td>
</td></tr>
<tr><td>In field (liquor digestate)</td><td>
</td></tr>
<tr><td>In store (whole digestate)</td><td>
</td></tr>
<tr><td>In store (liquor digestate)</td><td>
</td></tr>
<tr><td>In store (fibre digestate)</td><td>
</td></tr>
<tr><td>References</td><td>(Eihe et al., 2019); (Graves et al., 2019); (Hunolt et al., 2015); (Jacobsen, 2015); (Latacz-Lohmann, 2017); (Moore and Watkins, 2012); (N2 Applied, 2020); (Sánchez-Rodríguez et al., 2018a); (Regueiro et al., 2016)</td></tr>
</table>

4.1.4 Covered stores

TRL	**Commercial (TRL 9+)**

Digestate type	Food and farm
Digestate fraction(s)	Whole digestate / Separated liquor / Separated fibre
Description	The Environment Agency has indicated that future digestate stores will need to be covered, and that (for food waste AD plants) the cover system should be "provided with gas collection and extraction to abatement or gas recovery system". A risk-based approach can be adopted for farm plants. For our baseline we have assumed the 'least best' cover system (floating cover), which provides a degree of abatement for ammonia. A range of other cover systems is commonly supplied – including floating expanded clay balls, floating plastic tiles, fixed 'roof' covers and gas-tight covers. Slurry bags are also available, which provide an alternative gas-tight solution. For separated fibre digestates our baseline scenario assumes that any store will be uncovered. Plastic sheeting is commonly recommended as a cover for farmyard manures and offers potential for ammonia mitigation from fibre digestates. Storage within a closed room, with appropriate air extraction and abatement would also reduce emissions when compared with the baseline – although is extremely difficult to cost
References	(Environment Agency, 2020); (Giner Santonja *et al.*, 2017); (Misselbrook *et al.*, 2008);

4.1.5 Low emission spreading techniques

TRL	**Commercial (TRL 9+)**
Digestate type	Food and farm
Digestate fraction(s)	Whole digestate / Separated liquor
Description	Our baseline assumption is that the 'least best' low emission spreading technique is used for digestate application. Based on information provided in the National Atmospheric Emissions' Inventory, this technique is trailed hose application. Both trailing shoe and injection techniques offer potential for further ammonia abatement at the point of digestate application. Trailing hose systems place digestate in narrow bands above the soil

	surface while trailing shoe systems allow digestate to be placed on the soil surface beneath a crop canopy. Where soil and crop conditions allow, digestates may also be injected below the soil surface, providing further mitigation of ammonia
We have been unable to identify consistent evidence for the methane mitigation potential of different spreading techniques and would be grateful for any relevant insights into this point from Defra	
References	(Misselbrook and Gilhespy, 2021); (Misselbrook *et al.*, 2008); (Wiltshire and Martineau, 2018)

4.3 Methane-specific mitigation options

The following three options all alter the conditions of digestate such that conditions for methanogenesis are no longer present or favoured. The techniques have not been specifically designed and are not implemented for this purpose and data on their potential performance in such applications is consequently scarce. For this reason these options have not been modelled, but may warrant further investigation in future.

4.3.1 Aerated storage

TRL	**Commercial (TRL 9+)**
Digestate type	n/a
Digestate fraction(s)	Tier 2 for whole / separated liquor digestates
Description	A number of slurry aeration / mixing systems are commercially available. Some claim to increase slurry nitrogen contents, although the mechanisms for this are not elaborated. It is likely that aeration stimulates nitrification and mineralisation of organic N, to give a more consistent fertilising substrate. One of the key benefits is improved physical consistency and pumpability of the substrate. The technique is commonly applied in sewage sludge processing systems, for similar reasons (Matthew Smyth, *Pers Comm*). Feedback on performance of slurry aeration systems is variable, with high running costs (due to electrical demand), although compared with conventional agitation systems the air will impact on slurry biology. There are user comments around lower nitrogen content in aerated slurries (very possible, since ammonia could be stripped through active aeration). Aerated conditions are fundamentally detrimental to methanogenic microflora and aeration is reported to reduce methane emissions from stored slurries.
References	(Amon *et al.*, 2006); (Farming Forum)[3]; (Forum4Farming)[4].

4.3.2 Composting

TRL	**Commercial (TRL 9+)**
Digestate type	n/a

[3] https://thefarmingforum.co.uk/index.php?threads/slurry-aeration-systems.33590/
[4] https://www.forum4farming.com/forum/index.php?threads/slurry-aeration-systems.10867/

Digestate fraction(s)	Separated fibre digestate
Description	It is feasible and permissible to use digestate fibre as a feedstock in composting processes. As with nitrification and aeration of liquid digestates, this fundamentally alters the substrate microflora by shifting from anaerobic to aerobic conditions. This should reduce or prevent methane emissions from the composted digestate fibre.
References	(Ermolaev, 2015); (Hrad *et al.*, 2014)

4.3.3 Lime treatment

TRL	**Commercial (TRL 9+)**
Digestate type	n/a
Digestate fraction(s)	Tier 2 for separated fibre digestates
Description	Sewage sludges are commonly treated with lime, to increase pH and/or temperature for the purposes of attenuating pathogens within the material. Temperatures of over 55°C and pH >12 can be achieved, creating conditions unfavourable for biological activity including (potentially) methanogens. This approach could therefore reduce methane emissions during storage of fibre digestates. However, this pH change will likely cause significant ammonia emissions.
References	(Hoang et al., 2022); https://britishlime.org/technical/sewage_sludge_treatment.php

The following technique is used to extract dissolved methane from digested sewage sludges prior to their final dewatering and storage. This may offer temporary reductions in methane emissions from the digestate but is not expected to alter substrate conditions such that methanogenesis is no longer possible. In the absence of quantified effectiveness in reducing methane emissions during storage and use of digestates, this option has not been modelled.

4.3.4 Vacuum de-gassing

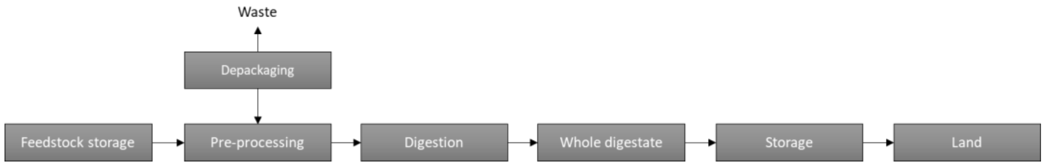
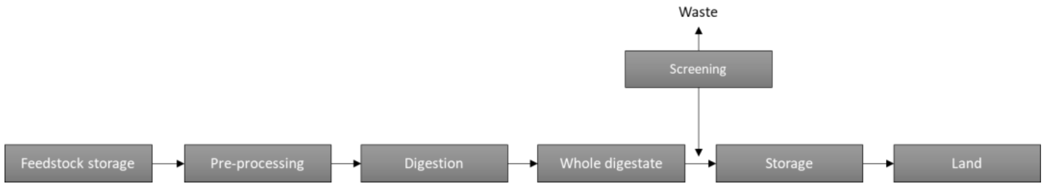
TRL	**Commercial (TRL 9+)**

Digestate type	n/a
Digestate fraction(s)	Tier 2 for whole digestates
Description	Vacuum de-gassing uses a vacuum pump to extract methane from the digested sludge, reducing greenhouse gas emissions while providing additional gas yield to the CHP. In theory this also reduces methane emissions during subsequent storage of processed sludge (or digestate). Vacuum de-gassing can be installed as a stand-alone system without disruption of existing treatment processes..
References	https://www.eliquo-tech.com/en/elovac.html https://cnp-cycles.de/en/cycles/energy-cycle/deprex-degassing-technology

4.4 Plastic mitigation

4.4.1 Depackaging and screening

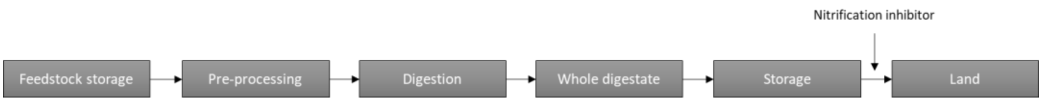
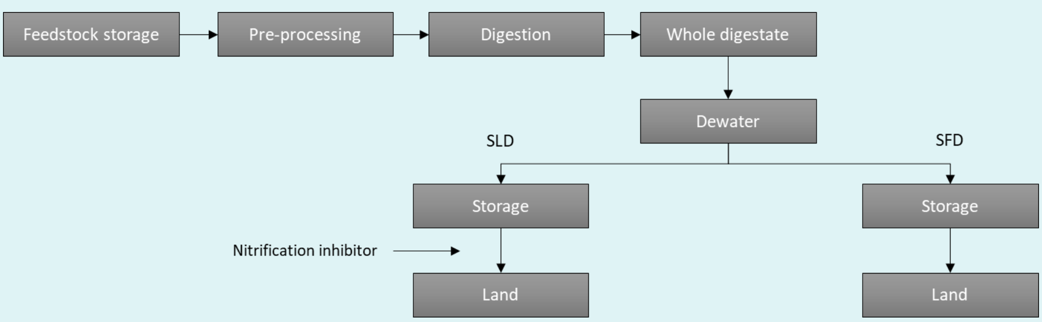
TRL	**Commercial (TRL 9+)**
Digestate type	Food
Digestate fraction(s)	Food waste feedstocks / Whole digestate
Description	Physical screening to remove packaging and other non-target materials is commonly applied at commercial food waste AD sites. These processes can be applied at various points before, during and after digestion to achieve the desired quality in the resulting whole/liquor digestates. Our evidence assessment did not identify any innovative approaches to mitigation of plastics, although we did identify one example where feedstocks are first autoclaved to create a pulp which is then screened. This is claimed to increase biogas potential from the processed wastes, and the autoclaving process will also alter the rheology of the material - which could improve the efficiency of subsequent screening. No performance data are publicly available for this latter configuration, and published performance data for any kind of screening/depackaging are very limited

Depackaging	
	Note that depackaging techniques are considered part of the baseline, since all commercial AD plants accepting packaged waste or food waste in caddy liners would require that the packaging be removed prior to digestion of the biowaste
Screening	
References	(Alessi *et al.*, 2020); (Bernstad *et al.*, 2013); (Do Carmo Precci Lopes *et al.*, 2019); (Hansen *et al.*, 2007); (Jank *et al.*, 2015)

4.5 Nitrate mitigation

In the absence of evidence for impact in a baseline scenario where digestates are applied to soils in the spring (as would be good practice for both commercial and farm digestates considered in this study) we are unable to recommend specific measures for mitigation. Nonetheless, nitrification inhibitors offer a potential solution under some circumstances, and are described below.

4.5.1 Nitrification inhibitors

TRL	**Commercial (TRL 9+)**
Digestate type	Food and farm
Digestate fraction(s)	Whole digestate / Separated liquor
Description	Numerous additives are available to retard biological conversion of ammoniacal-nitrogen to nitrate-nitrogen in soils. These additives are typically supplied for use for conventional urea fertilisers but have also been trialled with livestock slurries and various digestates. Not only do such inhibitors have the potential to reduce nitrate leaching, but they may also reduce N2O emissions. At least one manufacturer supplies inhibitors for use with digestates, although we have been unable to identify public data on the outcomes of any trials - which tend to have taken place at lower TRLs.
Use with whole digestates	
Use with separated liquor digestates	
Notes	
	8.8kg NO_3-N per hectare per year leached following spring application of manure digestate ahead of maize crop in Canada. This equated to leaching of between 1.9 and 2.1% of total N in spring-applied digestate in successive

	years of the field trial, with the authors concluding that losses were lower than for conventional fertilisers (Schwager *et al.*, 2016). Chambers, Smith and Pain (2000) report nitrate leaching data for various livestock manures – if poultry manure is used as a proxy for fibre digestates, then we can estimate 2% of total N lost as nitrate from spring application of this material. Nitrate leaching data for spring-applied UK digestates have also been published by (WRAP, 2016), although only presented in a single chart (which shows no leaching – in contrast to leaching over winter from autumn-applied digestates, which is significant).
References	(Federolf *et al.*, 2016) ; (Sánchez-Rodríguez *et al.*, 2018b)

5.0 Identifying valorisation options

More than 2,500 abstracts were reviewed, identifying 262 resources of potential interest which – when combined with resources already available to team members – provided a set of 163 resources that could be categorised as follows:

- 114 peer-reviewed scientific papers
- 3 PhD theses
- 45 pieces of 'grey literature' including technical reports, trade body documents, web pages and opinion pieces
- 1 conference paper

A wide range of options was identified, with those at TRL 7+ described in the following sections. They are divided into Tier 1 options (those demonstrated on food and/or farm digestates) and Tier 2 options (those demonstrated on similar substrates, such as livestock slurries and sewage sludges). Options within either tier at lower TRLs are grouped together and briefly described in Appendix 4:.

In a limited number of cases, we are aware of processing techniques that are permissible within UK regulatory frameworks, but for which published evidence is lacking. In the absence of evidence, we have therefore opted to omit the following examples from our analysis: use of whole or separated liquor digestates as wetting agents in composting systems; and aerobic stabilisation to treat separated fibre digestates before their use in growing media or other applications.

There is extensive overlap between mitigation and valorisation techniques, and several of the mitigation unit processes described above can be used in digestate valorisation systems. These combine multiple unit processes to deliver digestate derivatives that meet the needs of the specific AD business. For example, in an area with good land availability but little need for nitrogenous fertiliser, a valorisation system might include nitrification/denitrification, which will reduce the nitrogen concentration in digestate without reducing its volume. If local land availability is poor, then a valorisation system might further treat the liquor fraction to a point that water can be discharged to a local waterbody and might also dry / pelletise the fibre fraction to reduce the residual volumes requiring transport to available land. A good overview of the common unit processes and their combinations was provided by Fuchs & Drosg (2013), and variants of these remain the basis of most current valorisation approaches (Figure 2).

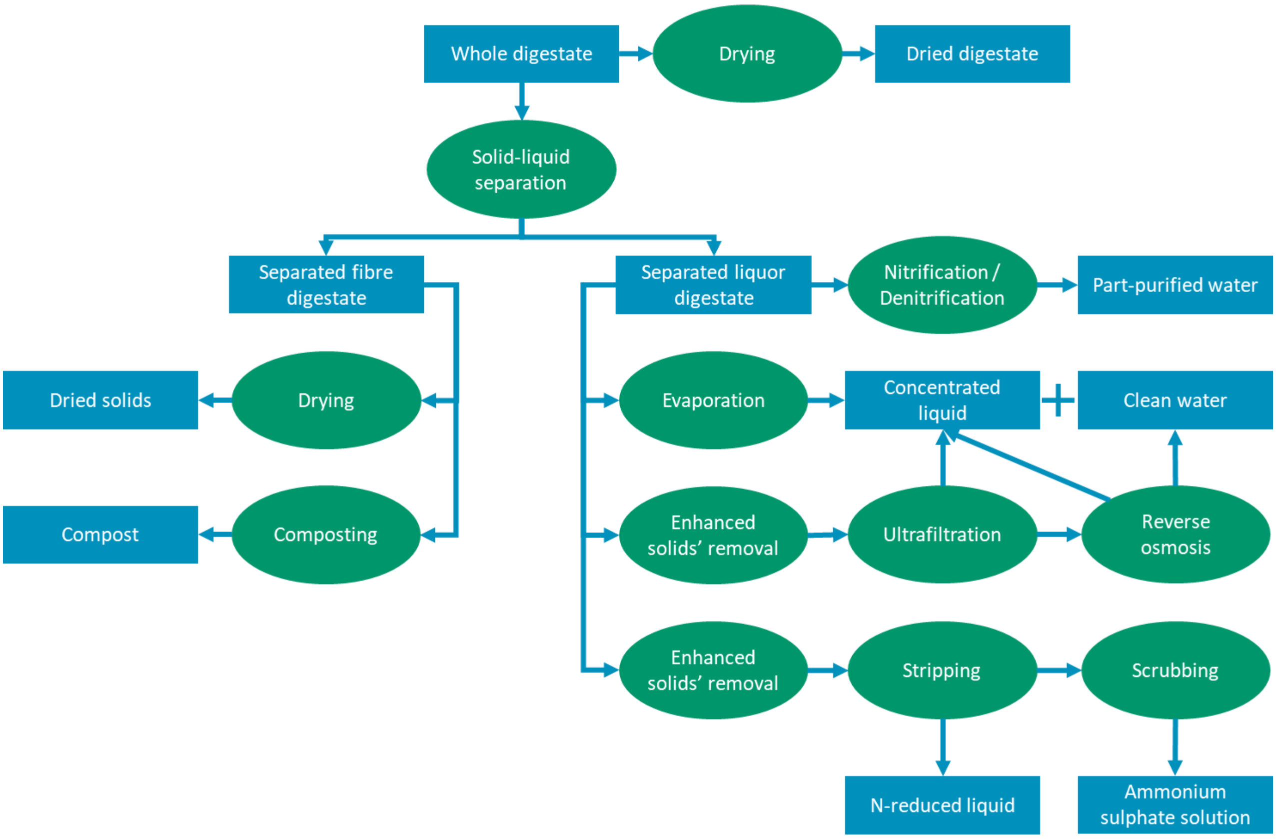


Figure 2 Overview of common digestate processing options. Adapted from Fuchs & Drosg (2013)

From the available evidence, it is clear that the specific combination of available unit processes is dictated by AD-business-specific drivers, and that the variation in digestate characteristics means that it is not necessarily feasible to cut and paste any one valorisation process train from one AD business to another without first piloting that process at the second site. This makes it difficult to generalise on the applicability of digestate valorisation approaches – even within one digestate category (such as farm digestates). Nonetheless, this section provides examples to illustrate the variety of process combinations that have been trialled at scale on farm and/or food digestates.

Of particular interest is the recent EU Horizon 2020 'SYSTEMIC' project, which has worked with forty AD plants across Europe to develop a library of twenty-one digestate nutrient recovery and reuse (NRR) cascades. Combined with financial data from sites and suppliers, this information underpins the 'NUTRICAS' Decision Support Tool which allows AD operators to select valorisation options that best suit their circumstances (Verbeke, Schoumans, *et al.*, 2021). An analysis of this tool is beyond the scope of this project, but SYSTEMIC provides a useful repository of information on practical implementation of digestate valorisation techniques, and an overview of participating AD sites and their NRR approaches is provided in Appendix 10:. UK involvement in the SYSTEMIC project has been limited, although the AFBI (Agri-Food and Biosciences Institute) AD facility in Northern Ireland is represented. Friday's poultry manure digester at Knoxbridge in Kent had originally been intended as a demonstration plant but was not completed in time to allow the NRR technology to be evaluated.

Another key point from the research is that many of the digestate valorisation techniques derive from systems which were created to process pig and / or cattle slurries in response to regional nutrient surpluses and a requirement to convert nutrients into formats that can be exported to less nutrient-constrained regions. Dewatering these materials (to produce separate fibre and liquor fractions) is relatively simple due to the presence of residual dietary fibres. The same is not necessarily true for digestates, and particularly food waste digestates. Indeed, our personal communication with some food waste AD operators suggests that successful dewatering is all but impossible. This will mean that some of the techniques we have identified may never be applicable to food waste digestates – but it is not possible to be certain of this without testing.

5.1 Tier 1 options

Tier 1 Options	TRL	Digestate type	Digestate fraction(s)	Description	References
Acidified digestate	7	Farm	Whole digestate / separated liquor	Digestate pH is reduced, which shifts the NH_4^+ / NH_3 equilibrium in favour of ammonium, reducing ammonia loss in storage and field	This end point is described earlier in this report, in the context of ammonia mitigation
Ammonia solution	9	Separated liquor	Food and farm	Vacuum evaporation of digestate is followed by condensation to create an ammonia solution that can be used as a liquid fertiliser (under limited conditions) or for other purposes, such as DeNOx (where it is used in place of urea as a NOx mitigation tool in incineration). Vacuum evaporation may instead be combined with acid scrubbing to produce ammonium sulphate solution. Ammonia removal can be maximised by combining heat and high pH, which shift the aqueous equilibrium towards dissolved ammonia. Heating digestate to ~80°C is usually required, delivering ammonia removals of up to 75%. Recovered waste heat (e.g. from CHP) can be used to support this. For DeNOx applications, recovered ammonia solution (10 to 25%) is injected into the combustion process as a replacement for higher grade ammonia or urea solutions.	(Verbeke, Van Dijk and Brienza, 2021); (Adriaens, Power, *et al.*, 2020); (Verbeke, Hermann, *et al.*, 2021)
Ammonium nitrate solution	9	Farm	Whole digestate / separated liquor	Ammonia gas is stripped from digestate and scrubbed from the gaseous phase with nitric acid to create an ammonium nitrate solution that can be used as-is or further processed into a fertiliser product. Nitric acid is less commonly used than sulphuric acid in such scrubbing systems due to its higher cost and environmental footprint. Phosphoric acid may also be used, to produce an ammonium phosphate scrubbing solution.	Vaneeckhaute *et al.* (2017); Sigurnjak *et al.* (2019); (NUTRIMAN, 2020h); (NUTRIMAN, 2020j); Adriaens, Harms, *et al.* (2020)

Tier 1 Options	TRL	Digestate type	Digestate fraction(s)	Description	References
Ammonium sulphate solution	9	Food and farm	Whole digestate / separated liquor	Carrier gas (normally air) is passed through digestate to remove a proportion of the dissolved ammonia. This is then scrubbed from the gas phase in an acid column. Stripping techniques are normally applied to the digestate liquor fraction – although side-stream removal during AD is also feasible. Similar results can be achieved through scrubbing following digestate evaporation, and membrane recovery of ammonium. Ammonia removal can be maximised by combining heat and high pH, which shift the aqueous equilibrium towards dissolved ammonia. Heating digestate to ~80°C is usually required, delivering ammonia removals of up to 75%. Recovered waste heat (e.g. from CHP) can be used to support this	This end point is described earlier in this report, in the context of ammonia mitigation
Animal bedding	9	Farm	Separated fibre	Fibre is used as livestock bedding in place of alternatives such as sawdust, straw and sand. Commonly used in the USA and elsewhere. Not permitted for dairy cattle in the UK, irrespective of input. Some types might be acceptable for other livestock.	(Alexander, 2012); (Ontario.ca, 2012); (Red Tractor Assurance, 2017)
Calcium carbonate (+ ammonium sulphate)	9	Farm	Whole digestate	Ammonia and CO_2 are stripped from digestate under vacuum and passed through a gypsum solution, resulting in a calcium carbonate suspension in ammonium sulphate solution. Digestate is first heated to 80°C before gas stripping. Gypsum is sourced from flue gas desulphurisation. Calcium carbonate is removed from the resulting suspension with a screw press. This process has been registered as ANA Strip® and has been implemented as part of the 'FiberPlus' process at the Benas AD site in Germany.	(SSM-Technology, 2009); (Verbeke, Van Dijk and Brienza, 2021); (Brienza *et al.*, 2021b)
Composting	9	Food and farm	Separated fibre	Fibre as an input to composting processes. This is assumed to be a common practice, although examples in the literature are infrequent. Fibre can be used as the sole input or as a component in a feedstock mix. This approach would be	(Bustamante *et al.*, 2012, 2013); (Adriaens, Harms, *et al.*, 2020); (NUTRIMAN, 2020b)

Tier 1 Options	TRL	Digestate type	Digestate fraction(s)	Description	References
				acceptable for end of waste composts in the UK providing associated deregulatory frameworks are followed.	
Discharge quality water	9	Food and farm	Separated liquor	Liquor digestates are passed through additional treatment, reaching a point where an aqueous fraction is suitable for discharge to the environment. Depending on the required water quality at the point of discharge, various process integrations can be used. Typically, the separated liquor digestate is acidified and then evaporated, with the distillate then condensed before polishing in a membrane (reverse osmosis) and/or ion-exchange unit. The liquor may also be processed in a DAF and then microfiltered before being presented to the reverse osmosis unit. In some instances, denitrified liquor from a nitrification / denitrification process may be of sufficient quality to discharge without additional membrane filtration or polishing.	(Verbeke, Van Dijk and Brienza, 2021); (Hermann, Hermann and Schoumans, 2020); (Verbeke, Hermann, et al., 2021)
Dried digestate	9	farm	Separated fibre	Fibre is dried to reduce weight and improved handling characteristics. However, the low bulk density of dried digestate may require pelletization or granulation for long-distance transportation. Ammonia emissions during drying need to be abated and there are risks of self-heating and fire	(NUTRIMAN, 2020d); (NUTRIMAN, 2020f)
Fertigation solution	7	Farm	Separated liquor	Liquor digestates are filtered (using microfiltration or ultrafiltration) prior to use as a fertigation solution, utilising conventional field irrigation equipment.	(Barzee *et al.*, 2019); (Circular Agronomics, 2020); (Mantovi *et al.*, 2018); (NUTRIMAN, 2020c)
Fertiliser pellets	9	Farm	Separated fibre	Dried fibre fraction is pelletised (with or without additional ingredients) for use as an organomineral fertiliser	(Adriaens, Harms, *et al.*, 2020); (Adriaens, Power, *et al.*, 2020); (NUTRIMAN, 2020a)

Tier 1 Options	TRL	Digestate type	Digestate fraction(s)	Description	References
Fuel pellets	9	Farm	Separated fibre	Dried fibre fraction is pelletised and can be used as a biomass fuel in a suitable combustion unit. Unless derived from non-waste inputs, such fuel pellets would (presumably) be supplied to appropriately permitted energy recovery facilities as waste - attracting high gate fees. Combusted pellets may have a high residual ash content, reducing their commercial attractiveness	(Cathcart *et al.*, 2021); (WRAP, 2012a) ; (Monlau *et al.*, 2015)
Fulvic acids	9	Farm	Separated liquor and fibre	Fulvic acids are isolated from pre-treated liquor digestates in a bespoke process for supply as 'biostimulants'. The process steps are described as: 1. Digested pig slurry is separated into fibre and liquor fractions, 2. Phosphorus salts are precipitated from the liquor fraction by addition of Mg and Ca, 3. Biological nitrification of the residual liquor converts ammonium to nitrate, 4. Potassium carbonate is added, forming potassium nitrate, which is concentrated together with humic acids by means of membrane filtration, 5. Fulvic acids are extracted by nanofiltration, 6. Residual liquors are processed via reverse osmosis to produce an NPK fertiliser solution and salt-rich permeate	This process has been patented by the Dutch company Van der Knaap.
Growing medium	9	Food and Farm	Separated fibre	Fibre is used as a component in growing media, with or without an initial stabilisation phase. High electrical conductivity and poor physical characteristics reduce attractiveness of some digestates. Those derived from crops only may be most attractive – but balancing with other constituents may overcome such constraints and allow digestate characteristics to be thoroughly exploited. Commercial experience is most developed in Europe and the opportunities have yet to be fully exploited in the UK	(Herbes, Dahlin and Kurz, 2020); (Adriaens, Harms, *et al.*, 2020); (Cheffins and Stainton, 2015); (Bek *et al.*, 2020)

Tier 1 Options	TRL	Digestate type	Digestate fraction(s)	Description	References
High-P fibre (+ low P liquor)	9	Farm	Separated liquor and fibre	Fine solids are removed from liquor digestate using a DAF or centrifuge, with the resulting sludge used alone or mixed with digestate fibre to increase its P content. This approach results in a P-depleted liquor that retains nitrogen and potash and could be a useful liquid fertiliser for soils with elevated P indices.	(Gorrie, 2018); (Porterfield *et al.*, 2020; Porterfield, Faulkner and Roy, 2020); (NUTRIMAN, 2020g)
Low-N fibre (+ ammonium sulphate)	7	Farm	Separated fibre	Ammonia is vacuum-stripped from whole digestate, and the resulting fibre dewatered. Fibres have been trialled for fibreboard and similar applications. Particularly suited to digestates derived from crops, manures or other fibrous materials. Commercial-scale pilot in Germany at the Benas-GNS site, where the technology is branded FiberPlus. Mulch mats have been produced at scale, for use in weed suppression in vineyards.	(Hermann and Hermann, 2019a); (Magaverde, no date)
Low-P fibre (+ calcium phosphate)	7	Farm	Separated fibre	Fibre is acidified to solubilise P, and P precipitated from the resulting solution using $Ca(OH)_2$. The residual fibre can be used as a soil improver in soils with no immediate phosphorus fertiliser requirement. Most suitable for crop-only AD, but interesting approach, nonetheless. Particularly suited to digestates derived from crops, manures or other fibrous materials. There are several commercial suppliers of wastewater treatment technology that utilises $Ca(OH)_2$ to increase substrate pH and cause phosphate to precipitate as $Ca_5(PO_4)_3OH$ (calcium hydroxyapatite). None of these technologies is applied to digestates. The RePeat process (as currently under development at the Groot Zevert AD site in the Netherlands – and unique to that site) is precipitating calcium phosphates from liquor pressed from acidified digestate fibre.	(Vaneeckhaute *et al.*, 2017); (Brienza *et al.*, 2020b); Schoumans *et al.* (2017); Verbeke, Van Dijk and Brienza (2021)

Tier 1 Options	TRL	Digestate type	Digestate fraction(s)	Description	References
Mushroom cultivation	7	Farm	Separated fibre	Various fibre digestates have been trialled as a substrate for cultivation of edible fungi. In one UK trial, maize-based digestates have been included in mushroom substrates at rates of up to 20% (fresh weight) with no impact on yield (although initial 'stabilisation' with straw and gypsum is required to volatilise excess ammonia). In a US trial, farm-based digestates (predominantly manure-derived) were successfully incorporated at rates of 50% (dry weight) with sawdust to cultivate Oyster mushroom.	(Noble, 2017); (O'Brien *et al.*, 2019)
N-enhanced digestate	8	Farm	Separated liquor	A plasma system uses electricity to fix atmospheric nitrogen, which is then captured in digestate to increase ammonium concentrations. This same approach is listed as a mitigation option as it delivers in-situ acidification. The technology providers target livestock slurries, although the approach is currently under commercial trial at a farm AD site in Northern Ireland. The enrichment process increases the fertiliser replacement value of the substrate, but this may place constraints on land bank and logistics	(NUTRIMAN, 2020k)
Nutrient concentrates	9	Food and farm	Separated liquor	Nutrient concentrates can be derived from digestates using a number of different process configurations. For example, acidification followed by evaporation of digestate liquors to remove water and reduce volume will result in a nutrient concentrate (typically rich in N and K) that can be used as a fertiliser. Other approaches include scraped heat-exchange/thickening techniques and membrane filtration. Where nitrogen recovery is not required, the low-N liquor from biological nitrification / denitrification processes can be concentrated using similar techniques.	Adriaens, Harms, *et al.* (2020); (Verbeke, Van Dijk and Brienza, 2021); (Verbeke, Hermann, et al., 2021); (Hermann, Hermann and Schoumans, 2020)

Tier 1 Options	TRL	Digestate type	Digestate fraction(s)	Description	References
Struvite	7	Farm	Whole digestate; Separated liquor	Phosphorus is precipitated from whole digestate as struvite under controlled conditions and can be used as a standalone fertiliser or ingredient in other fertilising materials. There are several commercial struvite technology suppliers at TRL 9, but they target sewage sludge or industrial AD systems rather than farm / food waste digestates. May require magnesium dosing to encourage struvite formation. Spanish REVAWASTE project is developing a struvite recovery solution for farm digestates. Our evidence assessment indicates that one TRL 8 struvite recovery system is currently under trial at a farm AD site in Spain. The technology is well established and commercialised in the municipal wastewater treatment sector, with systems provided by Paques, Veolia, SUEZ, NuReSys, Colsen, Eliquo, Ostara and other suppliers. In this application the technology is normally deployed to recover phosphorus from sludge dewatering liquors, after anaerobic digestion, where recovery helps to prevent accidental (and costly) struvite precipitation in process machinery and pipework. The cost model for struvite recovery is normally based on the offset maintenance costs that might otherwise accrue, rather than the sale value of struvite itself. Nonetheless, struvite is a useful slow-release phosphorus fertiliser (arbor, 2013). Sludge dewatering liquors stream is analogous to separated liquor digestates produced at farm and commercial AD sites. Although superficially similar, there are a number of reasons why struvite recovery has not been widely adopted outside the wastewater sector:	(Muys *et al.*, 2021); (NUTRIMAN, 2020l) ; (SYSTEMIC, 2018)

Tier 1 Options	TRL	Digestate type	Digestate fraction(s)	Description	References
				• A 1:1:1 molar ratio of Magnesium : Nitrogen : Phosphorus is required for struvite formation, and liquor digestates may be deficient in magnesium, resulting in sub-optimal phosphorus recovery (Orner *et al.*, 2020). Magnesium can be dosed into liquor digestates (for example, as an $MgCl_2$ solution), but this attracts further costs. • Solids and other dissolved minerals within liquor digestates (such as calcium) can interfere with the nucleation and growth of struvite crystals, reducing process efficiency and struvite quality Huchzermeier & Tao, 2012) (Taddeo *et al.*, 2018). • Concentrations and flows of phosphorus through farm and commercial AD facilities may be too low to warrant the necessary investment. At one struvite installation in the UK (Slough wastewater treatment works), daily flows of phosphorus in digested sewage sludges are almost 500kg (Kleemann *et al.*, 2015). By comparison, daily flows in a 'large' commercial AD facility could be ~200kg. Daily flows at a 'large' farm AD plant could be ~1000kg, making struvite recovery more attractive. In both cases these flows are based on standard P concentrations in food and farm digestates (AHDB, 2020).	
Vermicomposting	7	Farm	Separated fibre	Fibre is used as the sole or one of a number of inputs to a vermicomposting process. Although vermicomposting is fully commercial, the use of digestates in such systems remains experimental, and ammonia is known to be detrimental to earthworms	(Hanc and Vasak, 2015); (Krishnasamy, Nair and Bell, 2014); (Manyuchi, Mbohwa and Muzenda, 2018); (Stoknes *et al.*, 2016)

5.2 Tier 2 options

	TRL	Digestate type	Digestate fraction(s)	Description	References
Ashes in cementitious applications	9	Sewage sludges	Farm digestates (Separated fibre fraction)	Dried digestate pellets are combusted and the residual ash used in cementitious applications such as mortar, building blocks and lightweight aggregates. Commercial for sewage sludges.	(Wiechmann *et al.*, 2013)
Biochar (pyrolysis)	9	Sewage sludges and a range of other biomass materials	Farm digestates (Separated fibre fraction)	Dried digestate fibre is heated in the absence of oxygen at temperatures of between 250 and 750°C, at atmospheric pressures, producing char in addition to liquid and gaseous fractions. Available commercially for sewage sludge and other biomass (with minimum calorific value), but yet to be proven commercially for digestate	Cesaro (2021), Marzbali *et al.* (2021) and Monlau *et al.* (2015b)
Biocoal (hydrothermal carbonisation)	9	Sewage sludges and a range of other wet biomass materials	Farm and food digestates (Whole digestate)	Wet biomass is heated to between ~200 and 250°C under pressure of between ~1.5 and 2.0 MPa, causing conversion of biomass into a 'biocoal'. Commercialised for sewage sludge and other biomass, but not digestates. Biocoal usually incinerated for energy. Residual aqueous fraction requires additional treatment.	(Parmar and Ross, 2019)
Biocrude (hydrothermal liquefaction)	7	Sewage sludges and a range of other wet biomass materials	Farm and food digestates (Whole digestate)	Wet biomass is heated to between ~250 and 400°C under pressure of ~2 and 20MPa, causing conversion of biomass into a 'biocrude'. Near-commercial (TRL 7) for sewage sludge and other biomass, but not digestates. Aqueous fraction requires additional treatment	(Watson *et al.*, 2020)
Fibres as fuel in cement manufacture	9	Sewage sludges	Farm digestates (Separated fibre fraction)	Dried digestate pellets are co-fired with other fuels in a cement kiln. Commercial for sewage sludges.	(Wiechmann *et al.*, 2013)

	TRL	Digestate type	Digestate fraction(s)	Description	References
Phosphate salts, ammonium sulphate crystals, K-concentrate, discharge water and residual fibre	8	Pig slurries	Farm digestates (whole digestate)	These are outputs from the BioEcoSIM process in which livestock slurries are first acidified to solubilise P and then separated. The liquor is microfiltered, and P precipitated from the filtrate following pH increase with KOH (configuration to recover K-struvite has the potential to remove N, P & K in a single salt). Ammonium sulphate is stripped from the residual liquor, from which water is then extracted by evaporation. Solids may be land-applied or further processed. A related process is under development as NutriSep.	(NUTRIMAN, 2020e); (Verbeke, Van Dijk and Brienza, 2020)
Reedbed biomass	9	Sewage sludges	Food and farm digestates (Whole digestate and separated liquor fraction)	Reedbeds can be used to dewater / condition sewage sludge digestates as a batch process and have also been trialled as continuous processes for removing nutrients from the separated liquor fraction of pig slurries. In the latter configuration, significant dilution with fresh water is required to bring ammonia concentrations into tolerance range for the reeds. Ammonia-stripped (high pH) separated liquor digestate has been treated in a horizontal flow reedbed at bench scale.	(armreedbeds, 2017); (WRAP, 2012b); (Nolan *et al.*, 2012); (Lyu *et al.*, 2018)
Syngas (gasification)	9	Sewage sludges and a range of other biomass materials	Farm digestates (Separated fibre fraction)	Dried digestate fibre is heated to >800 °C at either atmospheric or elevated temperatures and in the controlled presence of steam or air to produce a syngas with varying proportions of CO, CH_4, H_2 and other gases. Available commercially for biomass and sewage sludges, but yet to be proven commercially for digestate.	Allesina *et al.* (2015), Antoniou *et al.* (2019) and Cesaro (2021)

5.3 Second set of workshops

Following development of the initial mitigation and valorisation 'longlists' workshops were held with both the project Advisory Board and a large group of external stakeholders (who had inputted to previous consultations around the digestate management requirements of the Green Gas Support Scheme). The objective of both workshops was to share findings, to check whether any important options had been missed – and to provide opportunities for stakeholder sense-checking on process costs and performance. The various points raised during these workshops are set out in Appendix 6:, along with associated project team responses.

After the workshop a survey was developed to seek stakeholder feedback on the cost and performance data for the mitigation options that had been discussed. A copy of the survey is provided in Appendix 8:. Although this survey was kindly circulated to members by relevant UK trade and professional bodies, there were no responses. As such the data that was collated was used unchallenged as the cost and performance data for the basis for the Techno-Economic Assessment.

5.4 Selection of valorisation scenarios for modelling

As outlined in the previous sections, a large number of possible digestate processing end points were identified – both at Tier 1 and Tier 2. However, the process of evidence gathering highlighted a number of points that make it difficult (or indeed, inappropriate) to generalize about the applicability of one or any of these end points to all possible commercial and farm AD businesses within the scope of this project. Challenges include:

1. In several cases it is possible to use multiple cascades of individual unit processes to achieve a similar end point.
2. Whether any process or end point adds value to or reduces costs associated with digestates is something that can only be determined on a case-by-case basis, making it impossible to generalise.
3. While most of the individual unit processes are commercially available from a range of suppliers, there are examples where those processes are either pre-commercial or commercial and controlled by a single potential supplier – which presents challenges both in understanding process performance and costs, and in recommending their use.

To overcome these challenges the Department for Energy Security & Net Zero and Defra agreed that the project should develop a shortlist of valorisation 'archetypes' that allow us to reflect common AD market drivers, including:

1. A desire to minimize digestate exports
2. A need to export specific nutrients
3. A desire to reduce reliance on conventional fertilisers

The archetypes also allow us to highlight regulatory impacts and the impacts of plastics in commercial feedstocks. For example:

1. Several crop only AD sites now export fibre for amenity use[5] at ~£100 per m^3. There are no technical reasons that fibre from farm AD plants couldn't be used in the same way or as a partial peat replacement in commercial horticulture, other than regulatory barriers. Contrast this with commercial systems where plastics partition to the fibre and the resulting mix has to be disposed to landfill or incineration at ~£100 per tonne.
2. A very similar situation has also developed with nutrient concentrates, which are sold for amenity / landscape use by at least two UK crop AD facilities.

Finally, the archetypes allow the mirroring of commercial process cascades, to give a sense of the order of magnitude of costs and benefits associated with these.

The valorisation scenarios are grouped according to the following drivers:

A. Where a farm AD plant is able to re-use all its own digestate, but seeks to add value by:
   i. Acidifying the whole digestate, which would increase nutrient use efficiency (NUE) and reduce fertiliser requirements

B. Where a farm AD plant is unable to use some or all of its own digestate, the costs of digestate logistics could possibly be reduced by:
   ii. Capturing and exporting phosphorus (P)
   iii. Capturing and exporting nitrogen (N)
   iv. Creating and selling nutrient concentrate for amenity use
   v. Selling the fibre fraction for amenity use
   vi. Separating the digestate and treating the liquor fraction such that the majority could be discharged to water course

C. Where a food AD plant does not have access to its own land, costs of digestate logistics could possibly be reduced by:
   vii. Creating and selling a nutrient concentrate for amenity use
   viii. Separating the digestate and treating the liquor fraction such that the majority can be discharged to sewer or used for AD feedstock dilution

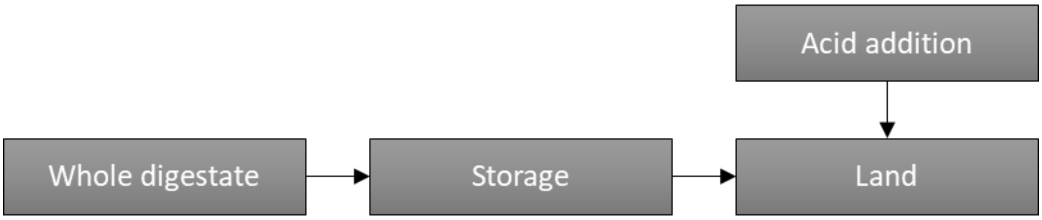
[5] For example: https://tinyurl.com/2p8byebu

5.4.1 Summarised valorisation scenarios for TEA modelling

Archetype 1

In this scenario whole or separated liquor digestates are acidified in the field with concentrated sulphuric acid. This reduces ammonia volatilization, increasing the nitrogen fertiliser value of the digestate. The sulphur also has a fertiliser value.

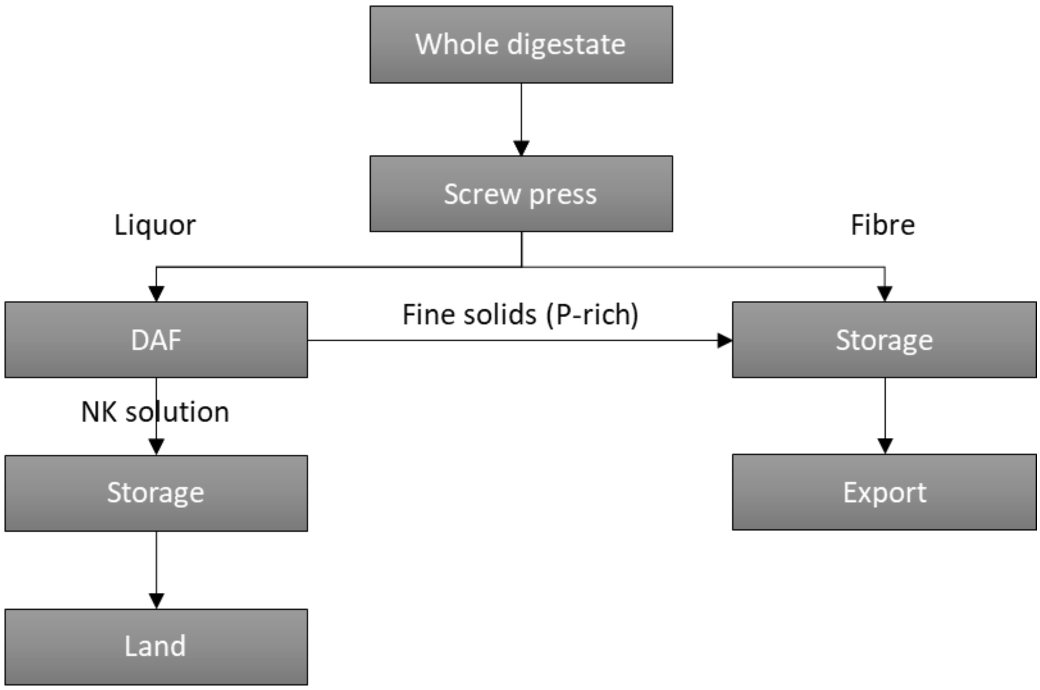
Figure 3 Process flow for valorisation archetype 1



Archetype 2

In this scenario a DAF (Dissolved Air Flotation) unit is used to capture fine suspended solids within liquor digestate. These solids represent a significant residue of phosphorus within this fraction of digestate, and the DAF allows them to be captured in a sludge that can be mixed with separated fibre digestate to increase its fertiliser value for export purposes.

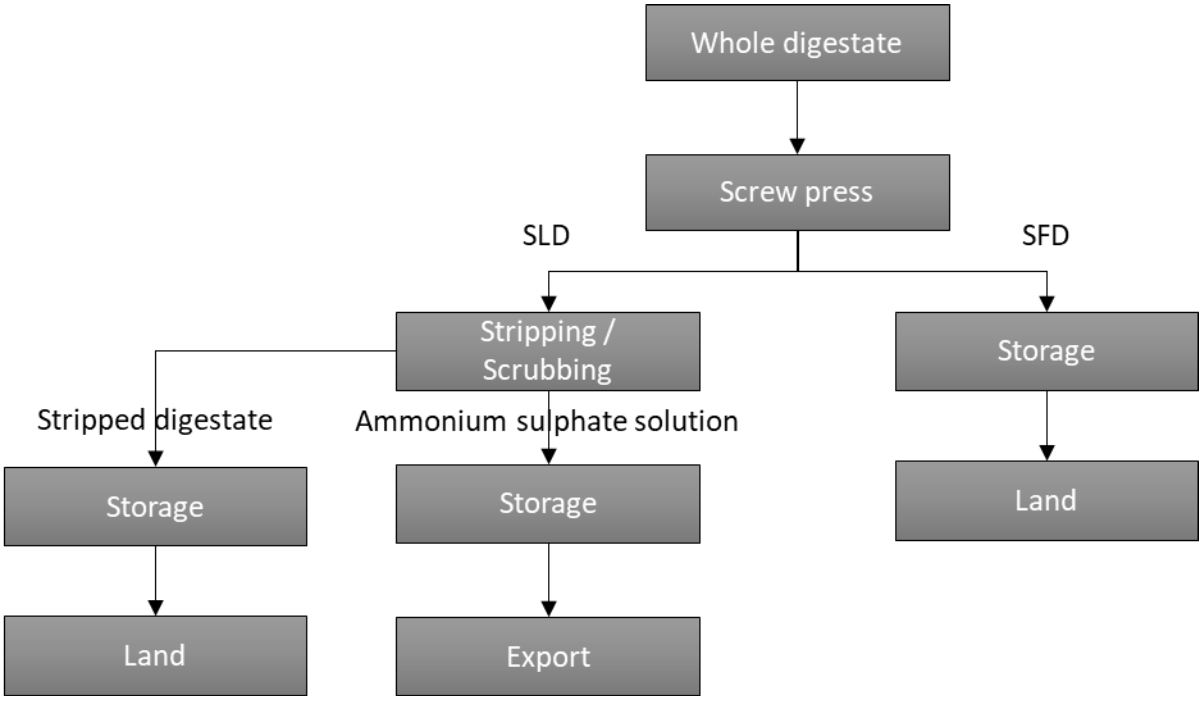
Figure 4 Process flow for valorisation archetype 2



Archetype 3

In this scenario nitrogen is removed and recovered from liquor digestate as ammonium sulphate solution using a stripping and scrubbing unit. The ammonium sulphate solution can be exported for use as a fertiliser.

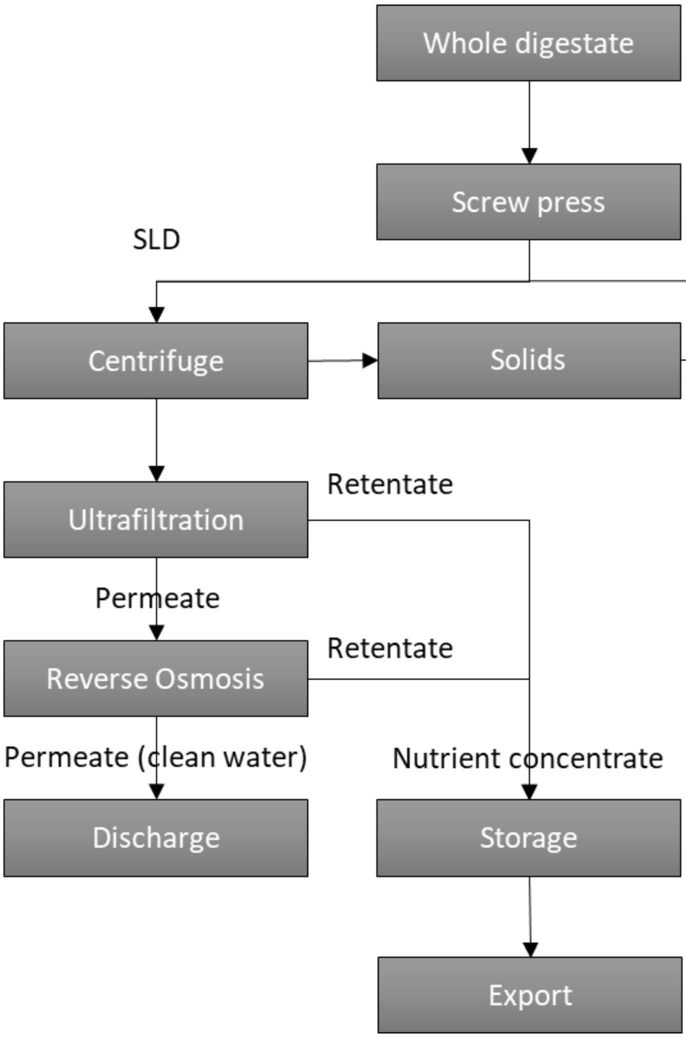
Figure 5 Process flow for valorisation archetype 3



Archetype 4

In this scenario a membrane system is used to create a nutrient concentrate from the separated liquor digestate that can be exported for use as an amenity fertiliser.

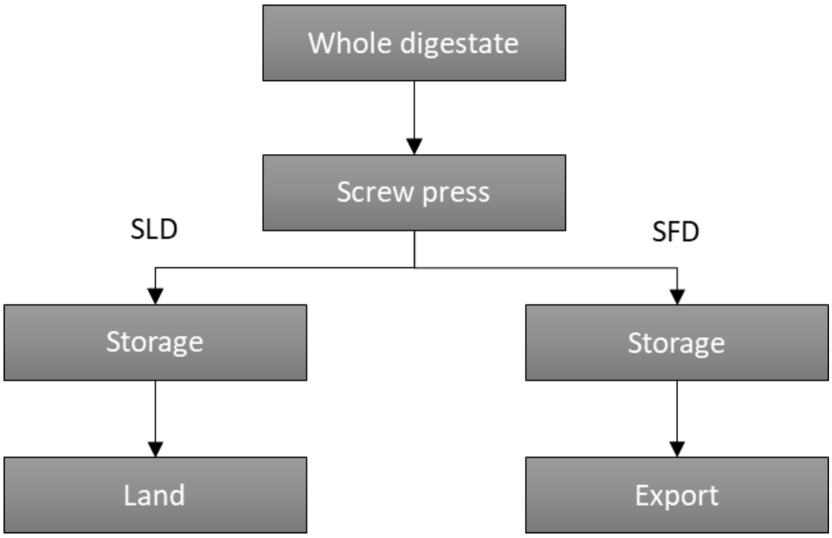
Figure 6 Process flow for valorisation archetype 4



Archetype 5

In this simple example, separated fibre digestate from a farm AD plant is exported from the site and sold for amenity use as a soil improver.

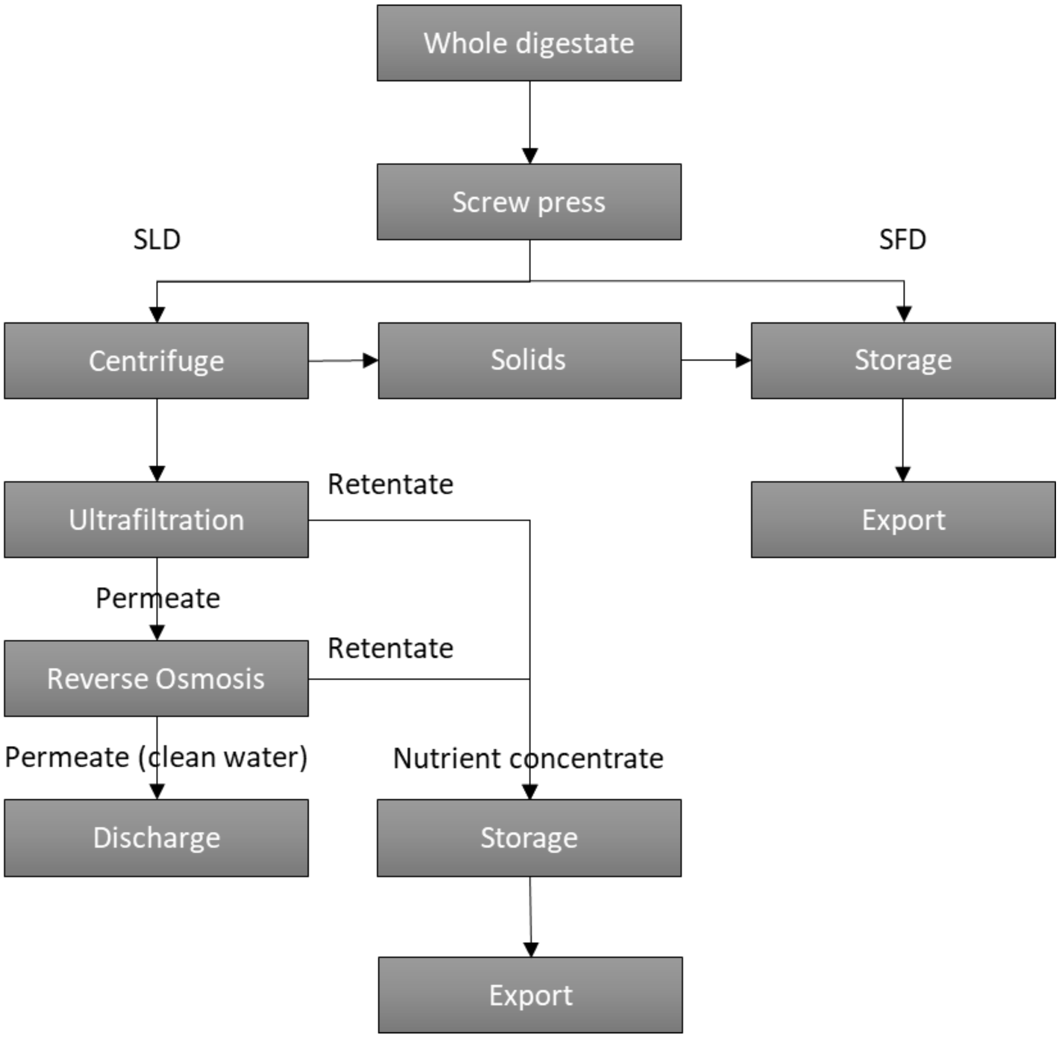
Figure 7 Process flow for valorisation archetype 5



Archetype 6

The objective of this scenario is to illustrate a solution that produces nutrient concentrate and fibre for sale into amenity markets off farm. Residual liquors are treated sufficiently to allow their safe discharge to the environment.

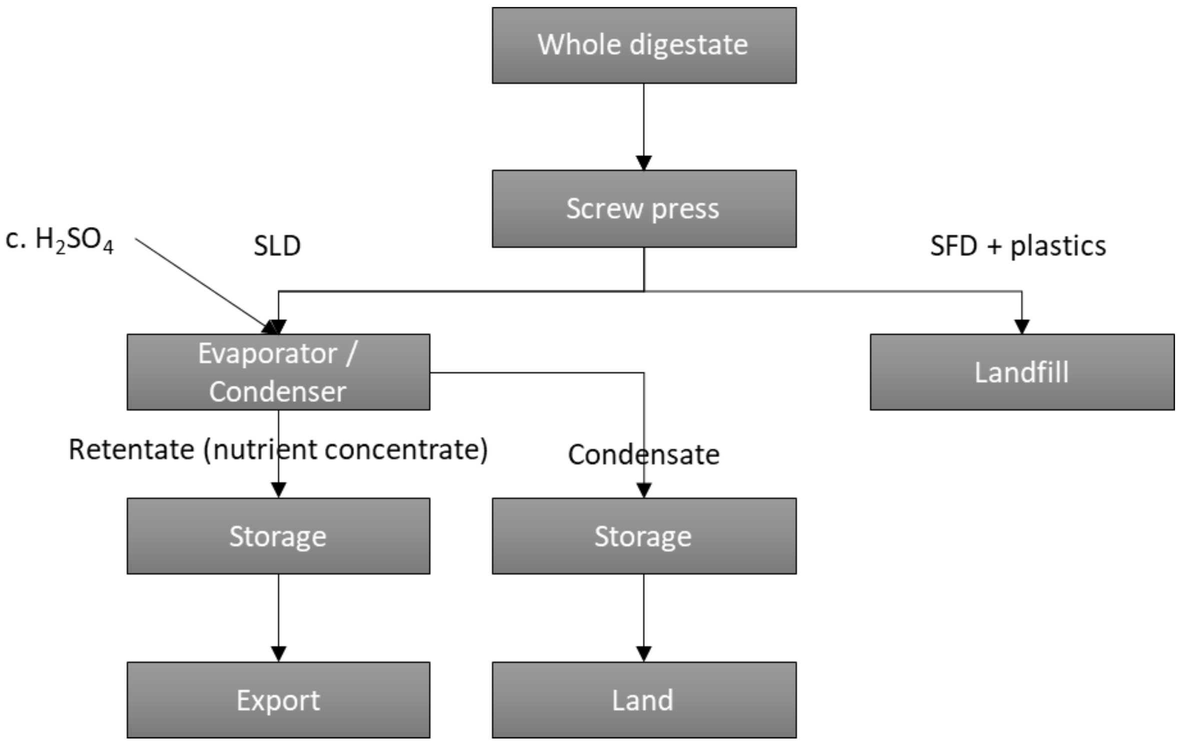
Figure 8 Process flow for valorisation archetype 6



Archetype 7

This scenario considers a commercial AD plant with limited access to a landbank, wishing to sell a nutrient concentrate to domestic customers. In contrast with the similar farm scenario (which relies on membrane separation) this scenario uses evaporation to concentrate a pre-acidified liquor digestate. Condensation liquors still require export and application to land as controlled wastes.

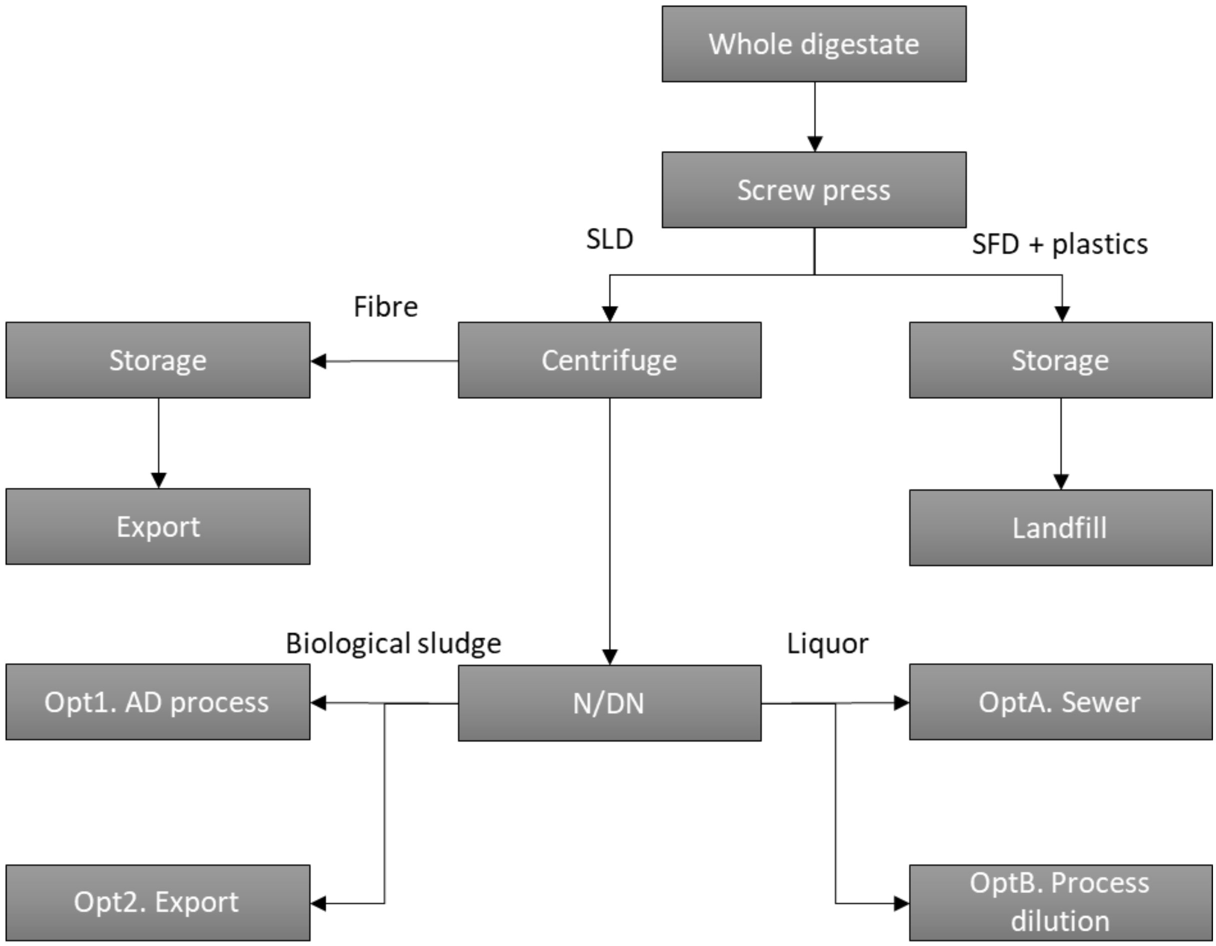
Figure 9 Process flow for valorisation archetype 7



Archetype 8

This final scenario considers a situation where a food AD plant has limited landbank and rather than treat liquor digestate to a point suitable for environmental discharge instead treats it to a point at which it could be discharged to the public sewer or used for feedstock / process dilution. A small quantity of clean digestate fibre could be sold for amenity use. The addition of a nitrification / denitrification step will generate a biological sludge that can either be returned to the AD process or exported for land application as a controlled waste.

Figure 10 Process flow for valorisation archetype 8



6.0 Technoeconomic modelling

6.1 Approach

Two separate models have been produced as part of this project: the mitigation model and the valorisation model. Both models were designed together and although intended to deliver different outputs, share many commonalities in approach and data.

The mitigation model focuses on the abatement of ammonia, methane, and plastic, modelling the level of abatement and associated costs of various abatement technologies. The main outputs of the mitigation model are the costs per kg abatement, cost per tonne of digestate, and cost per MWh of energy generated. This is done for small, medium, and large AD plants using commercial or farm inputs for whole digestate, separated liquor, or separated fibre. It should be noted that not every technology can be measured for all factors, for example, plastic mitigation is only done on commercial AD plants.

The valorisation model focuses on the valorisation of digestate, modelling the costs and/or revenues associated with various processing scenarios. The main outputs of the 'valorisation model' are the net cost per tonne of digestate treated, net cost per MWh of energy generated, and revenue or saving from the valorisation process as well as the CAPEX and OPEX of the various valorisation process blocks. Since valorisation techniques may not be universally applicable to all types of AD system modelling has been performed for small AD plants only using commercial or farm inputs for whole digestate, separated liquor, or separated fibre. The objective of this model is to illustrate the potential of various pre-defined valorisation archetypes to meet specified outcomes.

The main purpose of the models is to provide estimates for the outputs mentioned above for a set of predetermined and programmed inputs (e.g., the outputs at set small, medium, and large plants using a technology or process with predetermined values), these outputs then form the basis of the recommendations within this report. The ability of the models to adapt to changing inputs and model outputs from a variety of different inputs, (for example a reduced OPEX cost for a specific technology on the assumption that mass adoption would drive down costs), is not the primary purpose of the models. It is possible for both models to be changed in this way and for different figures to be entered but care should be taken when changing input values to ensure the model still works as intended. The following sections provide a brief guide on the structure of the model and how changes might be made, if desired.

Costs, abatements and valorisations are compared to a baseline and only represent the change in these factors not the total system costs. This means that if a cost is imposed by a certain technology, such as the additional cost of spreading acidified digestate to land, only the additional cost is included i.e. only the extra cost incurred by the spreading of acidified digestate is included not the total cost. Baseline costs are taken to be 0 as the model is only looking at changes in costs but in some cases baseline costs or abatements did have to be calculated to enable the difference to be calculated.

6.2 Baseline data used for mitigation technology modelling

The tables below set out the common data used across the modelling exercises for ammonia, methane and plastic mitigation technologies. All data was generated through the REA process and peer reviewed by the project team. All data is referenced to a relevant source which may include commercial suppliers. In a very limited number of cases expert judgement has been applied to develop assumptions that all scenarios to be completed. These are identified.

Table 3: Common data used across the modelling exercise

							Source
	Whole		Sep. liquor		Sep. fibre		WRAP calculation
	Commercial	Farm	Commercial	Farm	Commercial	Farm	
Tonnes of digestate	42,706	115,209	29,894	80,646	12,812	34,563	
	74,023	199,695	51,816	139,787	22,207	59,909	
	170,822	460,836	119,576	322,585	51,247	138,251	

		kWh / tonne (fresh)	**Nm^3CH_4 / tonne**	**tonne biogas / tonne**	**tonne digestate / tonne input**	**Source**
Feedstock energy yields	Food waste	1,100	110	0.22	0.78	THE DEPARTMENT FOR ENERGY SECURITY & NET ZERO (2021) and DEFRA (*pers comm*)
	Energy crop	642	64	0.13	0.87	
	Manure mix	376	38	0.08	0.92	
	Wet manure	124	12	0.03	0.97	

Farm plant digestate characteristics		**Dry matter (%)**	**N-total (kg/t fresh weight)**	**NH_4-N (kg/t fresh weight)**	**Source**
	Whole digestate	5.5	3.6	2.88	AHDB, 2021
	Separated liquor	3	1.9	1.52	
	Separated fibre	24	5.6	4.48	
Commercial plant		**Dry matter (%)**	**N-total (kg/t fresh weight)**	**NH_4-N (kg/t fresh weight)**	**Source**

digestate characteristics	Whole digestate	4.1	4.8	3.84	AHDB, 2021
	Separated liquor	3.8	4.5	3.6	
	Separated fibre	27	8.9	7.12	

Total N per year (kg)	**Whole**		**Sep. liquor**		**Sep fibre**		WRAP calculation using plant digestate characteristics
	Commercial	Farm	Commercial	Farm	Commercial	Farm	
	204,987	414,752	134,523	153,228	114,024	193,551	
	355,310	718,904	233,172	265,595	197,641	335,488	
	819,947	1,659,008	538,090	612,911	456,096	774,204	

Commercial plant Nm^3 of CH_4 per year	Small	6,044,400	WRAP calculation based on energy yields and feedstock types / volumes
	Medium	10,476,960	
	Large	24,177,600	
Farm plant Nm^3 of CH_4 per year	Small	6,044,400	
	Medium	10,476,960	
	Large	24,177,600	

Reduction of ammonia loss during storage using a floating cover			60%	Misselbrook & Gilhespy, 2021
Reduction of ammonia loss during application with trailing hose (Whole digestate and separated liquor)			30%	Misselbrook & Gilhespy, 2021
Reduction of ammonia loss during spreading of separated fibre			23%	Misselbrook & Gilhespy, 2021
Methane loss during storage of whole digestate			12%	Baldé et al., 2016
Methane loss during storage of separated liquor			0.782 Nm^3 CH_4 lost over one year per m^3 stored	Holly et al., 2017 and Maldaner et al., 2018
Methane loss during storage of separated fibre			20.770 Nm^3 CH_4 lost over one year per m^3 stored	Dinuccio, Berg & Bulsari, 2008
Costs for spreading digestates as wastes			£15	Supplier data
Cost of spreading for digestates as non-waste	WD	SLD	SFD	Marinari, 2019
	£3.00/t	£2.35 /t	£ 3.75/t	
Capital cost of baseline covered tank storage			£61.24 per m^3	Assumed 50% uplift on cost of uncovered stores as listed by Beattie, 2021

Depth of tanks used to store whole and separated liquor digestates	15m	Permastore[6]

6.3 Sensitivity analysis variables – mitigation model

A sensitivity analysis was conducted for each mitigation model and is reported in Sections 7.1.1 to 7.3.1. This was broken down by mitigation technologies with different factors being analysed for each with some degree of crossover. The sensitivity analysis was conducted to understand where the model is particularly sensitive to the factors or assumptions used as well as to highlight areas where change may make a technology more or less appealing. The following factors were considered: nitrogen and ammonia content, acid costs, acid use, acidification system price, energy prices, heat costs, storage costs, digestate offtake costs, feedstock mix, stripping and scrubbing removal efficiency (ammonia), nitrification/denitrification removal efficiency (ammonia), and plastic removal efficiency.

Feedstock selection has a direct impact on biogas yields from AD plants. We have assumed that commercial plants process 100% food waste, while farm plants derive 50% of their energy from crops and 50% from a mixture of livestock manures. Energy yields for each these materials are taken from the Department for Energy Security & Net Zero publications. Those same publications include alternative energy yields for 'wet manure', which are much lower (on a feedstock unit basis) and would require much larger AD plants to deliver equivalent biogas outputs – and produce much larger quantities of digestate. AD plants will not be able to claim support under the Green Gas Support Scheme if they derive >50% of their energy from purpose-grown crops. The following were explored in sensitivity analysis:

- 50% energy from crops + 50% from 'wet manure'
- 100% energy from 'manure mix'
- 100% energy from 'wet manure'

Data for total N contents of digestate are currently taken from RB209 (AHDB, 2020). Totals are converted to ammonium-N contents on the assumption that NH_4-N = 80% of N-total. This assumption is taken from (Misselbrook & Gilhespy, 2021) as it is used in calculating national ammonia emissions from agricultural activities.

Alternative data for total N contents of digestate were compiled from industry datasets[7]. These are for UK digestates that are part of the Biofertiliser Certification Scheme, and provide realistic ranges for total N. The categorisation (farm and waste) is broadly similar to that used for this project, and the farm categories have been merged to give the broadest ranges. These are converted to NH_4-N using the conversion outline above. Based on WRAP data, the amount of NH_4-N in digestate as a percentage of N-total can vary from 60 to 85% (Taylor et al., 2011) – providing a further factor for sensitivity analysis. Although the WRAP data were for whole

[6] https://www.permastore.com/wp-content/uploads/2021/02/P123-Rev-3-Series-1400-Slurry-Tank-Capacity-Chart-Nominal-Volume-m3.pdf
[7] https://www.realresearchhub.org.uk/research-projects/project-2

digestates, sensitivity explores the same approach for all digestate forms to give the ranges set out in Table 4 and Table 5.

Table 4 Ammoniacal nitrogen ranges, assuming that NH4-N = 60% of N-total, presented as min to max ranges on a kg per tonne fresh weight basis

NH_4-N	Whole Digestates	SLD	SFD
Farm	2.28 to 5.46	1.26 to 5.76	2.82 to 18
Commercial	1.56 to 7.08	0.48 to 5.7	3.3 to 40.74

Table 5 Ammoniacal nitrogen ranges, assuming that NH4-N = 85% of N-total, presented as min to max ranges on a kg per tonne fresh weight basis

NH_4-N	Whole Digestates	SLD	SFD
Farm	3.23 to 7.735	1.785 to 8.16	3.995 to 25.5
Commercial	2.21 to 10.03	0.686 to 8.075	4.675 to 57.715

Sulphuric acid (98% concentrated) costs were taken from a public forum[8] as £750 per tonne for virgin acid and £110 per tonne for 'second user' acid. In the absence of better data, virgin acid was compared to second user acid in the sensitivity analysis.

We have used supplier data to derive a rate of acid use in field (2.5L of 98% H_2SO_4 per m^3 of whole or liquor digestate), which delivers a relatively modest 25% reduction in ammonia emissions. Data for acidification in store use 16L of acid to deliver an 82% reduction in ammonia. Neither of these scenarios differentiates between the effects on whole and liquor digestates, although it is reasonable to assume that less acid would be required to deliver equivalent mitigation in liquor digestates when compared with whole digestates.

The data here are not robust, as acidification is not commercially applied to digestates. For the sensitivity analysis 5L acid per m^3 digestate were used in field, and 10L acid per m^3 digestate used in store. This compares with 2.5L in field and 16L in store used within the mitigation model. For alum acidification a dose of 130kg per tonne of separated fibre digestate was used in the sensitivity analysis as compared with 200kg per tonne in the mitigation model.

A single unit cost has been used for the acid storage + dosing system for all plant sizes and types in the model (£125k). This is based on data that are >10 years old, and we know from more recent data that prices for these systems can be as low as €10k (with an example from the UK case study of £35k). Given these uncertainties, a key output from sensitivity analysis is to understand whether this unit price is significant when compared with the OPEX for in store acidification using the lowest found CAPEX.

Wholesale electricity are taken from public Ofgem data[9]. This has been volatile over the past year. We assumed £100 per MWh for electricity. Prices peaked at £241 per MWh for electricity in December 2021. Recent February 2022 prices were modelled as extremes in the sensitivity

[8] https://thefarmingforum.co.uk/index.php?threads/covering-slurry-lagoons-good-thing-or-not.298461/page-4
[9] https://www.ofgem.gov.uk/energy-data-and-research/data-portal/wholesale-market-indicators

analysis. These are set out and converted to pence per kWh for both energy types in Table 6. Gas prices were also considered but had no impact within the model.

Table 6 Potential ranges for energy prices

Wholesale electricity	Feb 2022	172	£ per MWh	17.2	pence per kWh
	Modelled	100	£ per MWh	10.0	pence per kWh
	Dec 2021	241	£ per MWh	24.1	pence per kWh

A single unit price to purchase a boiler to provide heat was also used in the model. To understand whether the price of the boiler is relevant in comparison with the price of operating it a boiler of two times the cost was tested in sensitivity analysis.

In the absence of direct supplier feedback, we have assumed that a gas-tight store cover will cost 50% more than the equivalent non-gas-tight baseline (a tent cover on a storage tank). This assumption was not available for verification during our stakeholder workshop (Appendix 8:) and direct contacts with suppliers of storage solutions were not fruitful. The main cost differential between gas-tight and non-gas-tight covers is expected to relate to infrastructure associated with gas management, rather than the cover mechanism itself. In the absence of direct supplier feedback, a 25% and 100% cost differential between gas-tight and baseline storage was used in the sensitivity analysis. The impact of using a slurry bag for storage instead, at a cost of £31 per m^3, was also considered.

We assumed a basic offtake cost of £15 per m^3 (or tonne) for digestates. This was based on our industry experience and prior project work. For sensitivity analysis this was altered to £20 and £40 per tonne, as this reflects the range of costs incurred by livestock farmers for removal of their manures in other parts of N Europe.

We have assumed 90% efficiency (for removal of ammonia from digestate and recovery as ammonium sulphate solution). The literature illustrate a wide variance in this – with one source stating efficiency as low as 31%. Efficiency will be linked to a number of aspects (physical qualities of digestate, pH to which it is corrected and temperature to which it is increased before stripping etc). For illustrative purposes a value of 50% was used in the sensitivity analysis.

Data for nitrification (only) efficiency are scarce, as these systems aren't typically used. There is a significant aeration cost to nitrify ammonium, and it makes little agronomic sense to convert the forms of nitrogen in this way as crops will either absorb ammonium directly or the soil biology will perform the nitrification conversion at no cost. These systems are instead intended to be combined with denitrification phases which complete conversion from ammonium to nitrogen gas as a way of reducing subsequent nitrogen loadings to land. For illustrative purposes a nitrification (only) process efficiency of 50% was used in the sensitivity analysis compared to the 64% in the mitigation model.

Denitrification is also challenging, since the process requires a source of readily available carbon. We are assuming that this is coming from the digestate itself (which is why these systems are often designed with the denitrification reactor coming before the nitrification reactor), but available data show how variable the performance of these systems can be (47%

to 95% removal of NH_4-N). Again a 50% process efficiency was used in the sensitivity analysis for illustrative purposes.

We know that efficiencies of screw presses (and other similar 'separators') can vary hugely with respect to plastic removal. Trial data from one supplier varied between 60% and 100% removal. For the sensitivity analysis two factors were varied to test the impact on plastic removal:

- 95% efficiency of removal during digestate screening
- 50% efficiency of removal during digestate screening
- 95% efficiency of removal during depackaging

7.0 Mitigation technology modelled data sheets

7.1 Mitigation of ammonia losses from digestate

7.1.1 Stripping and Scrubbing of ammonia from digestate

Figure 11 Process flow diagram for stripping of whole digestate

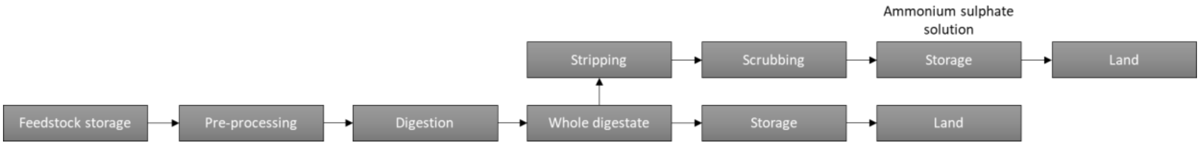
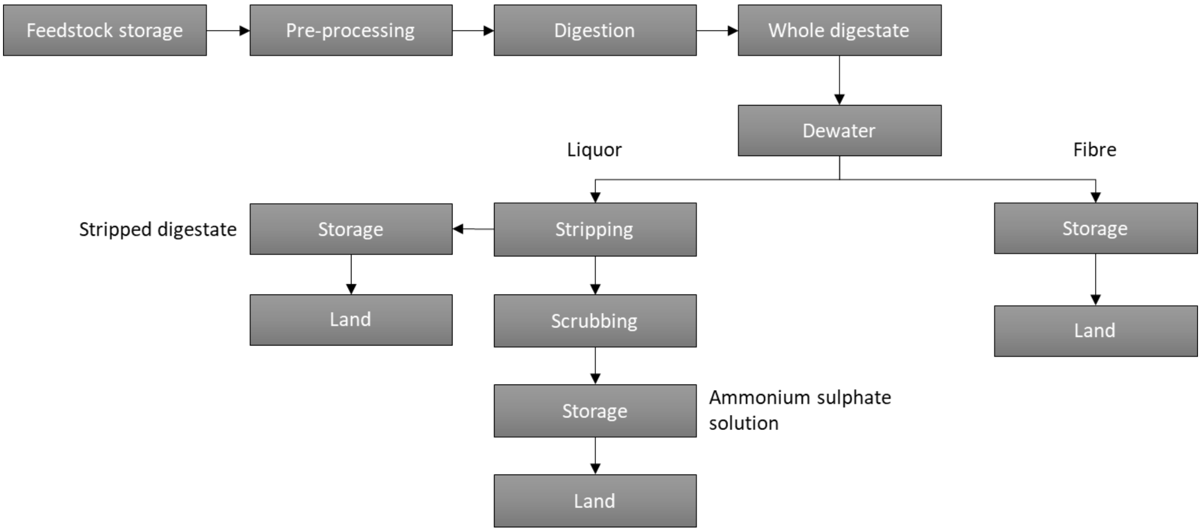


Figure 12 Process flow diagram for stripping of separated liquor



Model approach/process description

Stripping and scrubbing have been modelled for whole digestate and separated liquor. The modelling has two parts: the cost modelling and the abatement modelling. For the cost modelling, only additional costs incurred by the use of the stripping and scrubbing technology have been included. These additional costs are:

- Technology CAPEX
- Technology OPEX
- Heating CAPEX
- Heating OPEX
- Ammonium sulphate storage CAPEX
- Ammonium sulphate spreading OPEX

Costs have been modelled the above for small, medium, and large commercial and farm AD plants across their lifetime of 20 years. For the CAPEX it is assumed that the initial funding is borrowed and paid off over the lifetime of the plant at an interest rate of 2%. The total CAPEX and the OPEX over the 20 years are then combined and used to produce a single annualised cost.

For the abatement modelling the amount of ammonia abated annually using the stripping and scrubbing technology and is compared to the amount of ammonia abated in the baseline. The difference is then taken as the additional abatement due to the use of the stripping and scrubbing technology. The baseline abatement is calculated by estimating the amount of ammonia lost in the storage and spreading to land of whole digestate and separated liquor. The stripping and scrubbing abatement is estimated by calculating the amount of ammonia lost through the application of the ammonium sulphate and stripped digested produced to land, as well as what is lost in storage.

Table 7: Table of model parameters and units

Data	Figure	Source
Nitrogen removal rate for stripping and scrubbing	90% removal efficiency	Menkeld & Broeders, 2018, Bolzonella et al., 2018, and Fangueiro et al., 2017b
Operation costs for stripping and scrubbing	£1.47 per kg N	Menkeld & Broeders, 2018 and van Eekert et al., 2012
Operation costs for heat	£0.40 per kg N	Menkveld & Broeders, 2018
Operation costs for spreading ammonium sulphate	£14.16 per hectare	Farm management handbook 2021/22 (Beattie, 2021)
Capital costs for stripping and scrubbing	Whole: Food / Farm; Sep. liquor: Food / Farm £794,408 / £1,271,534 / £634,132 / £676,678 £1,136,329 / £1,963,348 / £858,518 / £932,265 £2,193,178 / £4,101,682 / £1,552,075 / £1,722,261	Calculated from the amount of nitrogen stripped and scaled using Verbeke, Van Dijk & Brienza, 2021
Capital costs for heat	£41,320 boiler reference price (scaled by plant size and type)	Supplier data
Capital costs for ammonium sulphate storage	£61.24 per m^3 of storage	Assumed 50% uplift on cost of uncovered stores as listed by Beattie, 2021

TRL: 9; Tier 1 Technology (farm)
Data Quality: **High (separated liquor digestates)**; **Medium (whole digestates).**
Confidence is high for CAPEX data but medium for OPEX, since the latter can be impacted by factors that include: quantities of caustic soda used for pH correction in digestate prior to stripping, quantities of acid used for scrubbing, costs to maintain the scrubbing bed, costs to heat the digestate. Confidence is also high for performance when applied to liquor digestates, but medium to low when applied to whole digestates,

the latter containing suspended solids that buffer pH changes and alter the rheology of the material.

Regulatory Complexity: Red. The technique produces an ammonium sulphate solution which is likely to be classified as a waste and need to be stored and used as such. The stripped digestate will have a different hazard profile to those underpinning end of waste or other deregulatory positions and may therefore remain a waste and need to be stored and used as such. Where recovered from digestates derived from manures (whether in whole or part) the ammonium sulphate will remain classified as a manure and NVZ restrictions will apply. It is possible that ABPR restrictions might also apply to the ammonium sulphate solution, particularly when derived from commercial digestates. Readers should contact their local environmental regulator and/or APHA representative to discuss their intentions

Pollution Swapping potential: Amber. Potential for acidification in some soils through extended use of ammonium sulphate (can be mitigated by liming); Process requires additional infrastructure and consumables, including heat.

Table 8 Modelled costs for stripping and scrubbing for small, medium, and large commercial and farm plants.

Plant type	Plant Size	Cost per tonne of:			Cost per Mwh of:			Cost per kg of ammoniacal nitrogen abated for:		
		WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
Commercial	S	£10.04	£10.39	-	£7.09	£5.14	-	£11.11	£12.28	-
	M	£9.78	£10.04	-	£6.91	£4.97	-	£10.83	£11.86	-
	L	£9.59	£9.76	-	£6.77	£4.83	-	£10.61	£11.53	-
Farm	S	£7.31	£4.06	-	£13.93	£5.42	-	£10.79	£11.36	-
	M	£7.21	£3.93	-	£13.74	£5.24	-	£10.64	£10.99	-
	L	£7.13	£3.82	-	£13.60	£5.10	-	£10.53	£10.69	-

Model sensitivity considerations

A sensitivity analysis was conducted for the stripping and scrubbing mitigation technology. This consisted of:

- The high and low range of ammoniacal nitrogen assuming that NH4-N = 60% of N-total. For whole digestate and separated liquor (commercial and farm)
- The high and low range of ammoniacal nitrogen assuming that NH4-N = 85% of N-total. For whole digestate and separated liquor (commercial and farm)
- An increase in the cost of a boiler by two times. For whole digestate and separated liquor (commercial and farm)
- Digestate offtake costs of £20 and £40. For whole digestate and separated liquor (commercial and farm)
- Stripping and scrubbing ammonia removal efficiency of 31% and 50%. For whole digestate and separated liquor (commercial and farm)

- Farm feedstock mix of 50% energy from crops + 50% from 'wet manure'. For whole digestate and separated liquor (farm)
- Farm feedstock mix of 100% energy from 'manure mix'. For whole digestate and separated liquor (farm), and
- Farm feedstock mix, 100% energy from 'wet manure'. For whole digestate and separated liquor (farm)

Results are presented for each of the different sensitivity factors considered and compared to the overall results from the model itself (Table 9).

Table 9 Stripping and scrubbing - Sensitivity analysis results

Sensitivity factor	Plant type	Size	£ per tonne digestate			£ per MWh			£ per kg of ammoniacal nitrogen abated		
			WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
Core model output:	**C**	**S**	**10.04**	**10.39**	**-**	**7.09**	**5.14**	**-**	**11.11**	**12.28**	**-**
NH4-N, 60%N, low, (kg/t fresh weight)	C	S	10.04	10.39	-	7.09	5.14	-	27.35	92.06	-
NH4-N, 60%N, high, (kg/t fresh weight)	C	S	10.04	10.39	-	7.09	5.14	-	6.03	7.75	-
NH4-N, 85%N, low, (kg/t fresh weight)	C	S	10.04	10.39	-	7.09	5.14	-	19.31	64.42	-
NH4-N, 85%N, high, (kg/t fresh weight)	C	S	10.04	10.39	-	7.09	5.14	-	4.25	5.47	-
2 x baseline boiler price	C	S	10.08	10.44	-	7.12	5.16	-	11.16	12.33	-
£20 offtake cost	C	S	10.04	10.39	-	7.09	5.14	-	11.11	12.28	-
£40 offtake cost	C	S	10.04	10.39	-	7.09	5.14	-	11.11	12.28	-
31% NH_3 removal efficiency	C	S	3.86	4.15	-	2.73	2.05	-	12.41	14.22	-
50% NH_3 removal efficiency	C	S	5.85	6.16	-	4.13	3.05	-	11.66	13.09	-
Core model output:	**F**	**S**	**7.31**	**4.06**	**-**	**13.93**	**5.42**	**-**	**10.79**	**11.36**	**-**
NH4-N, 60%N, low, (kg/t fresh weight)	F	S	7.31	4.06	-	13.93	5.42	-	13.62	13.71	-
NH4-N, 60%N, high, (kg/t fresh weight)	F	S	7.31	4.06	-	13.93	5.42	-	5.69	3.00	-
NH4-N, 85%N, low, (kg/t fresh weight)	F	S	7.31	4.06	-	13.93	5.42	-	9.62	9.67	-
NH4-N, 85%N, high, (kg/t fresh weight)	F	S	7.31	4.06	-	13.93	5.42	-	4.02	2.12	-
2 x baseline boiler price	F	S	7.34	4.09	-	13.99	5.46	-	10.83	11.45	-
£20 offtake cost	F	S	7.31	4.06	-	13.93	5.42	-	10.79	11.36	-
£40 offtake cost	F	S	7.31	4.06	-	13.93	5.42	-	10.79	11.36	-
50% energy from crops + 50% from 'wet manure'	F	S	7.18	3.88	-	31.60	11.96	-	10.59	10.86	-
100% energy from 'manure mix'	F	S	7.26	4.00	-	17.32	6.68	-	10.72	11.18	-
100% energy from 'wet manure'	F	S	7.14	3.83	-	51.62	19.37	-	10.54	10.70	-
31% NH_3 removal efficiency	F	S	2.68	1.62	-	5.10	2.16	-	11.47	13.14	-
50% NH_3 removal efficiency	F	S	4.17	2.41	-	7.94	3.21	-	11.07	12.11	-

The changes to digestate offtake costs have no impact on the results, this is because the changes in the model and the baseline are the same so there is no additional cost incurred by the mitigation technology. The increased boiler price has a negligible effect on the results.

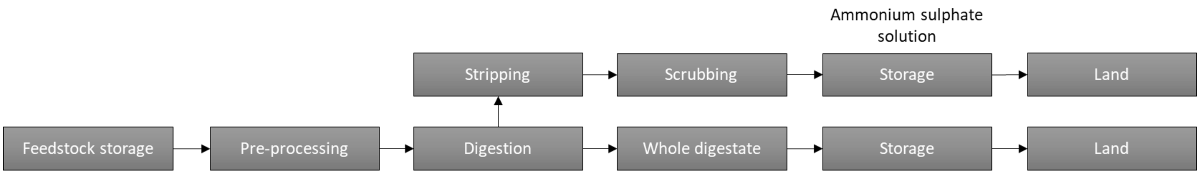
The changes to ammoniacal nitrogen content of digestate have a considerable impact on the £ per kg of ammoniacal nitrogen abated; there is no impact on the £ per tonne digestate or £ per MWh factors. The £ per kg of ammoniacal nitrogen abated for commercial separated liquor using the high end of the range assuming that NH_4-N = 60% of N-total is 7.5 times the modelled value. The £ per kg of ammoniacal nitrogen abated for farm separated liquor using the low end of the range assuming that NH_4-N = 85% of N-total is just under 20% of the modelled value. This highlights that the level of ammoniacal nitrogen in commercial and farm digestate is a key area of sensitivity in the model though the commercial plants are more sensitive than the farm plants.

Changes in the removal efficiency are also another key area of sensitivity. Decreases in the removal efficiency decrease CAPEX and OPEX costs, and therefore the £ per tonne digestate and £ per MWh, as the reduced amount of nitrogen removed decreased both of these costs in the model. However, despite the decreased CAPEX and OPEX costs the £ per kg of ammoniacal nitrogen abated actually increased by just over 15% for farm and commercial separated liquor because the decreased costs do not fully offset the reduction in ammoniacal nitrogen abated.

Changes in the farm feedstock mix also had a significant impact on the results though in all cases for £ per tonne digestate and £ per kg of ammoniacal nitrogen abated this was a fairly small decrease, for £ per MWh the effect was significant with large increases for all considered variables especially where 100% wet manure was used which increased by over three times the modelled value.

7.1.2 Side Stripping at 40% of digester volume

Figure 13 Process flow diagram for side-stream stripping / scrubbing of whole digestate



Model approach/process description

The modelling for side stripping follows a similar approach to stripping and scrubbing, since it uses the same technology on a circuit connected to the digestion vessel, removing and recovering a proportion of ammonia to manage digester biology. The only difference is that results for small, medium, and large commercial and plant farms are scaled by 40% to represent that side stripping only accounts for a fraction of the total digestate input. See Section 7.1.1 for further details.

Table 10: Table of model parameters and units

<table>
<tr><th>Data</th><th colspan="2">Figure</th><th>Source</th></tr>
<tr><td>Side stripping</td><td colspan="2">40% of whole digestate processed</td><td>Brienza et al., 2020</td></tr>
<tr><td>Operation costs for striping and scrubbing</td><td colspan="2">£1.47 per kg N</td><td>Menkeld & Broeders, 2018 and van Eekert et al., 2012</td></tr>
<tr><td>Operation costs for heat</td><td colspan="2">£0.40 per kg N</td><td>Menkveld & Broeders, 2018</td></tr>
<tr><td>Operation costs for ammonia sulphate spreading</td><td colspan="2">£14.16 per hectare</td><td>(Beattie, 2021)</td></tr>
<tr><td rowspan="5">Capital costs for striping and scrubbing</td><td colspan="2">Whole</td><td rowspan="5">Calculated from the amount of nitrogen stripped and scaled using Verbeke, Van Dijk & Brienza, 2021</td></tr>
<tr><td>Commercial</td><td>Farm</td></tr>
<tr><td>£514,654</td><td>£705,504</td></tr>
<tr><td>£651,422</td><td>£1,054,905</td></tr>
<tr><td>£1,074,162</td><td>£2,005,276</td></tr>
<tr><td>Capital costs for heat</td><td colspan="2">£41,320 boiler reference price (scaled by plant size and type)</td><td>Supplier data</td></tr>
<tr><td>Capital costs for ammonium sulphate storage</td><td colspan="2">£61.24 per m^3 of storage</td><td>Assumed 50% uplift on cost of uncovered stores as listed by Beattie, 2021</td></tr>
</table>

TRL: 9; Tier 1 Technology (farm)

Data Quality: Low. When used for side stripping there are considerable uncertainties around sizing and performance, although the latter is expected to be lower than for whole or liquor digestates since the organic nitrogen within the digester will only be partially mineralised (and therefore potentially available for scrubbing)

Regulatory Complexity: Red. The technique produces an ammonium sulphate solution which is likely to be classified as a waste and need to be stored and used as such. Since the technique is used as an AD process aid, the partially-stripped digestate may still comply with end of waste or other deregulatory positions. Where recovered from digestates derived from manures (whether in whole or part) the ammonium

sulphate will remain classified as a manure and NVZ restrictions will apply. It is possible that ABPR restrictions might also apply to the ammonium sulphate solution, particularly when derived from commercial digestates. Readers should contact their local environmental regulator and/or APHA representative to discuss their intentions
Pollution Swapping potential: Amber. Potential for acidification in some soils through extended use of ammonium sulphate (can be mitigated by liming); Process requires additional infrastructure and consumables, including heat

Table 11: Modelled costs for side stripping at 40% for small, medium, and large commercial and farm plants.

Plant type	Plant Size	Cost per tonne of:			Cost per Mwh of:			Cost per kg of ammoniacal nitrogen abated for:		
		WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
Commercial	S	£3.98	-	-	£2.81	-	-	£11.02	-	-
	M	£3.73	-	-	£2.64	-	-	£10.34	-	-
	L	£3.54	-	-	£2.50	-	-	£9.81	-	-
Farm	S	£2.93	-	-	£5.59	-	-	£10.82	-	-
	M	£3.15	-	-	£6.00	-	-	£11.61	-	-
	L	£3.08	-	-	£5.86	-	-	£11.35	-	-

Model sensitivity considerations

A sensitivity analysis was conducted for the side stripping mitigation technology. This consisted of:

- The high and low range of ammoniacal nitrogen assuming that NH_4-N = 60% of N-total. For whole digestate (commercial and farm)
- The high and low range of ammoniacal nitrogen assuming that NH_4-N = 85% of N-total. For whole digestate (commercial and farm)
- An increase in the cost of a boiler by two times. For whole digestate (commercial and farm)
- Digestate offtake costs of £20 and £40. For whole digestate (commercial and farm)
- Stripping and scrubbing nitrogen removal efficiency of 31% and 50%. For whole digestate (commercial and farm)
- Farm feedstock mix of 50% energy from crops + 50% from 'wet manure'. For whole digestate (farm)
- Farm feedstock mix of 100% energy from 'manure mix'. For whole digestate (farm), and
- Farm feedstock mix, 100% energy from 'wet manure'. For whole digestate (farm)

Results are presented for each of the different sensitivity factors considered and compared to the overall results from the model itself (Table 12).

Table 12 Side stripping - Sensitivity analysis results

Sensitivity factor	Plant type	Size	£ per tonne digestate			£ per MWh			£ per kg of ammoniacal nitrogen abated		
			WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
Core model output:	C	S	3.98	-	-	2.81	-	-	11.02	-	-
NH4-N, 60%N, low, (kg/t fresh weight)	C	S	3.98	-	-	2.81	-	-	27.12	-	-
NH4-N, 60%N, high, (kg/t fresh weight)	C	S	3.98	-	-	2.81	-	-	5.97	-	-
NH4-N, 85%N, low, (kg/t fresh weight)	C	S	3.98	-	-	2.81	-	-	19.14	-	-
NH4-N, 85%N, high, (kg/t fresh weight)	C	S	3.98	-	-	2.81	-	-	4.22	-	-
2 x baseline boiler price	C	S	4.00	-	-	2.83	-	-	11.07	-	-
£20 offtake cost	C	S	3.88	-	-	2.74	-	-	10.74	-	-
£40 offtake cost	C	S	3.48	-	-	2.46	-	-	9.63	-	-
31% NH_3 removal efficiency	C	S	1.56	-	-	1.10	-	-	12.54	-	-
50% NH_3 removal efficiency	C	S	2.34	-	-	1.65	-	-	11.66	-	-
Core model output:	F	S	2.93	-	-	5.59	-	-	10.82	-	-
NH4-N, 60%N, low, (kg/t fresh weight)	F	S	2.93	-	-	5.59	-	-	13.67	-	-
NH4-N, 60%N, high, (kg/t fresh weight)	F	S	2.93	-	-	5.59	-	-	5.71	-	-
NH4-N, 85%N, low, (kg/t fresh weight)	F	S	2.93	-	-	5.59	-	-	9.65	-	-
NH4-N, 85%N, high, (kg/t fresh weight)	F	S	2.93	-	-	5.59	-	-	4.03	-	-
2 x baseline boiler price	F	S	2.94	-	-	5.61	-	-	10.87	-	-
£20 offtake cost	F	S	2.93	-	-	5.59	-	-	10.82	-	-
£40 offtake cost	F	S	2.93	-	-	5.59	-	-	10.82	-	-
50% energy from crops + 50% from 'wet manure'	F	S	2.81	-	-	12.36	-	-	10.36	-	-
100% energy from 'manure mix'	F	S	2.89	-	-	6.89	-	-	10.66	-	-
100% energy from 'wet manure'	F	S	2.77	-	-	20.04	-	-	10.22	-	-
31% NH_3 removal efficiency	F	S	1.12	-	-	2.13	-	-	11.98	-	-
50% NH_3 removal efficiency	F	S	1.70	-	-	3.24	-	-	11.31	-	-

The results for side stripping are very similar to the results for stripping and scrubbing but do not cover separated liquor as the side stripping process is only for whole digestate. The changes to digestate offtake costs have no impact on any of the results, this is because the changes in the model and the baseline are the same so there is no additional cost incurred by the mitigation technology. The increased boiler price has a negligible effect on the results.

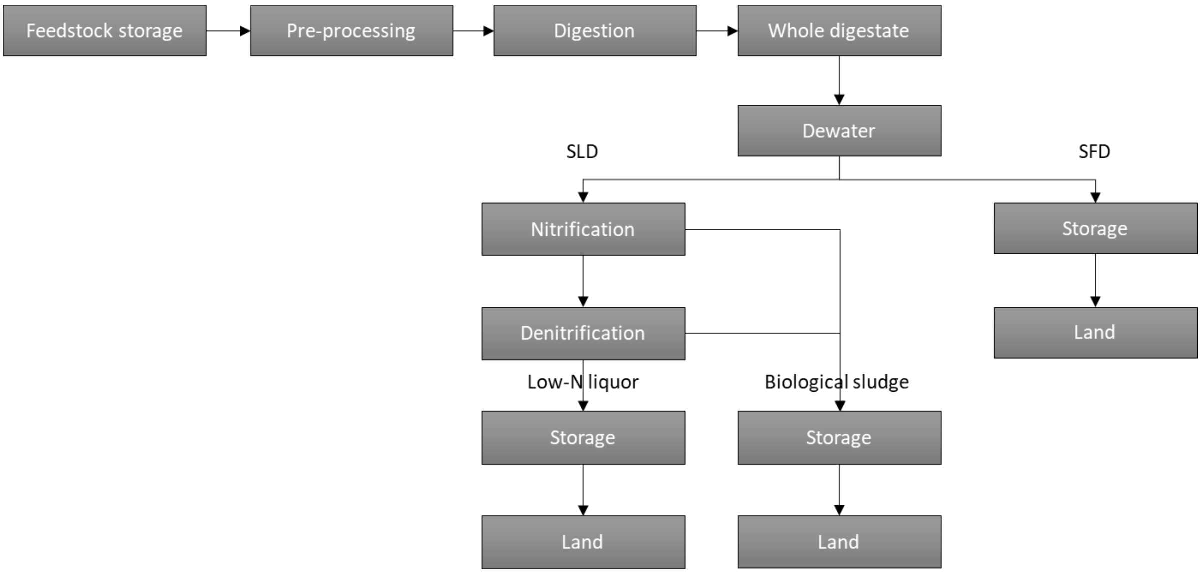
The changes to ammoniacal nitrogen have a considerable impact on the £ per kg of ammoniacal nitrogen abated, there is no impact on the £ per tonne digestate or £ per MWh factors. The £ per kg of ammoniacal nitrogen abated for commercial whole digestate using the high end of the range assuming that NH_4-N = 60% of N-total is almost 2.5 times the modelled value. The £ per kg of ammoniacal nitrogen abated for farm whole digestate using the low end of the range assuming that NH_4-N = 85% of N-total is under 40% of the modelled value. This highlights that the level of ammoniacal nitrogen in digestate is a key area of sensitivity in the model.

Changes in the removal efficiency are also another key area of sensitivity. Decreases in the removal efficiency decrease CAPEX and OPEX costs, and therefore the £ per tonne digestate and £ per MWh, as the reduced amount of nitrogen removed decreased both of these costs in the model. However, despite the decreased CAPEX and OPEX costs the £ per kg of ammoniacal nitrogen abated actually increased by over 10% for farm whole digestate because the decreased costs do not fully offset the reduction in ammoniacal nitrogen abated.

Changes in the farm feedstock mix also had a significant impact on the results though in all cases for £ per tonne digestate and £ per kg of ammoniacal nitrogen abated this was a fairly small decrease, for £ per MWh the effect was significant with large increases for all considered variables especially where 100% wet manure was used which increased by over three times the modelled value.

7.1.3 Nitrification / Denitrification

Figure 14 Process flow diagram for nitrification / denitrification of separated liquor



Model approach/process description
Nitrification & denitrification has been modelled for separated liquor, and includes cost modelling and abatement. For the cost modelling, only additional costs incurred by the use of the nitrification & denitrification technology have been included. These additional costs are:

- Technology CAPEX

- Technology OPEX
- Biological sludge disposal costs

The total by cost has been calculated by modelling the above for small, medium, and large commercial and farm AD plants across their lifetime of 20 years. For the CAPEX it is assumed that the initial funding is borrowed and paid off over the lifetime of the plant at an interest rate of 2%. The total CAPEX and the OPEX over the 20 years are then combined and used to produce a single annual cost for nitrification & denitrification.

The baseline abatement is calculated by estimating the amount of ammonia lost in the storage and spreading to land of separated liquor. The nitrification & denitrification abatement is estimated by calculating the amount of ammonia lost through the application of the low N liquor to land as well as what is lost in storage after the nitrification & denitrification process has occurred (removing much of the nitrogen and therefor ammonia). N_2O production is also calculated, to inform the qualitative assessment of pollution swapping

Table 13: Table of model parameters and units

Data	Figure	Source
NH4 removal rate for nitrification and denitrification	89.5% reduction in NH4	Foged et al., 2011, Melse & Verdoes, 2005, García-González, 2016, and Finzi et al., 2020
Operation costs for nitrification and denitrification	£3.73 per m3 of digestate	DeVrieze et al., 2019
Capital costs for nitrification and denitrification	£15 per m3 of digestate to be processed annually	DeVrieze et al., 2019
Biological sludge production by nitrification and denitrification	15% of treated volume	Hoeksma, Mosquera & Melse, 2012
Sludge disposal costs	£15 per m3	Supplier data
N2O production by nitrification and denitrification (not modelled)	During nitrification / denitrification 9% of input total nitrogen is lost as N2O	Willers et al., 1996

Model outputs

TRL: 9; Tier 1 Technology (farm)
Data Quality: **Medium.** Process cost data are from commercial sources. Performance data are drawn from literature on pig slurry treatment and may not therefore be fully representative of performance with digestates
Regulatory Complexity: **Red.** This technique is already integrated into some commercial AD processes, with the denitrified liquor further treated before use as a feedstock diluent. Where the denitrified liquor is intended for use on land, this technique may be considered a further treatment for digestate, causing it to fall outside the scope of current end of waste or other deregulatory positions and return to waste

status. The denitrified liquor is likely to remain an animal by-product and its use will have to comply with ABPR restrictions. Readers should contact their local environmental regulator and/or APHA representative to discuss their intentions

Pollution Swapping potential: Red. Potential for N_2O emissions from both the nitrification and denitrification stages. Since nitrogen is a key limiter on digestate application rates, use of denitrified digestate may encourage overapplication of phosphorus (or other nutrients)

Table 14: Modelled costs for Nitrification / Denitrification for small, medium, and large commercial and farm plants.

Plant type	Plant Size	Cost per tonne of:			Cost per Mwh of:			Cost per kg of ammoniacal nitrogen abated for:		
		WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
Commercial	S	-	£7.09	-	-	£3.51	-	-	£6.64	-
	M	-	£7.09	-	-	£3.51	-	-	£6.64	-
	L	-	£7.09	-	-	£3.51	-	-	£6.64	-
Farm	S	-	£7.09	-	-	£9.47	-	-	£15.72	-
	M	-	£7.09	-	-	£9.47	-	-	£15.72	-
	L	-	£7.09	-	-	£9.47	-	-	£15.72	-

Model sensitivity considerations

A sensitivity analysis was conducted for the nitrification and denitrification mitigation technology. This consisted of:

- The high and low range of ammoniacal nitrogen assuming that NH_4-N = 60% of N-total. For separated liquor (commercial and farm)
- The high and low range of ammoniacal nitrogen assuming that NH_4-N = 85% of N-total. For separated liquor (commercial and farm)
- The use of February 2022 wholesale electricity prices at 17.2 pence per kWh. For separated liquor (commercial and farm)
- Digestate offtake costs of £20 and £40. For separated liquor (commercial and farm)
- Nitrification and denitrification process efficiency of 50%. For separated liquor (commercial and farm)
- Farm feedstock mix of 50% energy from crops + 50% from 'wet manure'. For separated liquor (farm)
- Farm feedstock mix of 100% energy from 'manure mix'. For separated liquor (farm), and
- Farm feedstock mix, 100% energy from 'wet manure'. For separated liquor (farm)

Results are presented for each of the different sensitivity factors considered and compared to the overall results from the model itself (Table 15).

Table 15 Nitrification and denitrification - Sensitivity analysis results

Sensitivity factor	Plant type	Size	£ per tonne digestate			£ per MWh			£ per kg of ammoniacal nitrogen abated		
			WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
Core model output:	C	S	-	7.09	-	-	3.51	-	-	6.64	-
NH4-N, 60%N, low, (kg/t fresh weight)	C	S	-	7.09	-	-	3.51	-	-	49.78	-
NH4-N, 60%N, high, (kg/t fresh weight)	C	S	-	7.09	-	-	3.51	-	-	4.19	-
NH4-N, 85%N, low, (kg/t fresh weight)	C	S	-	7.09	-	-	3.51	-	-	34.83	-
NH4-N, 85%N, high, (kg/t fresh weight)	C	S	-	7.09	-	-	3.51	-	-	2.96	-
February 2022 wholesale electricity prices at 17.2 pence per kWh	C	S	-	8.17	-	-	4.04	-	-	7.65	-
£20 offtake cost	C	S	-	7.84	-	-	3.88	-	-	7.34	-
£40 offtake cost	C	S	-	10.84	-	-	5.36	-	-	10.15	-
50 % reduction in NH_3	C	S	-	7.09	-	-	3.51	-	-	12.04	-
Core model output:	F	S	-	7.09	-	-	9.47	-	-	15.72	-
NH4-N, 60%N, low, (kg/t fresh weight)	F	S	-	7.09	-	-	9.47	-	-	18.96	-
NH4-N, 60%N, high, (kg/t fresh weight)	F	S	-	7.09	-	-	9.47	-	-	4.15	-
NH4-N, 85%N, low, (kg/t fresh weight)	F	S	-	7.09	-	-	9.47	-	-	13.39	-
NH4-N, 85%N, high, (kg/t fresh weight)	F	S	-	7.09	-	-	9.47	-	-	2.93	-
February 2022 wholesale electricity prices at 17.2 pence per kWh	F	S	-	8.17	-	-	10.91	-	-	18.11	-
£20 offtake cost	F	S	-	7.84	-	-	10.47	-	-	17.38	-
£40 offtake cost	F	S	-	10.84	-	-	14.47	-	-	24.03	-
50% energy from crops + 50% from ‘wet manure’	F	S	-	7.09	-	-	21.86	-	-	15.72	-
100% energy from ‘manure mix’	F	S	-	7.09	-	-	11.85	-	-	15.72	-
100% energy from ‘wet manure’	F	S	-	7.09	-	-	35.92	-	-	15.72	-
50 % reduction in NH_3	F	S	-	7.09	-	-	9.47	-	-	28.52	-

As the offtake costs increase the sludge disposal costs also increase. In the model this impact is identical for commercial and farm plants.

The use of higher wholesale energy prices also has an impact, increasing costs by around 15% when using 17.2 pence per kWh, again this impact is the same for commercial and farm plants.

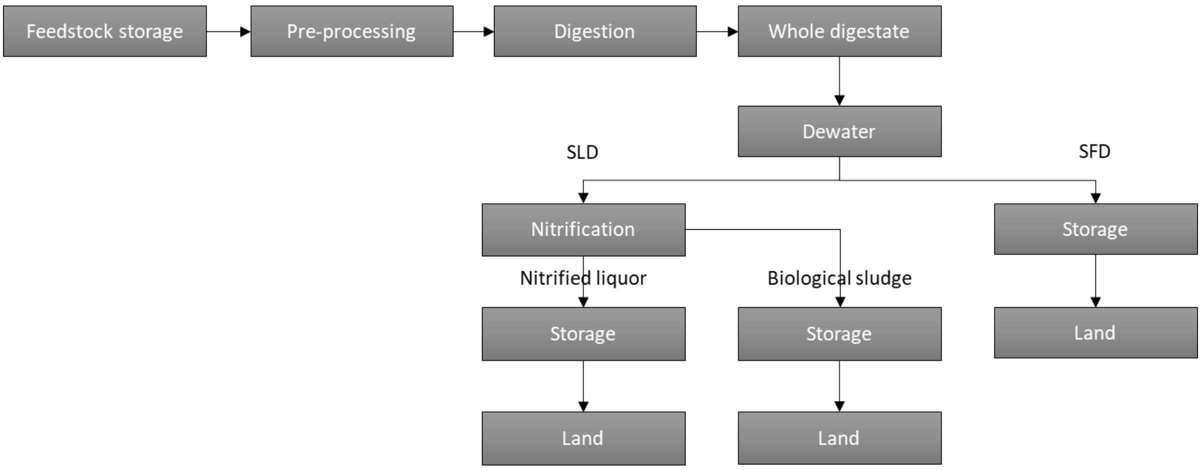
The changes to ammoniacal nitrogen have a considerable impact on the £ per kg of ammoniacal nitrogen abated, there is no impact on the £ per tonne digestate or £ per MWh factors. The £ per kg of ammoniacal nitrogen abated for commercial separated liquor using the high end of the range assuming that NH_4-N = 60% of N-total is 7.5 times the modelled value. The £ per kg of ammoniacal nitrogen abated for commercial separated liquor using the low end of the range assuming that NH_4-N = 85% of N-total is just under 20% of the modelled value. This highlights that the level of ammoniacal nitrogen in commercial and farm digestate is a key area of sensitivity in the model though the commercial plants are more sensitive than the farm plants.

Changes in ammonia removal efficiency are also another key area of sensitivity. Changes in the removal efficiency have no impact on the £ per tonne digestate and £ per MWh, unlike the stripping and scrubbing technology. However, the £ per kg of ammoniacal nitrogen abated still increases by over 80% for farm and commercial separated liquor as the CAPEX and OPEX remains unchanged but the amount of ammoniacal nitrogen removed in the process decreases.

Changes in the farm feedstock mix also had a significant impact on the £ per MWh. In all cases there was no impact on the £ per tonne digestate and £ per kg of ammoniacal nitrogen abated. For £ per MWh the effect was significant with a 3.7 times increase for 100% wet manure but all variations recorded an increase.

7.1.4 Nitrification only

Figure 15 Process flow diagram for nitrification of separated liquor



Model approach/process description
Nitrification has been modelled for separated liquor, and includes both costs and abatement, as well as quantification of nitrate, nitrite and nitrous oxide production. For the cost modelling, only additional costs incurred by the use of the nitrification technology over and above the baseline have been included. These additional costs are:

- Technology CAPEX
- Technology OPEX
- Sludge disposal costs

The total by cost has been calculated by modelling the above for small, medium, and large commercial and farm AD plants across their lifetime of 20 years. For the CAPEX it is assumed that the initial funding is borrowed and paid off over the lifetime of the plant at an interest rate of 2%. The total CAPEX and the OPEX over the 20 years are then combined and used to produce a single annual cost.

For the abatement modelling, the amount of ammonia abated annually using the nitrification technology is compared to the amount of ammonia abated in the baseline. The baseline abatement is calculated by estimating the amount of ammonia lost in storage and spreading to land of separated liquor. The nitrification abatement is estimated by subtracting the amount of ammonia still lost through the application of the low N liquor to land as well as what is still lost in storage after the nitrification process has occurred. NO_3^- (and NO_2^-) and N_2O production are calculated, with these data informing the qualitative assessment of pollution swapping.

Table 16: Table of model parameters and units

Data	Figure	Source
NH4 removal rate for nitrification	64% reduction in NH4	Foged et al., 2011
Operation costs for nitrification	£2.65 per m3 of digestate	Supplier data
Capital costs for nitrification	£5.41 per m3 of digestate to be processed annually	Supplier data
Biological sludge production by nitrification	15% of treated volume	Hoeksma, Mosquera & Melse, 2012
Sludge disposal costs	£15 per m3	Supplier data
NO2 and NO3 production by nitrification (not modelled)	During nitrification, 0.28kg NH4 produces 0.05kg NO3 and 0.05kg NO2 per tonne	Willers et al., 1996
N2O production by nitrification (not modelled)	During nitrification / denitrification 9% of input total nitrogen is lost as N2O	Willers et al., 1996

TRL: 9; Tier 1 Technology (farm)
Data Quality: **Medium.** Process cost data are from commercial sources. Performance data are drawn from literature on pig slurry treatment and may not therefore be fully representative of performance with digestates
Regulatory Complexity: **Red.** This technique may be considered a further treatment for digestate, causing it to fall outside the scope of current end of waste or other deregulatory positions and return to waste status. The nitrified liquor is likely to remain an animal by-product and its use will have to comply with ABPR restrictions. Readers should contact their local environmental regulator and/or APHA representative to discuss their intentions
Pollution Swapping potential: **Red.** Potential for N_2O emissions from nitrification, nitrate (and any residual) nitrite in digestate may be prone to leaching if nitrified digestate is inappropriately used

Table 17: Modelled costs for Nitrification for small, medium, and large commercial and farm plants.

Plant type	Plant Size	Cost per tonne of:			Cost per Mwh of:			Cost per kg of ammoniacal nitrogen abated for:		
		WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
Commercial	S	-	£5.30	-	-	£2.62	-	-	£6.98	-
	M	-	£5.30	-	-	£2.62	-	-	£6.98	-
	L	-	£5.30	-	-	£2.62	-	-	£6.98	-
Farm	S	-	£5.30	-	-	£7.07	-	-	£16.53	-
	M	-	£5.30	-	-	£7.07	-	-	£16.53	-
	L	-	£5.30	-	-	£7.07	-	-	£16.53	-

Model sensitivity considerations

A sensitivity analysis was conducted for the nitrification only mitigation technology. This consisted of the same sensitivity factors as nitrification and denitrification:

- The high and low range of ammoniacal nitrogen assuming that NH_4-N = 60% of N-total. For separated liquor (commercial and farm)
- The high and low range of ammoniacal nitrogen assuming that NH_4-N = 85% of N-total. For separated liquor (commercial and farm)
- The use of February 2022 wholesale electricity prices at 17.2 pence per kWh. For separated liquor (commercial and farm)
- Digestate offtake costs of £20 and £40. For separated liquor (commercial and farm)
- Nitrification and denitrification process efficiency of 50%. For separated liquor (commercial and farm)
- Farm feedstock mix of 50% energy from crops + 50% from 'wet manure'. For separated liquor (farm)
- Farm feedstock mix of 100% energy from 'manure mix'. For separated liquor (farm), and
- Farm feedstock mix, 100% energy from 'wet manure'. For separated liquor (farm)

Results are presented for each of the different sensitivity factors considered and compared to the overall results from the model itself (Table 18).

Table 18 Nitrification only - Sensitivity analysis results

Sensitivity factor	Plant type	Size	£ per tonne digestate			£ per MWh			£ per kg of ammoniacal nitrogen abated		
			WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
Core model output:	C	S	-	5.30	-	-	2.62	-	-	6.98	-
NH4-N, 60%N, low, (kg/t fresh weight)	C	S	-	5.30	-	-	2.62	-	-	52.33	-
NH4-N, 60%N, high, (kg/t fresh weight)	C	S	-	5.30	-	-	2.62	-	-	4.41	-
NH4-N, 85%N, low, (kg/t fresh weight)	C	S	-	5.30	-	-	2.62	-	-	36.62	-
NH4-N, 85%N, high, (kg/t fresh weight)	C	S	-	5.30	-	-	2.62	-	-	3.11	-
February 2022 wholesale electricity prices at 17.2 pence per kWh	C	S	-	5.89	-	-	2.91	-	-	7.76	-
£20 offtake cost	C	S	-	6.05	-	-	2.99	-	-	7.97	-
£40 offtake cost	C	S	-	9.05	-	-	4.47	-	-	11.92	-
50 % reduction in NH_3	C	S	-	5.30	-	-	2.62	-	-	8.99	-
Core model output:	F	S	-	5.30	-	-	7.07	-	-	16.53	-
NH4-N, 60%N, low, (kg/t fresh weight)	F	S	-	5.30	-	-	2.62	-	-	52.33	-
NH4-N, 60%N, high, (kg/t fresh weight)	F	S	-	5.30	-	-	7.07	-	-	4.36	-
NH4-N, 85%N, low, (kg/t fresh weight)	F	S	-	5.30	-	-	7.07	-	-	14.07	-
NH4-N, 85%N, high, (kg/t fresh weight)	F	S	-	5.30	-	-	7.07	-	-	3.08	-
February 2022 wholesale electricity prices at 17.2 pence per kWh	F	S	-	5.89	-	-	7.86	-	-	18.37	-
£20 offtake cost	F	S	-	6.05	-	-	8.07	-	-	18.87	-
£40 offtake cost	F	S	-	9.05	-	-	12.07	-	-	28.22	-
50% energy from crops + 50% from 'wet manure'	F	S	-	5.30	-	-	16.33	-	-	16.53	-
100% energy from 'manure mix'	F	S	-	5.30	-	-	8.85	-	-	16.53	-
100% energy from 'wet manure'	F	S	-	5.30	-	-	26.82	-	-	16.53	-
50 % reduction in NH_3	F	S	-	5.30	-	-	7.07	-	-	21.29	-

The changes to digestate offtake costs impacts on each of the results, which increase by more than 70% using a £40 value, this is because as the offtake costs increase the sludge disposal costs also increase. In the model the impact is identical for commercial and farm plants.

The use of higher wholesale energy prices also has an impact on each of the costs, which increase by around 11% when using 17.2 pence per kWh. Again this impact is the same for commercial and farm plants.

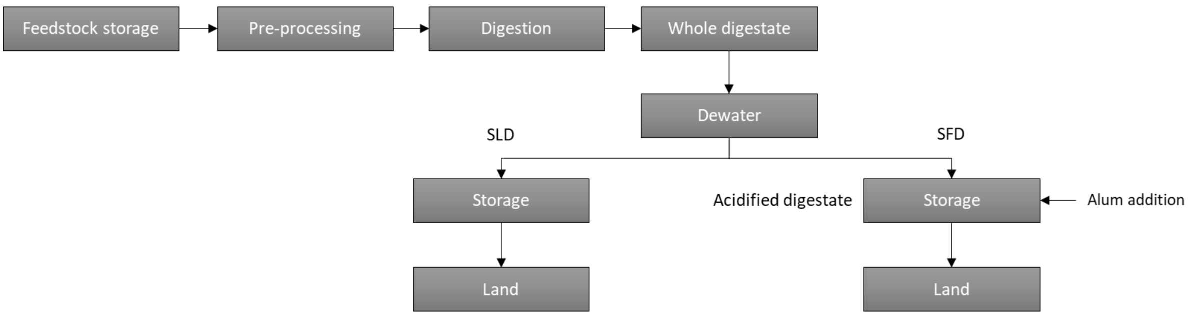
The changes to ammoniacal nitrogen have a considerable impact on the £ per kg of ammoniacal nitrogen abated, there is no impact on the £ per tonne digestate or £ per MWh factors. The £ per kg of ammoniacal nitrogen abated for commercial separated liquor using the high end of the range assuming that NH_4-N = 60% of N-total is 7.5 times the modelled value. The £ per kg of ammoniacal nitrogen abated for commercial separated liquor using the low end of the range assuming that NH_4-N = 85% of N-total is just under 20% of the modelled value. This highlights that the level of ammoniacal nitrogen in commercial and farm digestate is a key area of sensitivity in the model though the commercial plants are more sensitive than the farm plants.

Changes in the removal efficiency are also another area of sensitivity. Changes in the removal efficiency have no impact on the £ per tonne digestate and £ per MWh. However, the £ per kg of ammoniacal nitrogen abated increases by almost 30% for farm and commercial separated liquor as the CAPEX and OPEX remains unchanged but the amount of ammoniacal nitrogen removed in the process decreases. This is lower for nitrification only than nitrification and denitrification because whilst the same value of 50% is used for both in the sensitivity analysis, nitrification and denitrification has a higher process efficiency.

Changes in the farm feedstock mix also had a significant impact on the £ per MWh. In all cases there was no impact on the £ per tonne digestate and £ per kg of ammoniacal nitrogen abated. For £ per MWh the effect was significant with a 3.7 times increase for 100% wet manure but all variations recorded an increase.

7.1.5 Acidification – Alum

Figure 16 Process flow diagram for alum treatment of separated fibre



Model approach/process description

Alum acidification has been modelled for separated fibre, and includes both cost and abatement. For the cost modelling, only additional costs incurred by the use of the alum over and above the baseline have been included. These additional costs are:

- Technology OPEX

There is no technology CAPEX modelled for alum treatment since the technique is relatively simple (requiring that alum powder be mixed with fibre digestate fibre using a front end loader – which it assumed that the site will already have available). OPEX therefore dominates the model, and particularly the cost of the alum itself. The total by cost has been calculated by modelling the above for small, medium, and large commercial and farm AD plants across their lifetime of 20 years. The OPEX over the 20 years are used to produce a single annual cost for alum treatment.

For the abatement modelling, the amount of ammonia abated annually using alum treatment is compared to the amount of ammonia abated in the baseline. The difference is then taken as the additional abatement due to the use of the alum. The baseline abatement is calculated by estimating the amount of ammonia lost in the storage and spreading to land of separated fibre. The alum acidification abatement considers ammonia lost through the application of the acidified fibre to land as well as that lost in storage.

Table 19: Table of model parameters and units

Data	Figure	Source
Ammonia abatement	98% reduction	Regueiro et al., 2016, Buckley et al., 2020, Moore et al., 1996, and Eugene et al., 2015
Price of alum powder	£300 per tonne	Kavanagh et al., 2019
Required dose	200 kg per tonne of fibre	Regueiro et al., 2016, Buckley et al., 2020, Moore et al., 1996, and Eugene et al., 2015
Mixing and labour costs	£1.50 per tonne fibre	Supplier data
Operation costs of alum acidification	£61.50 per tonne fibre	Combination of the price of alum, required dose, and mixing and labour costs

TRL: 9 on farm plants, **TRL** 7 on commercial plants; Tier 2 Technology (farm)
Data Quality: Low. This technique is not commercially applied to fibre digestates, and data on both costs and performance are based on poultry litter, as the best available analogue
Regulatory Complexity: Amber. This technique may be considered a further treatment for digestate, causing it to fall outside the scope of current end of waste or other deregulatory positions and return to waste status. Readers should contact their local environmental regulator to discuss their intentions
Pollution Swapping potential: Amber. Potential for acidification of some soils through extended use of this technique, which can be mitigated through liming; Possible short term localised impacts on earthworms and other soil fauna through application of acidified digestates

Table 20: Modelled costs for Acidification (Alum) for small, medium, and large commercial and farm plants.

Plant type	Plant Size	Cost per tonne of:			Cost per Mwh of:			Cost per kg of ammoniacal nitrogen abated for:		
		WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
Commercial	S	-	-	£61.50	-	-	£13.04	-	-	£27.98
	M	-	-	£61.50	-	-	£13.04	-	-	£27.98
	L	-	-	£61.50	-	-	£13.04	-	-	£27.98
Farm	S	-	-	£61.50	-	-	£35.17	-	-	£44.47
	M	-	-	£61.50	-	-	£35.17	-	-	£44.47
	L	-	-	£61.50	-	-	£35.17	-	-	£44.47

Model sensitivity considerations

A sensitivity analysis was conducted for the acidification alum technology. This consisted of:

- The high and low range of ammoniacal nitrogen assuming that NH_4-N = 60% of N-total. For separated fibre (commercial and farm)
- The high and low range of ammoniacal nitrogen assuming that NH_4-N = 85% of N-total. For separated fibre (commercial and farm)
- Digestate offtake costs of £20 and £40. For separated fibre (commercial and farm)
- A dose of 130kg of alum per tonne of separated fibre digestate. For separated fibre (farm)
- Farm feedstock mix of 50% energy from crops + 50% from 'wet manure'. For separated fibre (farm)
- Farm feedstock mix of 100% energy from 'manure mix'. For separated fibre (farm), and
- Farm feedstock mix, 100% energy from 'wet manure'. For separated fibre (farm)

Results are presented for each of the different sensitivity factors considered and compared to the overall results from the model itself (Table 21).

Table 21 Acidification alum - Sensitivity analysis results

Sensitivity factor	Plant type	Size	£ per tonne digestate			£ per MWh			£ per kg of ammoniacal nitrogen abated		
			WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
Core model output:	C	S	-	-	61.50	-	-	13.04	-	-	27.98
NH4-N, 60%N, low, (kg/t fresh weight)	C	S	-	-	61.50	-	-	13.04	-	-	60.37
NH4-N, 60%N, high, (kg/t fresh weight)	C	S	-	-	61.50	-	-	13.04	-	-	4.89
NH4-N, 85%N, low, (kg/t fresh weight)	C	S	-	-	61.50	-	-	13.04	-	-	42.61
NH4-N, 85%N, high, (kg/t fresh weight)	C	S	-	-	61.50	-	-	13.04	-	-	3.45

Sensitivity factor	Plant type	Size	£ per tonne digestate			£ per MWh			£ per kg of ammoniacal nitrogen abated		
			WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
£20 offtake cost	C	S	-	-	61.50	-	-	13.04	-	-	27.98
£40 offtake cost	C	S	-	-	61.50	-	-	13.04	-	-	27.98
130kg alum dose	C	S	-	-	40.50	-	-	8.58	-	-	18.43
Core model output:	F	S	-	-	61.50	-	-	35.17	-	-	44.47
NH4-N, 60%N, low, (kg/t fresh weight)	F	S	-	-	61.50	-	-	35.17	-	-	87.38
NH4-N, 60%N, high, (kg/t fresh weight)	F	S	-	-	61.50	-	-	35.17	-	-	11.07
NH4-N, 85%N, low, (kg/t fresh weight)	F	S	-	-	61.50	-	-	35.17	-	-	49.87
NH4-N, 85%N, high, (kg/t fresh weight)	F	S	-	-	61.50	-	-	35.17	-	-	7.81
£20 offtake cost	F	S	-	-	61.50	-	-	35.17	-	-	44.47
£40 offtake cost	F	S	-	-	61.50	-	-	35.17	-	-	44.47
50% energy from crops + 50% from 'wet manure'	F	S	-	-	61.50	-	-	81.23	-	-	44.47
100% energy from 'manure mix'	F	S	-	-	61.50	-	-	44.01	-	-	44.47
100% energy from 'wet manure'	F	S	-	-	61.50	-	-	133.45	-	-	44.47
130kg alum dose	F	S	-	-	40.50	-	-	23.16	-	-	29.28

The changes to digestate offtake costs have no impact on any of the results, this is because the changes in the model and the baseline are the same so there is no additional cost incurred by the mitigation.

The changes to ammoniacal nitrogen have a large impact on the £ per kg of ammoniacal nitrogen abated, there is no impact on the £ per tonne digestate or £ per MWh factors. The £ per kg of ammoniacal nitrogen abated for commercial separated fibre using the high end of the range assuming that NH_4-N = 60% of N-total is over 2 times the modelled value. The £ per kg of ammoniacal nitrogen abated for commercial separated fibre using the low end of the range assuming that NH_4-N = 85% of N-total is under 15% of the modelled value. This highlights that the level of ammoniacal nitrogen in commercial and farm digestate is a key area of sensitivity in the model. The commercial plants are more sensitive than the farm plants but both experience a high degree of change.

Changes in the alum dose are also another area of sensitivity. Changes in the alum dose impacts each of the factors by the same amount for both types of plant. At a (lower) dosage of 130kg per tonne of separated fibre the £ per tonne digestate, £ per MWh and £ per kg ammoniacal nitrogen abated all decreased by just under 35%. If the dosage increased to levels above the level in the model, there would be an increase instead.

Changes in the farm feedstock mix also had an impact on the £ per MWh. In all cases there was no impact on the £ per tonne digestate and £ per kg of ammoniacal nitrogen abated. For £ per MWh the effect was a 3.7 times increase for 100% wet manure but all variations recorded an increase (though lower than 100% wet manure).

7.1.6 Acidification – in field (mitigation of ammonia losses)

Figure 17 Process flow diagram for in field acidification of whole digestate

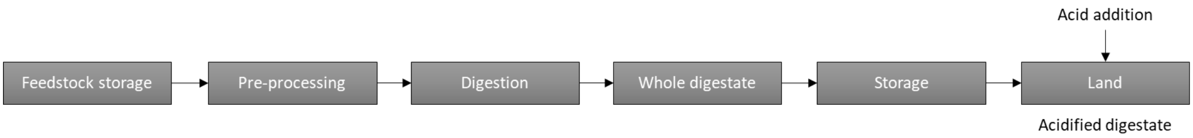
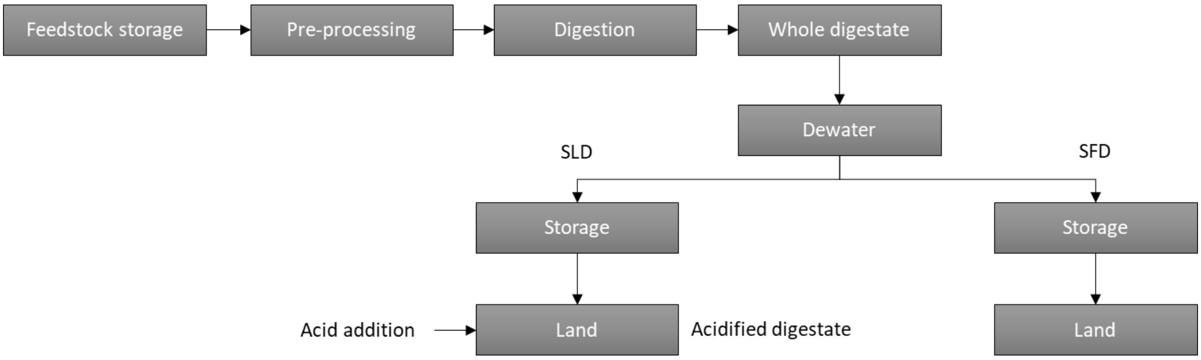


Figure 18 Process flow diagram for in field acidification of separated liquor



Model approach/process description

Field acidification has been modelled for whole digestate and separated liquor, the modelling for each including costs and abatement. Only additional costs incurred by the use of the acidification technology have been included. These additional costs are:

- Technology OPEX
- Acidified digestate spreading OPEX

There is no technology CAPEX modelled for field acidification because the solution involves hiring of bespoke equipment which is mounted onto digestate spreading systems. Hire costs and costs for the sulphuric acid mean that the model is OPEX-dominated. The total by cost has been calculated by modelling the above for small, medium, and large commercial and farm AD plants across their lifetime of 20 years. The OPEX over the 20 years are used to produce a single annual cost for field acidification.

For the abatement modelling, the amount of ammonia abated annually using the field acidification technology is compared to the amount of ammonia abated in the baseline. The difference is then taken as the additional abatement due to in field acidification. The baseline abatement is calculated by estimating the amount of ammonia lost in the storage and spreading to land of whole digestate and separated liquor. The field acidification abatement also considers ammonia lost through the application of the acidified digestate to land as well as that lost in storage.

Table 22: Table of model parameters and units

Data	Figure	Source
Ammonia abatement in application	25% reduction	Supplier data
Acidified digestate spreading cost	£20 per hectare	Supplier data
Acid requirements	2.5 litres per m^3 of digestate	Supplier data
Acid cost	£0.94 per litre	Farming Forum[10], 2019

TRL: 9 on farm plants, **TRL** 7 on commercial plants; Tier 1 Technology (farm)
Data Quality: **High.** Data have been moderated based on commercial feedback
Regulatory Complexity: **Amber.** This technique may be considered a further treatment for digestate, causing it to fall outside the scope of current end of waste or other deregulatory positions and return to waste status. Where 'second user' acid is used, this may further complicate the waste status of the digestate. Readers should contact their local environmental regulator to discuss their intentions
Pollution Swapping potential: **Amber.** Potential for acidification of some soils through extended use of this technique, which can be mitigated through liming; Possible short term localised impacts on earthworms and other soil fauna

Table 23: Modelled costs for acidification (field) for small, medium, and large commercial and farm plants.

Plant type	Plant Size	Cost per tonne of:			Cost per Mwh of:			Cost per kg of ammoniacal nitrogen abated for:		
		WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
Commercial	S	£2.91	£2.87	-	£2.05	£1.42	-	£10.62	£11.19	-
	M	£2.91	£2.87	-	£2.05	£1.42	-	£10.62	£11.19	-
	L	£2.91	£2.87	-	£2.05	£1.42	-	£10.62	£11.19	-
Farm	S	£2.77	£2.57	-	£5.27	£3.43	-	£13.47	£23.68	-
	M	£2.77	£2.57	-	£5.27	£3.43	-	£13.47	£23.68	-
	L	£2.77	£2.57	-	£5.27	£3.43	-	£13.47	£23.68	-

Model sensitivity considerations

A sensitivity analysis was conducted for the acidification in field technology. This consisted of:

- The high and low range of ammoniacal nitrogen assuming that NH_4-N = 60% of N-total. For whole digestate and separated liquor (commercial and farm)
- The high and low range of ammoniacal nitrogen assuming that NH_4-N = 85% of N-total. For whole digestate and separated liquor (commercial and farm)

[10] https://thefarmingforum.co.uk/index.php?threads/covering-slurry-lagoons-good-thing-or-not.298461/page-4

- Digestate offtake costs of £20 and £40. For whole digestate and separated liquor (commercial and farm)
- Acid use of 5L of per m^3 of digestate. For whole digestate and separated liquor (commercial and farm)
- Acid use of £110 per tonne of per tonne using second user acid. For whole digestate and separated liquor (commercial and farm)
- Farm feedstock mix of 50% energy from crops + 50% from 'wet manure'. For whole digestate and separated liquor (farm)
- Farm feedstock mix of 100% energy from 'manure mix'. For whole digestate and separated liquor (farm), and
- Farm feedstock mix, 100% energy from 'wet manure'. For whole digestate and separated liquor (farm)

Results are presented for each of the different sensitivity factors considered and compared to the overall results from the model itself (Table 24).

Table 24 Acidification (field) - Sensitivity analysis results

Sensitivity factor	Plant type	Size	£ per tonne digestate			£ per MWh			£ per kg of ammoniacal nitrogen abated		
			WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
Core model output:	C	S	**2.91**	**2.87**	**-**	**2.05**	**1.42**	**-**	**10.62**	**11.19**	**-**
NH4-N, 60%N, low, (kg/t fresh weight)	C	S	2.91	2.87	-	2.05	1.42	-	26.14	83.91	-
NH4-N, 60%N, high, (kg/t fresh weight)	C	S	2.91	2.87	-	2.05	1.42	-	5.76	7.07	-
NH4-N, 85%N, low, (kg/t fresh weight)	C	S	2.91	2.87	-	2.05	1.42	-	18.45	58.71	-
NH4-N, 85%N, high, (kg/t fresh weight)	C	S	2.91	2.87	-	2.05	1.42	-	4.06	4.99	-
£110 per tonne acid cost	C	S	0.91	0.87	-	0.64	0.43	-	3.32	3.40	-
5 litres of acid per m^3 digestate	C	S	5.25	5.22	-	3.71	2.58	-	19.17	20.31	-
£20 offtake cost	C	S	2.91	2.87	-	2.05	1.42	-	10.62	11.19	-
£40 offtake cost	C	S	2.91	2.87	-	2.05	1.42	-	10.62	11.19	-
Core model output:	F	S	**2.77**	**2.57**	**-**	**5.27**	**3.43**	**-**	**13.47**	**23.68**	**-**
NH4-N, 60%N, low, (kg/t fresh weight)	F	S	2.77	2.57	-	5.27	3.43	-	17.01	28.56	-
NH4-N, 60%N, high, (kg/t fresh weight)	F	S	2.77	2.57	-	5.27	3.43	-	7.10	6.25	-
NH4-N, 85%N, low, (kg/t fresh weight)	F	S	2.77	2.57	-	5.27	3.43	-	12.01	20.16	-
NH4-N, 85%N, high, (kg/t fresh weight)	F	S	2.77	2.57	-	5.27	3.43	-	5.02	4.41	-
£110 per tonne acid cost	F	S	0.77	0.57	-	1.46	0.76	-	3.73	5.23	-
5 litres of acid per m^3 digestate	F	S	5.11	4.91	-	9.74	6.55	-	24.88	45.29	-
£20 offtake cost	F	S	2.77	2.57	-	5.27	3.43	-	13.47	23.68	-
£40 offtake cost	F	S	2.77	2.57	-	5.27	3.43	-	13.47	23.68	-

Sensitivity factor	Plant type	Size	£ per tonne digestate			£ per MWh			£ per kg of ammoniacal nitrogen abated		
			WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
50% energy from crops + 50% from 'wet manure'	F	S	2.77	2.57	-	12.18	7.91	-	13.47	23.68	-
100% energy from 'manure mix'	F	S	2.77	2.57	-	6.60	4.29	-	13.47	23.68	-
100% energy from 'wet manure'	F	S	2.77	2.57	-	20.02	13.00	-	13.47	23.68	-

The changes to digestate offtake costs have no impact on any of the results, this is because the changes in the model and the baseline are the same so there is no additional cost incurred by the mitigation.

The changes to ammoniacal nitrogen have a large impact on the £ per kg of ammoniacal nitrogen abated, there is no impact on the £ per tonne digestate or £ per MWh factors. The £ per kg of ammoniacal nitrogen abated for commercial separated liquor using the high end of the range assuming that NH_4-N = 60% of N-total is over 7.5 times the modelled value. The £ per kg of ammoniacal nitrogen abated for farm separated liquor using the low end of the range assuming that NH_4-N = 85% of N-total is under 20% of the modelled value. This highlights that the level of ammoniacal nitrogen in commercial and farm digestate is a key area of sensitivity in the model.

Changes in the amount of acid used per m^3 of digestate is also another area of sensitivity. Changes in the acid use impacts each of the factors with whole digestate being impacted slightly less than separated liquor. At a usage of 5L per m^3 of digestate the £ per tonne digestate, £ per MWh and £ per kg ammoniacal nitrogen abated all increase by over 80% with farm plants having higher figures than commercial plants. The costs increase as the amount of acid used increased over the model if this decreased the costs would also decrease.

Changes in the cost of acid due also impacts each of the factors, with whole digestate being impacted slightly more than separated liquor. At a cost of £110 per tonne of acid the £ per tonne digestate, £ per MWh and £ per kg ammoniacal nitrogen abated all decreased by over 65% for commercial plants and 70% for farm plants.

Changes in the farm feedstock mix also had an impact on the £ per MWh. In all cases there was no impact on the £ per tonne digestate and £ per kg of ammoniacal nitrogen abated. For £ per MWh the effect was a 3.7 times increase for 100% wet manure but all variations recorded an increase (though lower than 100% wet manure).

7.1.7 Acidification – in store (mitigation of ammonia losses)

Figure 19 Process flow diagram for in store acidification of whole digestate

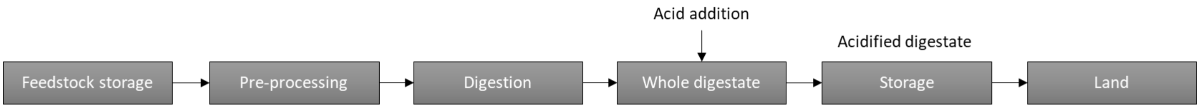
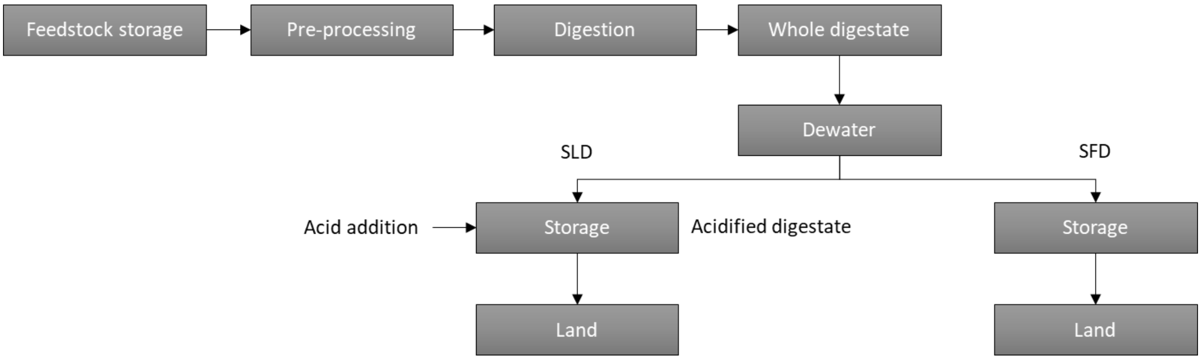


Figure 20 Process flow diagram for in store acidification of separated liquor



Model approach/process description

Acidification in store has been modelled for whole digestate and separated liquor, and includes both costs and abatement. For the cost modelling, only additional costs incurred by the use of the acidification technology have been included. These are:

- Technology CAPEX
- Technology OPEX

The total by cost has been calculated by modelling the above for small, medium, and large commercial and farm AD plants across their lifetime of 20 years. For the CAPEX it is assumed that initial funding is borrowed and paid off over the lifetime of the plant at an interest rate of 2%. The total CAPEX and the OPEX over the 20 years are then combined and used to produce a single annual cost.

For the abatement modelling, the amount of ammonia abated annually using the store acidification technology is compared to the amount of ammonia abated in the baseline. The difference is then taken as the additional abatement due to the use of store acidification. The baseline abatement is calculated by estimating the amount of ammonia lost in the storage and spreading to land of whole digestate and separated liquor. The store acidification abatement also considers the amount of ammonia lost through the application of the acidified digestate to land as well as that lost in storage.

Table 25: Table of model parameters and units

Data	Figure	Source
Ammonia abatement in store	82% reduction	Calculated from published sources (Misselbrook et al., 2016; Sommer et al., 2017; Petersen et al., 2012; Hou et al., 2017; Saue & Tamm, 2018; Foged et al., 2011
Ammonia abatement in application	67% reduction	Calculated from published sources (Willers et al., 1996; Nyord et al., 2013; Foged et al., 2011)

Data	Figure	Source
Acid requirements	16 litres per m^3 of digestate	Farming Forum[11]
Operation costs of field acidification	£0.94 per litre	Farming Forum[12]
Capital cost of store acidification	£125,000 (does not vary with size and type of plant)	Calculated from published sources (Tamm & Vettik, 2019; Foged et al., 2011)

TRL: 9 on farm plants, **TRL:** 7 on commercial plants; Tier 1 Technology (farm)
Data Quality: Medium. This technique is commonly applied to pig slurries, but rarely applied to digestates. As such, process costs are reasonably well characterised while performance is uncertain and based on livestock slurries (not digestates) as the best available analogue. Readers should note that costs may vary widely from those cited depending on the specific ancillaries used (such as the type and size of pumps for digestate) and the quantities of acid required to achieve the target pH.
Regulatory Complexity: Amber. This technique may be considered a further treatment for digestate, causing it to fall outside the scope of current end of waste or other deregulatory positions and return to waste status. Where 'second user' acid is used, this may further complicate the waste status of the digestate. Readers should contact their local environmental regulator to discuss their intentions
Pollution Swapping potential: Amber. Potential for acidification of some soils through extended use of this technique, which can be mitigated through liming; Possible short term localised impacts on earthworms and other soil fauna through application of acidified digestates

Table 26: Modelled costs for Acidification (Store & Field - ammonia) for small, medium, and large commercial and farm plants.

Plant type	Plant Size	Cost per tonne of:			Cost per Mwh of:			Cost per kg of ammoniacal nitrogen abated for:		
		WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
Commercial	S	£15.28	£15.41	-	£10.80	£7.62	-	£17.04	£18.32	-
	M	£15.16	£15.23	-	£10.71	£7.53	-	£16.91	£18.12	-
	L	£15.07	£15.10	-	£10.65	£7.47	-	£16.80	£17.96	-
Farm	S	£15.11	£15.15	-	£28.79	£20.21	-	£22.46	£42.68	-
	M	£15.06	£15.09	-	£28.71	£20.13	-	£22.39	£42.50	-
	L	£15.03	£15.04	-	£28.64	£20.06	-	£22.34	£42.36	-

[11] https://thefarmingforum.co.uk/index.php?threads/covering-slurry-lagoons-good-thing-or-not.298461/page-4
[12] https://thefarmingforum.co.uk/index.php?threads/covering-slurry-lagoons-good-thing-or-not.298461/page-4

Model sensitivity considerations

A sensitivity analysis was conducted for the acidification store & field technology. This consisted of:

- The high and low range of ammoniacal nitrogen assuming that NH_4-N = 60% of N-total. For whole digestate and separated liquor (commercial and farm)
- The high and low range of ammoniacal nitrogen assuming that NH_4-N = 85% of N-total. For whole digestate and separated liquor (commercial and farm)
- Digestate offtake costs of £20 and £40. For whole digestate and separated liquor (commercial and farm)
- Acid use of 0L of per m^3 of digestate. For whole digestate and separated liquor (commercial and farm)
- Acidification unit CAPEX of £10,000. For whole digestate and separated liquor (commercial and farm)
- Acid use of £110 per tonne of per tonne using second user acid. For whole digestate and separated liquor (commercial and farm)
- Farm feedstock mix of 50% energy from crops + 50% from 'wet manure'. For whole digestate and separated liquor (farm)
- Farm feedstock mix of 100% energy from 'manure mix'. For whole digestate and separated liquor (farm), and
- Farm feedstock mix, 100% energy from 'wet manure'. For whole digestate and separated liquor (farm)

Results are presented for each of the different sensitivity factors considered and compared to the overall results from the model itself (Table 27).

Table 27 Acidification store & field (methane) - Sensitivity analysis results

Sensitivity factor	Plant type	Size	£ per tonne digestate			£ per MWh			£ per kg of ammoniacal nitrogen abated		
			WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
Core model outputs:	C	S	15.28	15.41	-	10.80	7.62	-	17.04	18.32	-
NH4-N, 60%N, low, (kg/t fresh weight)	C	S	15.28	15.41	-	10.80	7.62	-	41.95	137.42	-
NH4-N, 60%N, high, (kg/t fresh weight)	C	S	15.28	15.41	-	10.80	7.62	-	9.24	11.57	-
NH4-N, 85%N, low, (kg/t fresh weight)	C	S	15.28	15.41	-	10.80	7.62	-	29.61	96.16	-
NH4-N, 85%N, high, (kg/t fresh weight)	C	S	15.28	15.41	-	10.80	7.62	-	6.52	8.17	-
£110 per tonne for acid	C	S	2.48	2.61	-	1.76	1.29	-	2.77	3.10	-
10 litres of acid per m^3 digestate	C	S	9.66	9.78	-	6.82	4.84	-	10.77	11.63	-
£10K CAPEX for acidification unit	C	S	15.08	15.12	-	10.66	7.48	-	16.82	17.98	-
£20 offtake cost	C	S	15.28	15.41	-	10.80	7.62	-	17.04	18.32	-
£40 offtake cost	C	S	15.28	15.41	-	10.80	7.62	-	17.04	18.32	-

Sensitivity factor	Plant type	Size	£ per tonne digestate			£ per MWh			£ per kg of ammoniacal nitrogen abated		
			WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
Core model outputs:	F	S	15.11	15.15	-	28.79	20.21	-	22.46	42.68	-
NH4-N, 60%N, low, (kg/t fresh weight)	F	S	15.11	15.15	-	28.79	20.21	-	28.37	51.48	-
NH4-N, 60%N, high, (kg/t fresh weight)	F	S	15.11	15.15	-	28.79	20.21	-	11.85	11.26	-
NH4-N, 85%N, low, (kg/t fresh weight)	F	S	15.11	15.15	-	28.79	20.21	-	20.02	36.34	-
NH4-N, 85%N, high, (kg/t fresh weight)	F	S	15.11	15.15	-	28.79	20.21	-	8.36	7.95	-
£110 per tonne for acid	F	S	2.31	2.35	-	4.39	3.14	-	3.43	6.62	-
10 litres of acid per m^3 digestate	F	S	9.48	9.53	-	18.07	12.71	-	14.09	26.83	-
£10K CAPEX for acidification unit	F	S	15.03	15.04	-	28.65	20.07	-	22.35	42.38	-
£20 offtake cost	F	S	15.11	15.15	-	28.79	20.21	-	22.46	42.68	-
£40 offtake cost	F	S	15.11	15.15	-	28.79	20.21	-	22.46	42.68	-
50% energy from crops + 50% from 'wet manure'	F	S	15.05	15.07	-	66.24	46.43	-	22.37	42.44	-
100% energy from 'manure mix'	F	S	15.08	15.12	-	35.98	25.25	-	22.42	42.59	-
100% energy from 'wet manure'	F	S	15.03	15.04	-	108.70	76.15	-	22.34	42.36	-

The changes to digestate offtake costs have no impact on any of the results, this is because the changes in the model and the baseline are the same so there is no additional cost. The decreased CAPEX for the acidification unit does have an impact on each of the sensitivity factors but this is minor at no more than 3% at its maximum level of impact.

The changes to ammoniacal nitrogen have a large impact on the £ per kg of ammoniacal nitrogen abated, there is no impact on the £ per tonne digestate or £ per MWh factors. The £ per kg of ammoniacal nitrogen abated for commercial separated liquor using the high end of the range assuming that NH_4-N = 60% of N-total is over 7.5 times the modelled value. The £ per kg of ammoniacal nitrogen abated for farm separated liquor using the low end of the range assuming that NH_4-N = 85% of N-total is under 20% of the modelled value. This highlights that the level of ammoniacal nitrogen in commercial and farm digestate is a key area of sensitivity in the model as seen in other mitigation technologies.

Changes in the amount of acid used per m^3 of digestate is also another area of sensitivity, impacting on each of the factors with whole digestate being impacted slightly less than separated liquor. At a usage of 10L per m^3 of digestate the £ per tonne digestate, £ per MWh and £ per kg ammoniacal nitrogen abated all decrease by almost 40% with farm plants a slightly larger decrease than commercial plants. The costs decreased as the amount of acid used decreased over the model if this increased the costs would also increase.

Changes in the cost of acid also impacts each of the factors, with whole digestate being impacted slightly more than separated liquor. At a cost of £110 per tonne of acid the £ per tonne digestate, £ per MWh and £ per kg ammoniacal nitrogen abated all decreased by over 80% for commercial plants farm plants.

Changes in the farm feedstock mix also had an impact on the £ per MWh. In all cases there was a small negative impact on the £ per tonne digestate and £ per kg of ammoniacal nitrogen abated. For £ per MWh the effect was a 3.7 times increase for 100% wet manure but all variations recorded an increase (though lower than 100% wet manure).

7.1.8 Use of a gas-tight cover (modelling the mitigation of ammonia emissions)

Figure 21 Process flow diagram for gas-tight storage of whole digestate

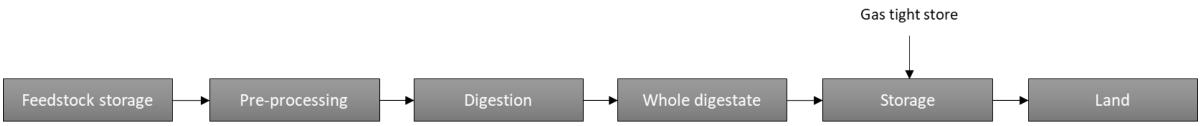
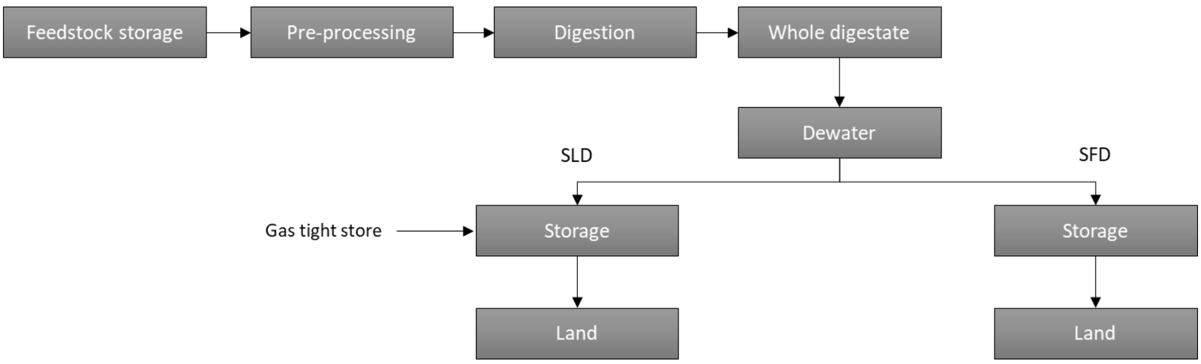


Figure 22 Process flow diagram for gas-tight storage of separated liquor



Model approach/process description
Gas-tight cover has been modelled for whole digestate and separated liquor, including costs and abatement. For the cost modelling, only additional costs incurred by the use of the gas-tight cover have been included. These are:

- Technology CAPEX

There is no modelled OPEX for the gas-tight cover as though the captured gas needs to be managed, inferring additional cost, this could not be included in the modelling due to a lack of data. The total by cost has been calculated by modelling the above for small, medium, and large commercial and farm AD plants across their lifetime of 20 years. For the CAPEX it is assumed that the initial funding is borrowed and paid off over the lifetime of the plant at an interest rate of 2%. The total CAPEX with interest over the 20 years are then combined and used to produce a single annual cost for the gas-tight cover technology.

For the abatement modelling, the amount of ammonia abated annually using the gas-tight storage technology is compared to the amount of ammonia abated in the baseline. The difference is then taken as the additional abatement due to the use of the gas-tight storage. The baseline abatement is calculated by estimating the amount of ammonia lost in the storage and spreading to land for whole digestate and separated liquor. The gas-tight storage abatement also considers ammonia lost in the storage and spreading to land of whole digestate and separated liquor.

Table 28: Table of model parameters and units

Data	Figure	Source
Ammonia abatement in store	100% reduction	Assumed
Capital cost of gas-tight cover	£81.15 per m^2	Assumption , based on 50% additional cost compared with non gas-tight cover (Tamm & Vettik, 2019 and Santonja et al., 2017)

TRL: 9; Tier 1 Technology (farm)
Data Quality: Low. Although we can be confident in abatement performance, cost estimates for this solution are very difficult to develop as they will vary considerably depending on the digestate storage solution used
Regulatory Complexity: Green. The use of gas-tight covers is considered very unlikely to change the regulatory status of any digestate that they cover. Readers should contact their local environmental regulator to confirm
Pollution Swapping potential: Green. Green. It will not be possible to retrofit gas-tight covers to all digestate storage tanks, requiring demolition and construction of more robust facilities. Where storage facilities are close to fields (but remote from AD plants) then additional infrastructure will be required to abate captured off-gases

Table 29: Modelled costs for Gas-tight cover (ammonia) for small, medium, and large commercial and farm plants.

Plant type	Plant Size	Cost per tonne of:			Cost per Mwh of:			Cost per kg of ammoniacal nitrogen abated for:		
		WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
Commercial	S	£0.20	£0.20	-	£0.14	£0.10	-	£1.44	£1.54	-
	M	£0.20	£0.20	-	£0.14	£0.10	-	£1.44	£1.54	-
	L	£0.20	£0.20	-	£0.14	£0.10	-	£1.44	£1.54	-
Farm	S	£0.20	£0.20	-	£0.38	£0.27	-	£1.92	£3.64	-
	M	£0.20	£0.20	-	£0.38	£0.27	-	£1.92	£3.64	-
	L	£0.20	£0.20	-	£0.38	£0.27	-	£1.92	£3.64	-

Model sensitivity considerations

A sensitivity analysis was conducted for the gas-tight storage technology. This consisted of:

- The high and low range of ammoniacal nitrogen assuming that NH_4-N = 60% of N-total. For whole digestate and separated liquor (commercial and farm)
- The high and low range of ammoniacal nitrogen assuming that NH_4-N = 85% of N-total. For whole digestate and separated liquor (commercial and farm)
- Digestate offtake costs of £20 and £40. For whole digestate and separated liquor (commercial and farm)
- Increased gas-tight cover costs by 1.25 and 2 times the non gas-tight cover. For whole digestate and separated liquor (commercial and farm)
- The use of slurry bags for storage. For whole digestate and separated liquor (commercial and farm)
- Farm feedstock mix of 50% energy from crops + 50% from 'wet manure'. For whole digestate and separated liquor (farm)
- Farm feedstock mix of 100% energy from 'manure mix'. For whole digestate and separated liquor (farm), and
- Farm feedstock mix, 100% energy from 'wet manure'. For whole digestate and separated liquor (farm)

Results are presented for each of the different sensitivity factors considered and compared to the overall results from the model itself (Table 30).

Table 30 Gas-tight cover (ammonia) - Sensitivity analysis results

Sensitivity factor	Plant type	Size	£ per tonne digestate			£ per MWh			£ per kg of ammoniacal nitrogen abated		
			WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
Core model output:	C	S	**0.20**	**0.20**	**-**	**0.14**	**0.10**	**-**	**1.44**	**1.54**	**-**
NH4-N, 60%N, low, (kg/t fresh weight)	C	S	0.20	0.20	-	0.14	0.10	-	3.54	11.52	-
NH4-N, 60%N, high, (kg/t fresh weight)	C	S	0.20	0.20	-	0.14	0.10	-	0.78	0.97	-
NH4-N, 85%N, low, (kg/t fresh weight)	C	S	0.20	0.20	-	0.14	0.10	-	2.50	8.06	-
NH4-N, 85%N, high, (kg/t fresh weight)	C	S	0.20	0.20	-	0.14	0.10	-	0.55	0.68	-
1.25x baseline cover price	C	S	0.17	0.17	-	0.12	0.08	-	1.20	1.28	-
2x baseline cover price	C	S	0.27	0.27	-	0.19	0.13	-	1.92	2.05	-
Slurry bag for storage	C	S	1.16	1.16	-	0.82	0.57	-	8.32	8.87	-
£20 offtake cost	C	S	0.20	0.20	-	0.14	0.10	-	1.44	1.54	-
£40 offtake cost	C	S	0.20	0.20	-	0.14	0.10	-	1.44	1.54	-
Core model output:	F	S	**0.20**	**0.20**	**-**	**0.38**	**0.27**	**-**	**1.92**	**3.64**	**-**
NH4-N, 60%N, low, (kg/t fresh weight)	F	S	0.20	0.20	-	0.38	0.27	-	2.43	4.39	-
NH4-N, 60%N, high, (kg/t fresh weight)	F	S	0.20	0.20	-	0.38	0.27	-	1.01	0.96	-
NH4-N, 85%N, low, (kg/t fresh weight)	F	S	0.20	0.20	-	0.38	0.27	-	1.71	3.10	-
NH4-N, 85%N, high, (kg/t fresh weight)	F	S	0.20	0.20	-	0.38	0.27	-	0.71	0.68	-
1.25x baseline cover price	F	S	0.17	0.17	-	0.32	0.22	-	1.60	3.03	-
2x baseline cover price	F	S	0.27	0.27	-	0.51	0.36	-	2.56	4.85	-
Slurry bag for storage	F	S	1.16	1.16	-	2.21	1.55	-	11.09	21.01	-
£20 offtake cost	F	S	0.20	0.20	-	0.38	0.27	-	1.92	3.64	-
£40 offtake cost	F	S	0.20	0.20	-	0.38	0.27	-	1.92	3.64	-
50% energy from crops + 50% from 'wet manure'	F	S	0.20	0.20	-	0.88	0.62	-	1.92	3.64	-
100% energy from 'manure mix'	F	S	0.20	0.20	-	0.48	0.34	-	1.92	3.64	-
100% energy from 'wet manure'	F	S	0.20	0.20	-	1.45	1.02	-	1.92	3.64	-

The changes to digestate offtake costs have no impact on any of the results, this is because the changes in the model and the baseline are the same so there is no additional cost incurred by the mitigation.

The changes to ammoniacal nitrogen have a considerable impact on the £ per kg of ammoniacal nitrogen abated, there is no impact on the £ per tonne digestate or £ per MWh factors. The £ per kg of ammoniacal nitrogen abated for commercial separated liquor using the high end of the range assuming that NH_4-N = 60% of N-total is 7.5 times the modelled value. The £ per kg of ammoniacal nitrogen abated for farm separated liquor using the low end of the range assuming that NH_4-N = 85% of N-total is just under

20% of the modelled value. This highlights that the level of ammoniacal nitrogen in commercial and farm digestate is a key area of sensitivity in the model.

Changes in the cost of the gas-tight cover had a noticeable impact on each of the results. For both plant types and all sensitivity factors having the gas-tight store cost only 1.25x the non gas-tight cover lead to all factors decreasing by over 15%. For both plant types and all sensitivity factors having the gas-tight store cost 2x the non gas-tight cover lead to all factors increasing by over 30%. Changing from a gas-tight store to a slurry bag has an even larger impact, increasing costs for all factors and both plant types by over 5.5 times showing that these two technologies cannot, in costs terms, be substituted for one another.

Changes in the farm feedstock mix also had an impact on the £ per MWh. In all cases there was no impact on the £ per tonne digestate and £ per kg of ammoniacal nitrogen abated. For £ per MWh the effect was a 3.7 times increase for 100% wet manure but all variations recorded an increase (though lower than 100% wet manure).

7.1.9 Spreading using injection equipment

Figure 23 Process flow diagram for injection application of whole digestate

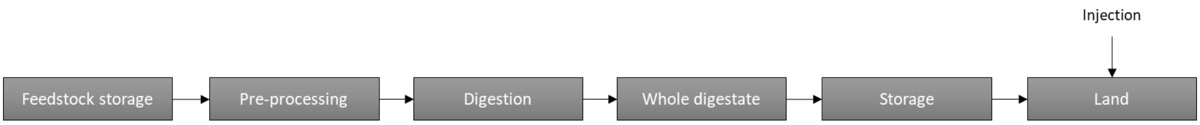
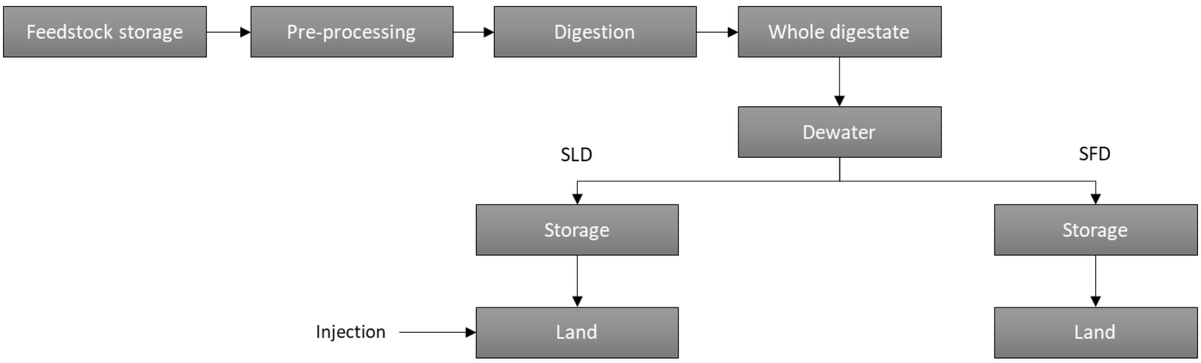


Figure 24 Process flow diagram for injection application of separated liquor



Model approach/process description
Injection spreading has been modelled for whole digestate and separated liquor, and includes both costs and abatement. For the cost modelling, only additional costs incurred by the use of injection have been included. These additional costs are:

- Technology OPEX

There is no CAPEX for injection as it is assumed that injection will be performed by a contractor. The total by cost has been calculated by modelling the above for small, medium, and large commercial and farm AD plants across their lifetime of 20 years. The total OPEX over the 20 years is then combined and used to produce a single annual cost for the injection spreading technology.

For the abatement modelling, the amount of ammonia abated annually using injection is compared to the amount of ammonia abated in the baseline. The difference is then taken as the additional abatement due to the use of injection. The baseline abatement is calculated by estimating the amount of ammonia lost in the storage and spreading to land for whole digestate and separated liquor. The injection abatement also considers ammonia lost in storage and spreading, for whole digestate and separated liquor.

Table 31: Table of model parameters and units

Data	Figure	Source
Ammonia abatement on application	70%	Misselbrook & Gilhespy, 2021
OPEX for injection	£1.40 per m^3 premium compared with baseline trailing hose application	Misselbrook et al., 2008

TRL: 9; Tier 1 Technology (farm)
Data Quality: **Medium.** Cost and performance are based on livestock slurry analogues, rather than digestates
Regulatory Complexity: **Green.** The use of injection is considered good practice where soil and substrate conditions permit and not considered likely to change the regulatory status of the material under use. Readers should contact their local environmental regulator if they are in any doubt
Pollution Swapping potential: **Green.** Potential localised and temporary impact on earthworms and other soil fauna due to physical action of injection, and positioning of digestate

Table 32: Modelled costs for Injection Spreading for small, medium, and large commercial and farm plants.

Plant type	Plant Size	Cost per tonne of:			Cost per Mwh of:			Cost per kg of ammonia abated for:		
		WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
Commercial	S	£1.40	£1.40	-	£0.99	£0.69	-	£2.24	£2.39	-
	M	£1.40	£1.40	-	£0.99	£0.69	-	£2.24	£2.39	-
	L	£1.40	£1.40	-	£0.99	£0.69	-	£2.24	£2.39	-
Farm	S	£1.40	£0.22	-	£2.67	£0.30	-	£2.98	£0.90	-
	M	£1.40	£0.22	-	£2.67	£0.30	-	£2.98	£0.90	-
	L	£1.40	£0.22	-	£2.67	£0.30	-	£2.98	£0.90	-

Model sensitivity considerations

A sensitivity analysis was conducted for the injection spreading technology. This consisted of:

- The high and low range of ammoniacal nitrogen assuming that NH_4-N = 60% of N-total. For whole digestate and separated liquor (commercial and farm)
- The high and low range of ammoniacal nitrogen assuming that NH_4-N = 85% of N-total. For whole digestate and separated liquor (commercial and farm)
- Digestate offtake costs of £20 and £40. For whole digestate and separated liquor (commercial and farm)
- Farm feedstock mix of 50% energy from crops + 50% from 'wet manure'. For whole digestate and separated liquor (farm)
- Farm feedstock mix of 100% energy from 'manure mix'. For whole digestate and separated liquor (farm), and
- Farm feedstock mix, 100% energy from 'wet manure'. For whole digestate and separated liquor (farm)

Results are presented for each of the different sensitivity factors considered and compared to the overall results from the model itself (Table 33).

Table 33 Injection spreading - Sensitivity analysis results

Sensitivity factor	Plant type	Size	£ per tonne digestate			£ per MWh			£ per kg of ammoniacal nitrogen abated		
			WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
Core model output:	C	S	1.40	1.40	-	0.99	0.69	-	2.24	2.39	-
NH4-N, 60%N, low, (kg/t fresh weight)	C	S	1.40	1.40	-	0.99	0.69	-	5.50	17.89	-
NH4-N, 60%N, high, (kg/t fresh weight)	C	S	1.40	1.40	-	0.99	0.69	-	1.21	1.51	-
NH4-N, 85%N, low, (kg/t fresh weight)	C	S	1.40	1.40	-	0.99	0.69	-	3.89	12.52	-
NH4-N, 85%N, high, (kg/t fresh weight)	C	S	1.40	1.40	-	0.99	0.69	-	0.86	1.06	-
£20 offtake cost	C	S	1.40	1.40	-	0.99	0.69	-	2.24	2.39	-
£40 offtake cost	C	S	1.40	1.40	-	0.99	0.69	-	2.24	2.39	-
Core model output:	F	S	1.40	0.22	-	2.67	0.30	-	2.98	0.90	-
NH4-N, 60%N, low, (kg/t fresh weight)	F	S	1.40	0.22	-	2.67	0.30	-	3.77	1.08	-
NH4-N, 60%N, high, (kg/t fresh weight)	F	S	1.40	0.22	-	2.67	0.30	-	1.57	0.24	-
NH4-N, 85%N, low, (kg/t fresh weight)	F	S	1.40	0.22	-	2.67	0.30	-	2.66	0.76	-
NH4-N, 85%N, high, (kg/t fresh weight)	F	S	1.40	0.22	-	2.67	0.30	-	1.11	0.17	-
£20 offtake cost	F	S	1.40	0.22	-	2.67	0.30	-	2.98	0.90	-
£40 offtake cost	F	S	1.40	0.22	-	2.67	0.30	-	2.98	0.90	-
50% energy from crops + 50% from 'wet manure'	F	S	1.40	0.10	-	6.16	0.30	-	2.98	0.39	-
100% energy from 'manure mix'	F	S	1.40	0.18	-	3.34	0.30	-	2.98	0.72	-
100% energy from 'wet manure'	F	S	1.40	0.06	-	10.13	0.30	-	2.98	0.24	-

The changes to digestate offtake costs have no impact on any of the results, this is because the changes in the model and the baseline are the same so there is no additional cost incurred by the mitigation.

The changes to ammoniacal nitrogen have a considerable impact on the £ per kg of ammoniacal nitrogen abated, there is no impact on the £ per tonne digestate or £ per MWh factors. The £ per kg of ammoniacal nitrogen abated for commercial separated liquor using the high end of the range assuming that NH_4-N = 60% of N-total is 7.5 times the modelled value. The £ per kg of ammoniacal nitrogen abated for farm separated liquor using the low end of the range assuming that NH_4-N = 85% of N-total is just under 20% of the modelled value. This highlights that the level of ammoniacal nitrogen in commercial and farm digestate is a key area of sensitivity in the model.

Changes in the farm feedstock mix also had an impact on the £ per MWh. There was no impact on the £ per tonne digestate and £ per kg of ammoniacal nitrogen abated for whole digestate but there was for separated liquor digestate which had significant reductions in cases with a decrease of almost 75% for 100% wet manure being the largest. For £ per MWh the effect was a 3.7 times increase for 100% wet manure but all variations recorded an increase (though lower than 100% wet manure). Changes were only observed for whole digestate with separated liquor not altering with farmstock mix for the £ per MWh.

7.2 Mitigation of methane losses from digestate

7.2.1 Acidification – in store (mitigation of methane losses)

Figure 25 Process flow diagram for acidification of whole digestate in store

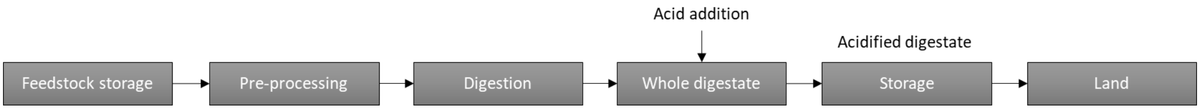
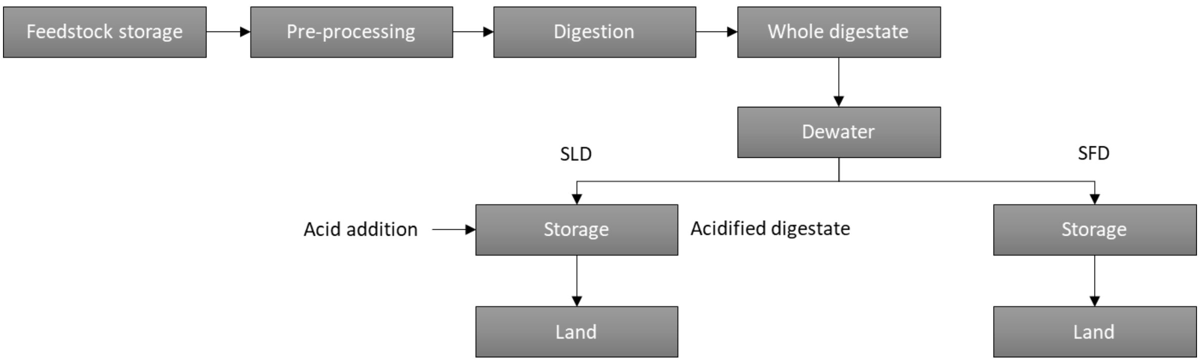


Figure 26 Process flow diagram for acidification of separated liquor in store



Model approach/process description

Acidification in store has been modelled for whole digestate and separated liquor, and includes both costs and abatement. For the cost modelling, only additional costs incurred by the use of the acidification technology have been included. These are:

- Technology CAPEX
- Technology OPEX

The total by cost has been calculated by modelling the above for small, medium, and large commercial and farm AD plants across their lifetime of 20 years. For the CAPEX it is assumed that initial funding is borrowed and paid off over the lifetime of the plant at an interest rate of 2%. The total CAPEX and the OPEX over the 20 years are then combined and used to produce a single annual cost.

For the abatement modelling, the amount of methane abated annually using the store acidification technology is compared to the amount of methane abated in the baseline. The difference is then taken as the additional abatement due to the use of store acidification. The baseline abatement is calculated by estimating the amount of methane lost in the storage of whole digestate and separated liquor. The store acidification abatement also considers the amount of methane lost through the storage of whole and separated liquor digestates.

Table 34: Table of model parameters and units

Data	Figure	Source
Methane abatement in store	78% reduction	Willers et al., 1996, Petersen et al., 2012, Sommer et al., 2017, and Misselbrook et al., 2016
Acid requirements	0.96 litres per m^3 of digestate	Calculated from Sokolov et al., 2021
Operational costs of store acidification	£0.94 per litre	Farming Forum[13], 2019
Capital cost of store acidification	£125,000 (does not vary with size and type of plant)	Academic literature (calculated average)

TRL: 9 on farm plants, **TRL:** 7 on commercial plants; Tier 1 Technology (farm)
Data Quality: Low. This technique is commonly applied to pig slurries, but rarely applied to digestates. As such, process costs are reasonably well characterised while performance is uncertain and based on livestock slurries (not digestates) as the best available analogue. Readers should note that costs may vary widely from those cited depending on the specific ancillaries used (such as the type and size of pumps for digestate) and the quantities of acid required to achieve the target pH.
Regulatory Complexity: Amber. This technique may be considered a further treatment for digestate, causing it to fall outside the scope of current end of waste or other deregulatory positions and return to waste status. Where 'second user' acid is used, this may further complicate the waste status of the digestate. Readers should contact their local environmental regulator to discuss their intentions

[13] https://thefarmingforum.co.uk/index.php?threads/covering-slurry-lagoons-good-thing-or-not.298461/page-4

Pollution Swapping potential: Amber. Potential for acidification of some soils through extended use of this technique, which can be mitigated through liming; Possible short term localised impacts on earthworms and other soil fauna through application of acidified digestates

Table 35: Modelled costs for Acidification (Store & Field - methane) for small, medium, and large commercial and farm plants.

Plant type	Plant Size	Cost per tonne of:			Cost per Mwh of:			Cost per m^3 of methane abated for:		
		WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
Commercial	S	£1.18	£1.31	-	£0.84	£0.65	-	£0.09	£2.16	-
	M	£1.06	£1.13	-	£0.75	£0.56	-	£0.08	£1.87	-
	L	£0.97	£1.00	-	£0.69	£0.50	-	£0.07	£1.65	-
Farm	S	£1.01	£1.05	-	£1.92	£1.40	-	£0.21	£1.73	-
	M	£0.96	£0.99	-	£1.83	£1.32	-	£0.20	£1.63	-
	L	£0.93	£0.94	-	£1.77	£1.25	-	£0.19	£1.55	-

Model sensitivity considerations

A sensitivity analysis was conducted for the acidification store & field technology. This consisted of:

- Digestate offtake costs of £20 and £40. For whole digestate and separated liquor (commercial and farm)
- Acid use of 5L of per m^3 of digestate. For whole digestate and separated liquor (commercial and farm)
- Acidification unit CAPEX of £10,000. For whole digestate and separated liquor (commercial and farm)
- Acid price of £110 per tonne. For whole digestate and separated liquor (commercial and farm)
- Farm feedstock mix of 50% energy from crops + 50% from 'wet manure'. For whole digestate and separated liquor (farm)
- Farm feedstock mix of 100% energy from 'manure mix'. For whole digestate and separated liquor (farm), and
- Farm feedstock mix, 100% energy from 'wet manure'. For whole digestate and separated liquor (farm)

Results are presented for each of the different sensitivity factors considered and compared to the overall results from the model itself (Table 36).

Table 36 Acidification store & field (methane) - Sensitivity analysis results

Sensitivity factor	Plant type	Size	£ per tonne digestate			£ per MWh			£ per m^3 of methane abated		
			WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
Core model output:	C	S	1.18	1.31	-	0.84	0.65	-	0.09	2.16	-
£110 per tonne acid cost	C	S	0.42	0.54	-	0.29	0.27	-	0.03	0.89	-
£10K CAPEX	C	S	0.98	1.02	-	0.70	0.50	-	0.07	1.68	-
£20 offtake cost	C	S	1.18	1.31	-	0.84	0.65	-	0.09	2.16	-
£40 offtake cost	C	S	1.18	1.31	-	0.84	0.65	-	0.09	2.16	-
5 litres of acid per m^3 digestate	C	S	4.97	5.09	-	3.51	2.52	-	0.38	8.41	-
Core model output:	F	S	1.01	1.05	-	1.92	1.40	-	0.21	1.73	-
£110 per tonne acid cost	F	S	0.24	0.28	-	0.45	0.38	-	0.05	0.47	-
£10K CAPEX	F	S	0.93	0.94	-	1.78	1.26	-	0.19	1.56	-
£20 offtake cost	F	S	1.01	1.05	-	1.92	1.40	-	0.21	1.73	-
£40 offtake cost	F	S	1.01	1.05	-	1.92	1.40	-	0.21	1.73	-
50% energy from crops + 50% from 'wet manure'	F	S	0.95	0.97	-	4.16	2.97	-	0.45	1.59	-
100% energy from 'manure mix'	F	S	0.98	1.02	-	2.35	1.70	-	0.25	1.68	-
100% energy from 'wet manure'	F	S	0.93	0.94	-	6.71	4.76	-	0.72	1.55	-
5 litres of acid per m^3 digestate	F	S	4.79	4.84	-	9.14	6.46	-	0.98	7.98	-

The changes to digestate offtake costs have no impact on any of the results, this is because the changes in the model and the baseline are the same so there is no additional cost incurred by the mitigation technology.

The decreased CAPEX for the acidification unit does have an impact on each of the sensitivity factors this is larger than for the ammonia variant. The largest impact is for the £ per kg of ammoniacal nitrogen abated for separated liquor for commercial plant as just over 78% of the modelled value.

Changes in the amount of acid used per m^3 of digestate is an area of significant sensitivity. Changes in the acid use impacts each of the factors with whole digestate being impacted more than separated liquor. At a usage of 5L per m^3 of digestate the £ per tonne digestate, £ per MWh and £ per m^3 methane abated all increased by more than 3.5 times for commercial plants and more than 4.5 times for farm plants.

Changes in the cost of acid also impacts all each of the factors, with whole digestate being impacted slightly more than separated liquor. At a cost of £110 per tonne of acid the £ per tonne digestate, £ per MWh and £ per m^3 methane abated were all less than 30% of the modelled value for farm plants and over 50% for commercial plants.

Changes in the farm feedstock mix also had an impact on the £ per MWh. For £ per tonne digestate all values decreased with the greatest decrease being just over 10% for farm 100% wet manure. The £ per m^3 methane abated costs increased significantly for whole digestate by over 3.5 times for 100% wet manure but decreased for separated liquor by over 10% for 100% wet manure. For £ per MWh the effect was a >3 times increase for 100% wet manure but all variations recorded an increase (though lower than 100% wet manure).

7.2.2 Use of a gas-tight cover (mitigation of methane losses)

Figure 27 Process flow diagram for gas-tight storage of whole digestate

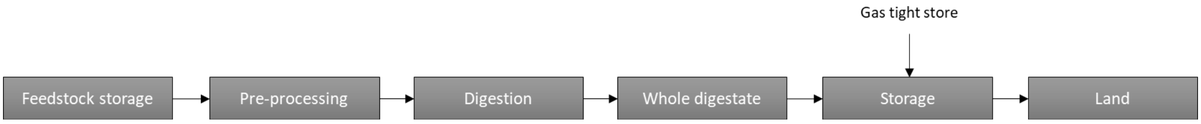
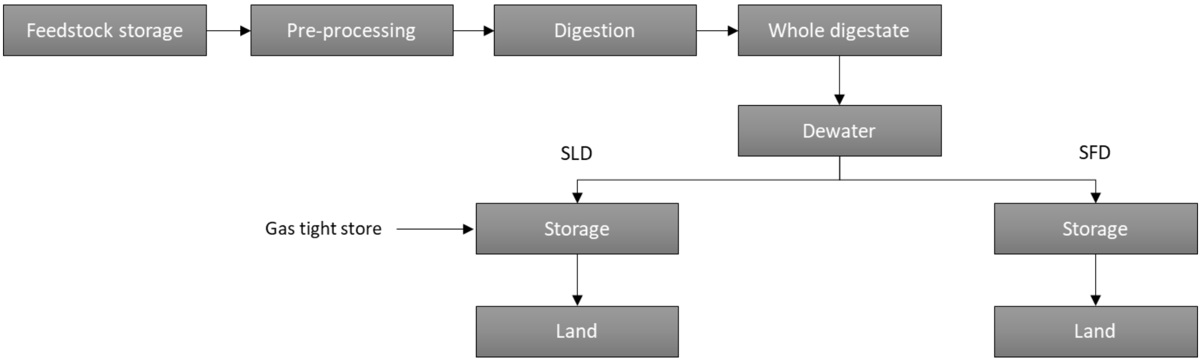


Figure 28 Process flow diagram for gas-tight storage of separated liquor



Model approach/process description
Gas-tight cover has been modelled for whole digestate and separated liquor, including costs and abatement. For the cost modelling, only additional costs incurred by the use of the gas-tight cover have been included. These are:

- Technology CAPEX

There is no modelled OPEX for the gas-tight cover as though the captured gas needs to be managed, inferring additional cost, this could not be included in the modelling due to a lack of data. The total by cost has been calculated by modelling the above for small, medium, and large commercial and farm AD plants across their lifetime of 20 years. For the CAPEX it is assumed that the initial funding is borrowed and paid off over the lifetime of the plant at an interest rate of 2%. The total CAPEX with interest over the 20 years are then combined and used to produce a single annual cost for the gas-tight cover technology.

For the abatement modelling, the amount of methane abated annually using the gas-tight storage technology is compared to the amount of methane abated in the baseline. The difference is then taken as the additional abatement due to the use of the gas-tight storage. The baseline and mitigation abatements are both calculated by estimating the amount of methane lost in storage only, for whole and separated liquor digestates.

Table 37: Table of model parameters and units

Data	Figure	Source
Methane abatement in store	100% reduction	Assumed
Capital cost of gas-tight cover	£81.15 per m^2	Assumption , based on 50% additional cost compared with non gas-tight cover (Tamm & Vettik, 2019 and Santonja et al., 2017)

TRL: 9; Tier 1 Technology (farm)
Data Quality: Low. Although we can be confident in abatement performance, cost estimates for this solution are very difficult to develop as they will vary considerably depending on the digestate storage solution used
Regulatory Complexity: Green. The use of gas-tight covers is considered very unlikely to change the regulatory status of any digestate that they cover. Readers should contact their local environmental regulator to confirm
Pollution Swapping potential: Green. Green. It will not be possible to retrofit gas-tight covers to all digestate storage tanks, requiring demolition and construction of more robust facilities. Where storage facilities are close to fields (but remote from AD plants) then additional infrastructure will be required to abate captured off-gases

Table 38: Modelled costs for Gas-tight cover (methane) for small, medium, and large commercial and farm plants.

Plant type	Plant Size	Cost per tonne of:			Cost per Mwh of:			Cost per m^3 of methane abated for:		
		WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
Commercial	S	£0.20	£0.20	-	£0.14	£0.10	-	£0.01	£0.26	-
	M	£0.20	£0.20	-	£0.14	£0.10	-	£0.01	£0.26	-
	L	£0.20	£0.20	-	£0.14	£0.10	-	£0.01	£0.26	-
Farm	S	£0.20	£0.20	-	£0.38	£0.27	-	£0.03	£0.26	-
	M	£0.20	£0.20	-	£0.38	£0.27	-	£0.03	£0.26	-
	L	£0.20	£0.20	-	£0.38	£0.27	-	£0.03	£0.26	-

Model sensitivity considerations

A sensitivity analysis was conducted for the gas-tight storage technology. This consisted of:

- Digestate offtake costs of £20 and £40. For whole digestate and separated liquor (commercial and farm)
- Increased gas-tight cover costs by 1.25, and 2 times the cost of the median tent cover. For whole digestate and separated liquor (commercial and farm)
- The use of slurry bags for storage as opposed to a gas-tight cover. For whole digestate and separated liquor (commercial and farm)

- Farm feedstock mix of 50% energy from crops + 50% from 'wet manure'. For whole digestate and separated liquor (farm)
- Farm feedstock mix of 100% energy from 'manure mix'. For whole digestate and separated liquor (farm), and
- Farm feedstock mix, 100% energy from 'wet manure'. For whole digestate and separated liquor (farm)

Results are presented for each of the different sensitivity factors considered and compared to the overall results from the model itself (Table 39).

Table 39 Gas-tight storage (methane) - Sensitivity analysis results

Sensitivity factor	Plant type	Size	£ per tonne digestate			£ per MWh			£ per m^3 of methane abated		
			WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
Core model output:	C	S	0.20	0.20	-	0.14	0.10	-	0.01	0.26	-
1.25x baseline cover price	C	S	0.17	0.17	-	0.12	0.08	-	0.01	0.21	-
2x baseline cover price	C	S	0.27	0.27	-	0.19	0.13	-	0.02	0.34	-
Slurry bag for storage	C	S	1.16	1.16	-	0.82	0.57	-	0.07	1.48	-
£20 offtake costs	C	S	0.20	0.20	-	0.14	0.10	-	0.01	0.26	-
£40 offtake costs	C	S	0.20	0.20	-	0.14	0.10	-	0.01	0.26	-
Core model output:	F	S	0.20	0.20	-	0.38	0.27	-	0.03	0.26	-
1.25x baseline cover price	F	S	0.17	0.17	-	0.32	0.22	-	0.03	0.21	-
2x baseline cover price	F	S	0.27	0.27	-	0.51	0.36	-	0.04	0.34	-
Slurry bag for storage	F	S	1.16	1.16	-	2.21	1.55	-	0.18	1.48	-
£20 offtake costs	F	S	0.20	0.20	-	0.38	0.27	-	0.03	0.26	-
£40 offtake costs	F	S	0.20	0.20	-	0.38	0.27	-	0.03	0.26	-
50% energy from crops + 50% from 'wet manure'	F	S	0.20	0.20	-	0.88	0.62	-	0.07	0.26	-
100% energy from 'manure mix'	F	S	0.20	0.20	-	0.48	0.34	-	0.04	0.26	-
100% energy from 'wet manure'	F	S	0.20	0.20	-	1.45	1.02	-	0.12	0.26	-

The results for the sensitivity analysis for gas-tight store (methane) are very similar to the results for gas-tight store (ammonia).

The changes to digestate offtake costs have no impact on any of the results, this is because the changes in the model and the baseline are the same so there is no additional cost incurred by the mitigation technology.

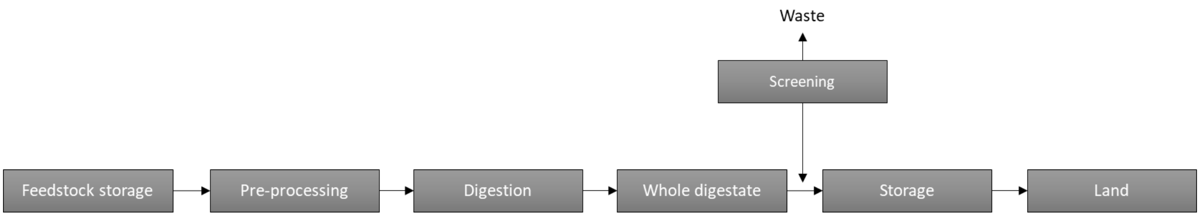
Changes in the cost of the gas-tight cover had a noticeable impact on each of the results. For both plant types and all sensitivity factors having the gas-tight store cost only 1.25x the non gas-tight cover lead to all factors decreasing by over 15%. For both plant types and all sensitivity factors having the gas-tight store cost 2x the non gas-tight cover lead to all factors increasing by over 30%. Changing from a gas-tight store to a slurry bag has an even larger impact, increasing costs for all factors and both plant types by over 5.5 times showing that these two technologies cannot, in costs terms, be substituted for one another.

Changes in the farm feedstock mix also had an impact on the £ per MWh. In all cases there was no impact on the £ per tonne digestate and £ per kg of ammoniacal nitrogen abated. For £ per MWh the effect was a 3.7 times increase for 100% wet manure but all variations recorded an increase (though lower than 100% wet manure).

7.3 Mitigation of plastics in digestate

7.3.1 Screening

Figure 29 Process flow diagram for plastics removal via screening of whole digestate



Model approach/process description
Screening has been modelled for whole digestate, and includes both costs and abatement. For the cost modelling, only additional costs incurred by screening technology have been included. These additional costs are:

- Technology CAPEX
- Technology OPEX
- Additional disposal costs for the plastic-contaminated separated fraction

The total by cost has been calculated by modelling the above for small, medium, and large commercial AD plants across their lifetime of 20 years. Three types of commercial plants were modelled (at each size):

- Screening digestate derived from de-packaged feedstock contaminated with 5% plastic
- Screening digestate that met the PAS110 plastic contamination limits
- Screening digestate the met the Scottish plastic contamination limits

For the CAPEX it is assumed that the initial funding is borrowed and paid off over the lifetime of the plant at an interest rate of 2%. The total CAPEX and the OPEX over the 20 years are then combined and used to produce a single annual cost. Additional disposal costs are those incurred by the requirement to dispose of plastics removed from the digestate. This was found to be an insignificant element of the operation costs.

For the abatement modelling, the amount of plastic abated annually using the screen is compared to the amount of plastic abated in the baseline (which includes depackaging but no screening). As there is no agreed figure for a baseline amount of plastic left in the feedstock after depackaging, starting points were back-calculated assuming that one plant was exactly meeting the PAS110 standard, one exactly meeting the Scottish limits. A third starting point assumed 5% contamination before depackaging. The abatement was then calculated as the extra plastics removed through screening. The model is only applicable for commercial plants as plastic contamination is not relevant to farm AD plants. Screening is applied to whole digestate only.

Table 40: Table of model parameters and units

Data	Figure	Source
Downstream screening abatement	72% reduction	Supplier data
Operational costs of screening	£0.04 per tonnes of digestate treated	Supplier data
Capital costs of screening	£0.38 per tonne of digestate treated annually	Supplier data
Plastic contaminated waste disposal costs via landfill	£113 per tonne	WRAP, 2021
PAS110 limits*	0.18 kg/tonne	BSI, 2014
Scottish limits*	0.0144 kg/tonne	SEPA, 2017
***Note that limits for plastics in digestate are set on a sliding scale depending on total nitrogen content of digestate, with higher limits set where digestate contains more nitrogen. Total nitrogen contents in digestate were taken from RB209 (AHDB, 2021) and plastic limits selected accordingly**		

TRL: 9; Tier 1 Technology (farm)
Data Quality: High. Cost and performance data are from commercial suppliers, although performance data are (relatively) scant
Regulatory Complexity: Green. Routes for processing and downstream disposal or recovery of packaging are well established and not expected to raise regulatory uncertainties. Waste and animal by-product regulatory controls will apply to this material. Readers should contact their local environmental regulator and/or APHA representative to discuss their intentions
Pollution Swapping potential: Red. Separated plastics likely to be incinerated or landfilled (although can be washed and recycled under some circumstances)

Table 41: Modelled costs for Plastics (downstream) for small, medium, and large commercial and farm plants.

Plant type	Plant Size	Cost per tonne of:			Cost per Mwh of:			Cost per kg of plastic abated for:		
		WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
Commercial (5% contamination)	S	£0.28	-	-	£0.19	-	-	£0.15	-	-
	M	£0.28	-	-	£0.19	-	-	£0.15	-	-
	L	£0.28	-	-	£0.19	-	-	£0.15	-	-
Commercial (PAS110)	S	£0.09	-	-	£0.06	-	-	£0.67	-	-
	M	£0.09	-	-	£0.06	-	-	£0.67	-	-
	L	£0.09	-	-	£0.06	-	-	£0.67	-	-
	S	£0.07	-	-	£0.05	-	-	£7.14	-	-

Commercial (SEPA)	M	£0.07	-	-	£0.05	-	-	£7.14	-	-
	L	£0.07	-	-	£0.05	-	-	£7.14	-	-

Model sensitivity considerations

A sensitivity analysis was conducted for the plastic removal downstream technology. This consisted of:

- Digestate offtake costs of £20 and £40. For whole digestate (commercial)
- 95% plastic removal efficiency during digestate screening. For whole digestate (commercial)
- 50% plastic removal efficiency during digestate screening. For whole digestate (commercial), and
- 50% plastic removal efficiency during depackaging. For whole digestate (commercial)

Results are presented for each of the different sensitivity factors considered and compared to the overall results from the model itself (Table 42).

Table 42 Plastic removal downstream - Sensitivity analysis results.

Sensitivity factor	Plant type	Size	£ per tonne digestate			£ per MWh			£ per kg of plastic abated		
			WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
Core model output:	C (5% contamination)	S	0.28	-	-	0.19	-	-	0.15	-	-
£20 offtake cost	C (5% contamination)	S	0.28	-	-	0.19	-	-	0.15	-	-
£40 offtake cost	C (5% contamination)	S	0.28	-	-	0.19	-	-	0.15	-	-
95% screening efficiency	C (5% contamination)	S	0.34	-	-	0.24	-	-	0.14	-	-
50% screening efficiency	C (5% contamination)	S	0.21	-	-	0.15	-	-	0.17	-	-
50% depackaging efficiency	C (5% contamination)	S	2.10	-	-	1.49	-	-	0.12	-	-
Core model output:	C (PAS110)	S	0.09	-	-	0.06	-	-	0.67	-	-
£20 offtake cost	C (PAS110)	S	0.09	-	-	0.06	-	-	0.67	-	-
£40 offtake cost	C (PAS110)	S	0.09	-	-	0.06	-	-	0.67	-	-
95% screening efficiency	C (PAS110)	S	0.09	-	-	0.07	-	-	0.54	-	-
50% screening efficiency	C (PAS110)	S	0.08	-	-	0.06	-	-	0.92	-	-
50% depackaging efficiency	C (PAS110)	S	0.09	-	-	0.06	-	-	0.67	-	-
Core model output:	C (SEPA)	S	0.07	-	-	0.05	-	-	7.14	-	-
£20 offtake cost	C (SEPA)	S	0.07	-	-	0.05	-	-	7.14	-	-
£40 offtake cost	C (SEPA)	S	0.07	-	-	0.05	-	-	7.14	-	-

Sensitivity factor	Plant type	Size	£ per tonne digestate			£ per MWh			£ per kg of plastic abated		
			WD	SLD	SFD	WD	SLD	SFD	WD	SLD	SFD
95% screening efficiency	C (SEPA)	S	0.07	-	-	0.05	-	-	5.43	-	-
50% screening efficiency	C (SEPA)	S	0.07	-	-	0.05	-	-	10.21	-	-
50% depackaging efficiency	C (SEPA)	S	0.07	-	-	0.05	-	-	7.14	-	-
The results for decreasing the removal efficiency of plastic during depackaging suggest no change for the PAS110 and Scottish compliant models but large increases across all measures for the 5% contamination model. This is a factor of the modelling and is not representative of real conditions. These figures are provided for completeness only and no inferences should be made from them. The reason for the unexpected results is due to the modelling assuming the plants are either PAS110 or Scottish compliant, or have 5% contamination before the downstream screening commences. Due to how this was calculated in the model, changes to the depackaging efficiency for PAS110 and Scottish compliant plants has no effect as they are always modelled as reaching those targets after the depackaging step, this is done differently for the 5% contamination model which generates an apparent impact accordingly											

The changes to digestate offtake costs have no impact on any of the results, this is because the changes in the model and the baseline are the same so there is no additional cost incurred by the mitigation technology.

Increasing plastic removal efficiency to 95% for screening increases the £ per tonne digestate and £ per tonne MWh by small amounts for the PAS110 and Scottish compliant models but by a much greater degree (<20%) for the 5% contamination model. This is because the added cost is the disposal of plastic-contaminated fibre and more of this is generated in the 5% contamination model as it contains more plastic. In all cases the £ per kg of plastic abated drops but this is a much more significant drop (over 20%) for the PAS110 and Scottish compliant models than the 5% contamination model which is less than 10%.

Decreasing plastic removal efficiency to 50% for screening decreases the £ per tonne digestate and £ per tonne MWh by small amounts for the PAS110 and Scottish compliant models (>10%) but by a much greater degree for the 5% contamination model (<20%). This is because the reduced cost is from the non-disposal of plastics contaminated fibre and this reduction is greater for the 5% contamination model as there is more plastic to begin with. In all cases the £ per kg of plastic abated increases but this is more significant (over 35% and 40% respectively) for the PAS110 and Scottish compliant models than the 5% contamination model which is just over 10%. This result however is slightly misleading as due to the structure of the model the 5% contamination model has more plastic to abate so the decrease in abatement level has less impact than on the other plants.

8.0 Valorisation archetypes modelled data sheets

The complete dataset developed for valorisation modelling is provided in Appendix 7: Data common to the various modelled archetypes are listed below:

Table 43 Standard values used in the modelling of the valorisation archetypes

							Source
Tonnes of digestate	Whole		Separated liquor		Separated fibre		WRAP calculation
	Commercial	Farm	Commercial	Farm	Commercial	Farm	
	42,706	115,209	38,435	103,688	4,271	11,521	
	74,023	199,695	66,621	179,726	7,402	19,970	
	170,822	460,836	153,740	414,752	17,082	46,084	

Feedstock energy yields		**kWh/tonne (fresh)**	**Nm^3CH_4 / tonne**	**tonne biogas / tonne**	**tonne digestate / tonne input***	
	Food waste	1100	110	0.22	0.78	THE DEPARTMENT FOR ENERGY SECURITY & NET ZERO (2021) and DEFRA (*Pers Comm*)
	Energy crop	642	64.2	0.13	0.87	
	Manure mix	376	37.6	0.08	0.92	
	Wet manure	124	12.4	0.03	0.97	

Nutrient value (per kg)			
Nitrogen	£1.79 (calculated from UK produced AN)	per kg	AHDB[14]
Phosphorus	£2.61 (calculated from Triple super phosphate)	per kg	AHDB [15]
Potassium	£1.07 (calculated from Muriate of potash)	per kg	AHDB [16]
Sulphur	£1.00 (calculated from Ammonium sulphate)	per kg	The Anderson Centre[17]

Total N per year	**Whole**		**Separated liquor**		**Separated fibre**		
	Commercial	Farm	Commercial	Farm	Commercial	Farm	WRAP calculation using plant digestate characteristics
	204,987	414,752	172,958	197,007	38,008	64,517	
	355,310	718,904	299,793	341,479	65,880	111,829	
	819,947	1,659,008	691,830	788,029	152,032	258,068	

[14] https://ahdb.org.uk/fertiliser-information
[15] https://ahdb.org.uk/fertiliser-information
[16] https://ahdb.org.uk/fertiliser-information
[17] https://theandersonscentre.co.uk/fertiliser-prices-selected-products/

Farm plant digestate characteristics		Dry matter (%)	N-total (kg/t fresh weight)	NH4-N (kg/t fresh weight)	
	Whole digestate	5.5	3.6	2.88	AHDB, 2021
	Separated liquor	3	1.9	1.52	
	Separated fibre	24	5.6	4.48	
Commercial plant digestate characteristics		**Dry matter (%)**	**N-total (kg/t fresh weight)**	**NH4-N (kg/t fresh weight)**	AHDB, 2021
	Whole digestate	4.1	4.8	3.84	
	Separated liquor	3.8	4.5	3.6	
	Separated fibre	27	8.9	7.12	

Costs for spreading digestates as wastes	£15			Project team
Cost of spreading for digestates as non-waste	WD £3.00/t	SLD £2.35 /t	SFD £ 3.75/t	Marinari, 2019
Capital cost of covered tank storage	£61.24 per m^3			Assumed 50% uplift on cost of uncovered stores as listed by Beattie, 2021
	N	P	K	
Farm plant nutrient content (kg/tonne fresh weight)	3.6	0.74	3.65	AHDB, 2021
Commercial plant nutrient content (kg/tonne fresh weight)	4.8	0.48	1.99	AHDB, 2021
Nutrient values (£/tonne)	1.79	2.61	1.07	Calculated from the above with prices from AHDB[18]

8.1 Sensitivity analysis variables – valorisation model

Sensitivity analyses were broken down by valorisation process, with different factors being analysed for each with some degree of crossover. These were conducted to highlight where each valorisation model might be particularly sensitive to the factors or assumptions used, as well as to highlight areas where change might make a scenario more or less commercially attractive. Factors taken into account in the sensitivity analysis included fertiliser prices and alternative uses or sale routes for the end

[18] https://ahdb.org.uk/GB-fertiliser-prices

products of valorisation, such as the sale of fibre as soil improver and sale of nutrient concentrates at retail prices.

Fertiliser prices could have a large impact on the profitability of the various valorisation processes. As such high and low fertiliser prices were included in the sensitivity analysis. The high and low prices are taken from the Agriculture and Horticulture Development Board (AHDB)[19].

A screengrab of their website shows the difference in fertiliser prices in March 2022 as compared with March 2021 (Figure 30). Year-on-year prices for the key nutrients (N, P & K) have either doubled or tripled. There was also a 15 to 30% change in prices between February and March 2022. This volatility makes it tricky to select both the baseline and extremes. We used prices of £616, £532 and £524 per tonne of AN, MOP and TSP, respectively in the model. Ranges for sensitivity analysis have been taken from March 2021 and March 2022 prices, as set out in Table 44.

Figure 30 Screengrab of fertiliser price data from AHDB: https://ahdb.org.uk/GB-fertiliser-prices

	Mar-22 (£/tonne)	Feb-22 (£/tonne)	Change from previous month (%)	Mar-21 (£/tonne)	Change from previous year (%)
AN – UK produced (34.5% N)	839	649	29%	283	196%
AN – Imported* (34.5% N)	N/a	643	N/a	271	N/a
Granular Urea - Standard Specification (46% N)	911	724	26%	318	186%
UAN (30% N w/w kg per 100kg)	N/a	N/a	N/a	N/a	N/a
Muriate of Potash (MOP)	626	543	15%	254	146%
Diammonium Phosphate (DAP)	N/a	799	N/a	454	N/a
Triple Super Phosphate (TSP)	717	539	33%	343	109%

Table 44 Fertiliser prices, converted to nutrient prices

Fertiliser	Fertiliser price (£/tonne)	Nutrient	Nutrient price (£/tonne)
Ammonium nitrate (AN)	283	N	820
	616	N	1,786
	839	N	2,432
Muriate of potash (MOP)	254	P	510
	532	P	1,068
	626	P	1,257
Triple super phosphate (TSP)	343	K	1,710
	524	K	2,613
	717	K	3,575

[19] https://projectblue.blob.core.windows.net/media/Default/Market%20Intelligence/GBFertiliserPriceSeries.xlsx

Sensitivity analysis on the CAPEX and OPEX of the valorisation scenarios was not conducted as they could be almost infinitely varied depending on unit cost and performance. However, the following end points were considered:

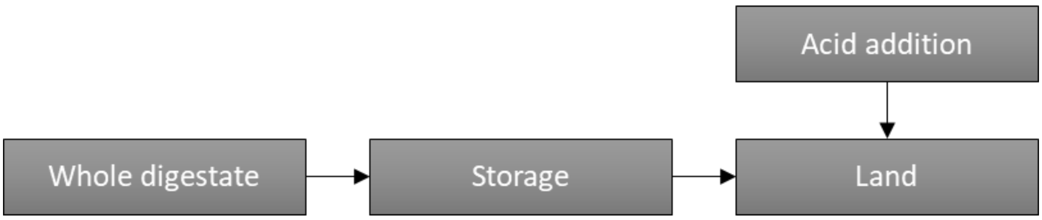
- Bulk sale of fibre as a soil improver for £0.21 per kg, and
- Sale of nutrient concentrate at retail value of £30 per 10L container

Additional costs would be incurred by these two alternate sale routes but as shown in the following individual valorisation scenarios, these additional costs have been found to be orders of magnitude smaller than the revenue derived from these materials.

8.2 Valorisation of digestate – valorisation processes

8.2.1 Archetype 1. In field acidification and increased nutrient use efficiency – farm plant

Figure 31 Process flow for valorisation archetype 1



In field acidification and increased nutrient use efficiency have been modelled for whole digestate only. The modelling has three parts: the cost modelling; mass balance; and nutrient flows. The mass balance and nitrogen and sulphur flow modelling are used to complete the cost modelling. The mass flows have been used to calculate spreading costs and the nitrogen and sulphur flows to calculate the fertiliser value of exported materials. Additional costs and revenues of the valorisation process that have been modelled are:

- Acid cost and dose rate (OPEX)
- Cost to use acidification system (compared with baseline) (OPEX)
- Fertiliser purchase savings (Revenue)

The total costs have been modelled for small farm AD plants across their lifetime of 20 years. The CAPEX and OPEX of the valorisation process blocks have been combined with revenues to give an annual revenue per tonne of digestate processed. A positive revenue means the digestate as valorised delivers an income, while a negative revenue means that costs have increased compared to the relevant 'non valorisation' baseline.

For this archetype, valorisation has been calculated as the increased nitrogen and sulphur content of the digestate spread to land caused by in field acidification, meaning less conventional fertiliser need be purchased. To calculate the increased nitrogen and sulphur content, they are tracked through each of the process steps as percentages. These are then combined with the mass flows to estimate the amount of additional nitrogen and sulphur spread to land which is given a value.

Table 45 Critical modelled data points for Archetype 1

Data	Figure	Source
Acid cost	£0.94 per litre	Supplier data
Acid dose rate	2.5 litres per m^3 digestate	Supplier data
Additional cost to use acidification system	£20 per hectare	Supplier data

Table 46 Modelled data outputs

Technology step	Annual CAPEX (£)	Annual OPEX (£)	Revenue (£)
Acidification	0	-270,696	0
Spreading to land savings	0	-48,794	0
Fertiliser savings	0	0	129,316

Revenue per tonne digestate treated (£/t)	-1.65
Revenue per MWh generated (£/t)	-3.15

The negative figures from the modelling exercise indicate that there will net a net cost per tonne of digestate of £1.65 per tonne of digestate treated or £3.15 per MWh.

Model sensitivity considerations

The sensitivity analysis for this scenario examined:

- A high and low value for Ammonium Nitrate of £283 and £839
- A high and low value for Muriate of potash of £254 and £626
- A high and low value for Triple super phosphate of £343 and £717, and
- A lower costs per tonne of acid of £110 due to the use of second user acid

Both the muriate of potash and triple super phosphate price variation will have no impact on the revenues expected for this process as these nutrients are not included in the value calculations for this process as it only impacts nitrogen.

Results are presented for each of the different sensitivity factors considered and compared to the overall results from the model itself (Table 47).

Table 47 Acidification and increased NUE - Sensitivity analysis results

Sensitivity factor	Plant type	Size	Revenue per tonne digestate treated (£/t)	Revenue per MWh generated (£/t)
Core model output:	**F**	**S**	**-1.65**	**-3.15**
Ammonium nitrate (AN), low, £283	F	S	-2.26	-4.30
Ammonium nitrate (AN), high, £839	F	S	-1.24	-2.37
Muriate of potash (MOP), low, £254	F	S	-1.65	-3.15
Muriate of potash (MOP), high, £626	F	S	-1.65	-3.15
Triple super phosphate (TSP), low, £343	F	S	-1.65	-3.15
Triple super phosphate (TSP), high, £717	F	S	-1.65	-3.15
Acid cost (H_2SO_4), low, £110 per tonne (second users)	F	S	0.35	0.68

The variation in ammonium nitrate values changes the calculated value of nitrogen used in the model. As nitrogen prices rise the value of the exported product increases and vice versa if the price falls. This valorisation process is sensitive to the change in nitrogen prices. Revenues per tonne digestate treated and per MWh generated decreased by over 35% with the low value and increased by almost 25% with the high value. The low ammonium nitrate value makes the net cost for both factors more negative and therefore even further from profitability. Whilst the high prices bring the net cost closer to zero it is not enough to make the process profitable. The acidification and increased nutrient use efficiency scenario would be sensitive to the costs of sulphur but this has not been included in the sensitivity analysis as within the current model the price of sulphur varies with nitrogen, so its impact is included within the nitrogen sensitivity analysis.

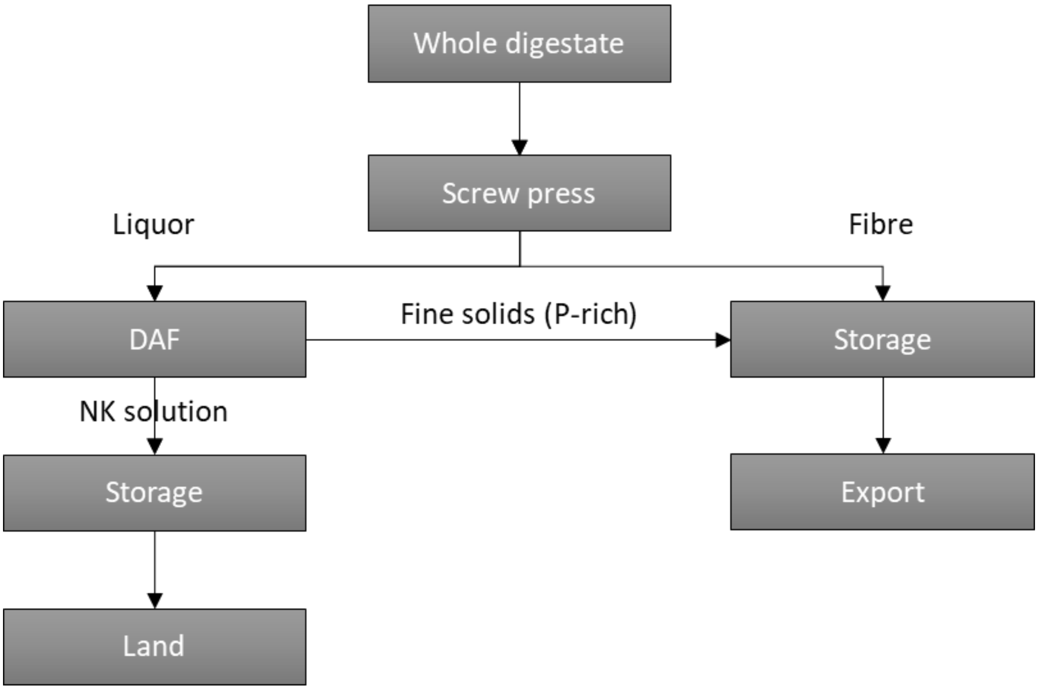
The variation in muriate of potash values changes the calculated value of potassium used in the model, but acidification has no impact on potash and does not therefore change the overall commercial position.

The variation in triple super phosphate values changes the calculated value of phosphorus used in the model but acidification has no impact on phosphate and does not therefore change the overall commercial position.

The use of second user acid makes a great difference to the revenues per tonne digestate treated and per MWh generated with a price change from £750 per tonne for virgin acid to £100 per tonne for second use acid causing the process to become profitable within the model. This shows this process is sensitive to the cost of acid with large changes seen from the reduction in acid cost and the subsequent change to profitability.

8.2.2 Archetype 2. Capture of phosphorus for export

Figure 32 Process flow for valorisation archetype 2



Phosphorus capture modelling has three parts: costs; mass flows; and phosphorus flows. Additional costs and revenues of the valorisation process that have been modelled are:

- Screw press (CAPEX/OPEX)
- Dissolved air flotation - DAF (CAPEX/OPEX)
- Spreading costs for NK solution (OPEX)
- Phosphorus-enhanced fibre export (Revenue based on phosphorus content)

The total costs have been modelled for small farm AD plants across their lifetime of 20 years. The CAPEX and OPEX of the valorisation process blocks have been combined with revenues to give an annual revenue per tonne of digestate processed. A positive revenue means the digestate as valorised delivers an income, while a negative revenue means that costs have increased compared to the relevant 'non valorisation' baseline.

Valorisation has been calculated as the fertiliser value of the exported P-enriched fibre. To calculate the phosphorus content in the fibre the flow of phosphorus is tracked through each of the process blocks as a percentage, this can then be allocated a value.

Table 48 Critical modelled data points for Archetype 2

Data	Figure	Source
Screw press CAPEX	£100,476	Supplier data
Screw press OPEX	£13,838 per year	Supplier data

Screw press separation rates and nutrient flows		partitions to fibre	partitions to liquor	SYSTEMIC, 2021
	Mass	30%	70%	
	Water	27%	73%	
	N-total	35%	65%	
	P-total	45%	55%	
	K-total	27%	73%	
DAF CAPEX	£84,000			Verbeke, Van Dijk & Brienza, 2021
DAF OPEX	£227,651 per year			Verbeke, Van Dijk & Brienza, 2021
DAF separation rates and nutrient flows		partitions to fibre	partitions to liquor	Verbeke, Van Dijk & Brienza, 2021
	Mass	31%	69%	
	Water	31%	69%	
	N-total	34%	66%	
	P-total	92%	8%	
	K-total	24%	76%	
Hopper to fill bulk bag (CAPEX)	£600			Website[20]

Table 49 Modelled data outputs

Technology step	Annual CAPEX (£)	Annual OPEX (£)	Revenue (£)
Screw press	-100,476	-13,838	0
Dissolved air flotation (DAF)	-84,000	-227,651	0
Spreading to land savings	0	188,236	0
Hopper for fibre bagging	-600	0	0
Fibre export (59,600t)	0	0	213,288

Revenue per tonne digestate treated (£/t)	1.31
Revenue per MWh generated (£/t)	2.49

Positive modelled figure indicates that there will be an income to the business £1.31 per tonne of digestate treated or £2.49 per MWh generated

Model sensitivity considerations

A sensitivity analysis was conducted for the capture of phosphorus for export valorisation process. This consisted of:

[20] https://metalcagesandpallets.co.uk/products/free-standing-bulk-bag-tonne-bag-filling-hopper?variant=32823191273569

- A high and low value for ammonium nitrate of £283 and £839
- A high and low value for Muriate of potash of £254 and £626, and
- A high and low value for Triple super phosphate of £343 and £717
- Though not fully within the sensitivity analysis the sale of fibre as a bulk soil improver for £0.21 per kg was also considered

Results are presented for each of the different sensitivity factors considered and compared to the overall results from the model itself (Table 50).

Table 50 Capture of phosphorus for export - Sensitivity analysis

Sensitivity factor	Plant type	Size	Revenue per tonne digestate treated (£/t)	Revenue per MWh generated (£/t)
Core model output:	**F**	**S**	**1.31**	**2.49**
Ammonium nitrate (AN), low, £283	F	S	1.31	2.49
Ammonium nitrate (AN), high, £839	F	S	1.31	2.49
Muriate of potash (MOP), low, £254	F	S	1.31	2.49
Muriate of potash (MOP), high, £626	F	S	1.31	2.49
Triple super phosphate (TSP), low, £343	F	S	0.67	1.28
Triple super phosphate (TSP), high, £717	F	S	1.99	3.79

The variation in ammonium nitrate values changes the calculated value of nitrogen used in the model, but acidification has no impact on potash and does not therefore change the overall commercial position.

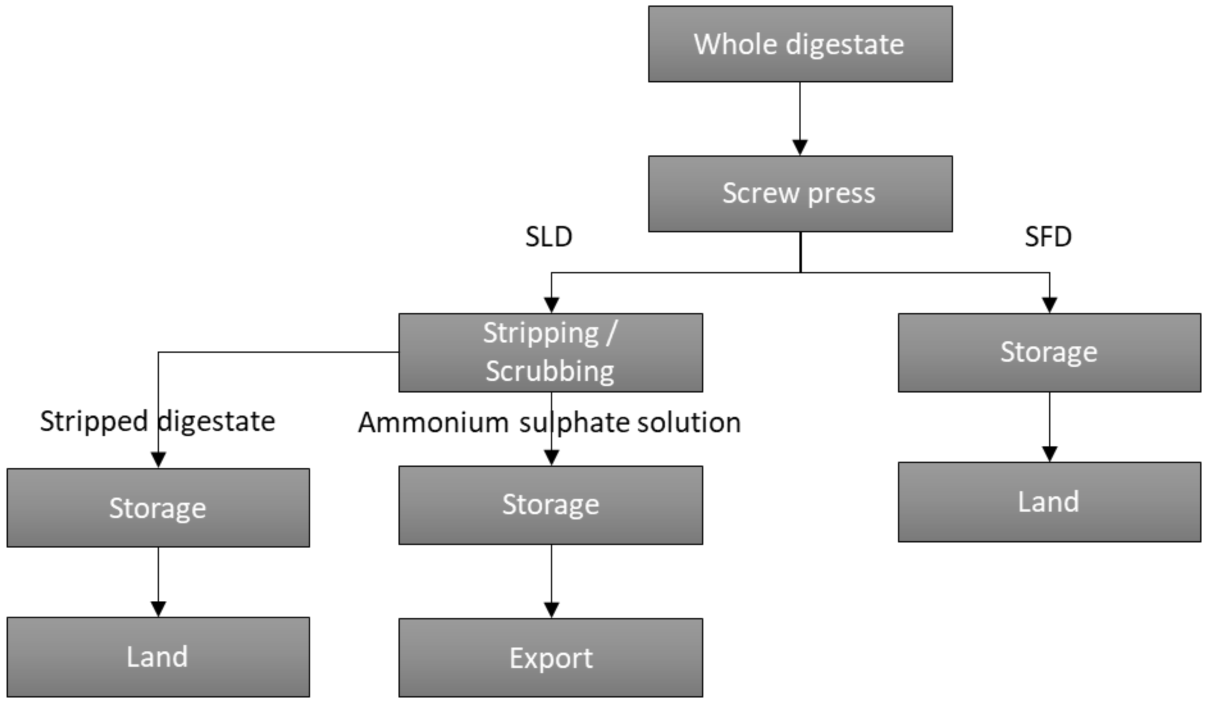
The variation in muriate of potash values changes the calculated value of potassium used in the model, but acidification has no impact on potash and does not therefore change the overall commercial position.

The variation in triple super phosphate values changes the calculated value of phosphorus used in the model but acidification has no impact on phosphate and does not therefore change the overall commercial position. Since this valorisation process values phosphorus, changes in P fertiliser prices are reflected in changes in value of exported fibre digestate. Revenues per tonne digestate treated and per MWh generated decreased by almost 50% with the low value and increased by over 50% with the high value. The low triple super phosphate value makes the net revenue for both factors lower but still positive and therefore still profitable, while high values increase profitability even more.

For this archetype, sale of fibre as a bulk soil improver was also considered. Annually this was found to have a value of over £12 million, far in excess of the £210,000 annually from sale for the nutrient value. This indicates large potential in this alternative revenue source, but this was not considered further in the sensitivity analysis.

8.2.3 Archetype 3. N capture for export as ammonium sulphate

Figure 33 Process flow for valorisation archetype 3



Modelling nitrogen capture for export as ammonium sulphate includes costs and mass balances. The mass flows have been used to calculate the amount of ammonium sulphate produced. Additional costs and revenues considered in this scenario included:

- Screw press (CAPEX/OPEX)
- Stripping and scrubbing (CAPEX/OPEX)
- Ammonium sulphate storage (CAPEX)
- Ammonium sulphate export (Revenue)

The total costs have been modelled for small farm AD plants across their lifetime of 20 years. The CAPEX and OPEX of the valorisation process blocks have been combined with revenues to give an annual revenue per tonne of digestate processed. A positive revenue means the digestate as valorised delivers an income, while a negative revenue means that costs have increased compared to the relevant 'non valorisation' baseline.

Valorisation has been calculated as the value of the exported ammonium sulphate. To calculate the amount of ammonium sulphate produced the amount of nitrogen stripped in the stripping and scrubbing technology from the abatement modelling has been used, this is then converted to an amount of ammonium sulphate that can be valued.

Table 51 Critical modelled data points for Archetype 3

Data	Figure			Source
Screw press CAPEX	£100,476			Supplier data
Screw press OPEX	£13,838 per year			Supplier data
Screw press separation rates and nutrient flows		partitions to fibre	partitions to liquor	SYSTEMIC, 2021
	Mass	30%	70%	
	Water	27%	73%	
	N-total	35%	65%	
	P-total	45%	55%	
	K-total	27%	73%	
Stripping/scrubbing CAPEX	£1,591,801			Verbeke, Van Dijk & Brienza, 2021
Stripping/scrubbing OPEX	£935,000 per year			Verbeke, Van Dijk & Brienza, 2021
Ammonia sulphate value	£170.96 per t of recovered ammonium sulphate solution (calculated from UK produced AN)			AHDB[21]

Table 52 Modelled data outputs Archetype 3

Technology step	Annual CAPEX (£)	Annual OPEX (£)	Revenue (£)
Screw press	-100,476	-13,838	0
Stripping and scrubbing	-1,697,103	-935,000	0
Spreading to land savings	0	0	0
Ammonium sulphate storage (3,440t)	-105,302	0	0
Ammonium sulphate export (3,440t)	0	0	587,915

Revenue per tonne digestate treated (£/t)	-3.96
Revenue per MWh generated (£/t)	-7.55

Negative modelled figures indicate a cost of £3.96 per tonne of digestate treated or £7.55 per MWh generated

[21] https://ahdb.org.uk/fertiliser-information

Model sensitivity considerations

Sensitivity analysis considered:

- A high and low value for Ammonium Nitrate of £283 and £839
- A high and low value for Muriate of potash of £254 and £626, and
- A high and low value for Triple super phosphate of £343 and £717

Both the muriate of potash and triple super phosphate price variation will have no impact on the revenues expected for this process as these nutrients are not included in the value calculations for this process as revenue is only derived from the sale of ammonium sulphate which is linked to the nitrogen price only.

Results are presented for each of the different sensitivity factors considered and compared to the overall results from the model itself (Table 53).

Table 53 N capture for export as ammonium sulphate - Sensitivity analysis results

Sensitivity factor	Plant type	Size	Revenue per tonne digestate treated (£/t)	Revenue per MWh generated (£/t)
Core model output:	**F**	**S**	**-3.96**	**-7.55**
Ammonium nitrate (AN), low, £283	F	S	-6.72	-12.80
Ammonium nitrate (AN), high, £839	F	S	-2.11	-4.02
Muriate of potash (MOP), low, £254	F	S	-3.96	-7.55
Muriate of potash (MOP), high, £626	F	S	-3.96	-7.55
Triple super phosphate (TSP), low, £343	F	S	-3.96	-7.55
Triple super phosphate (TSP), high, £717	F	S	-3.96	-7.55

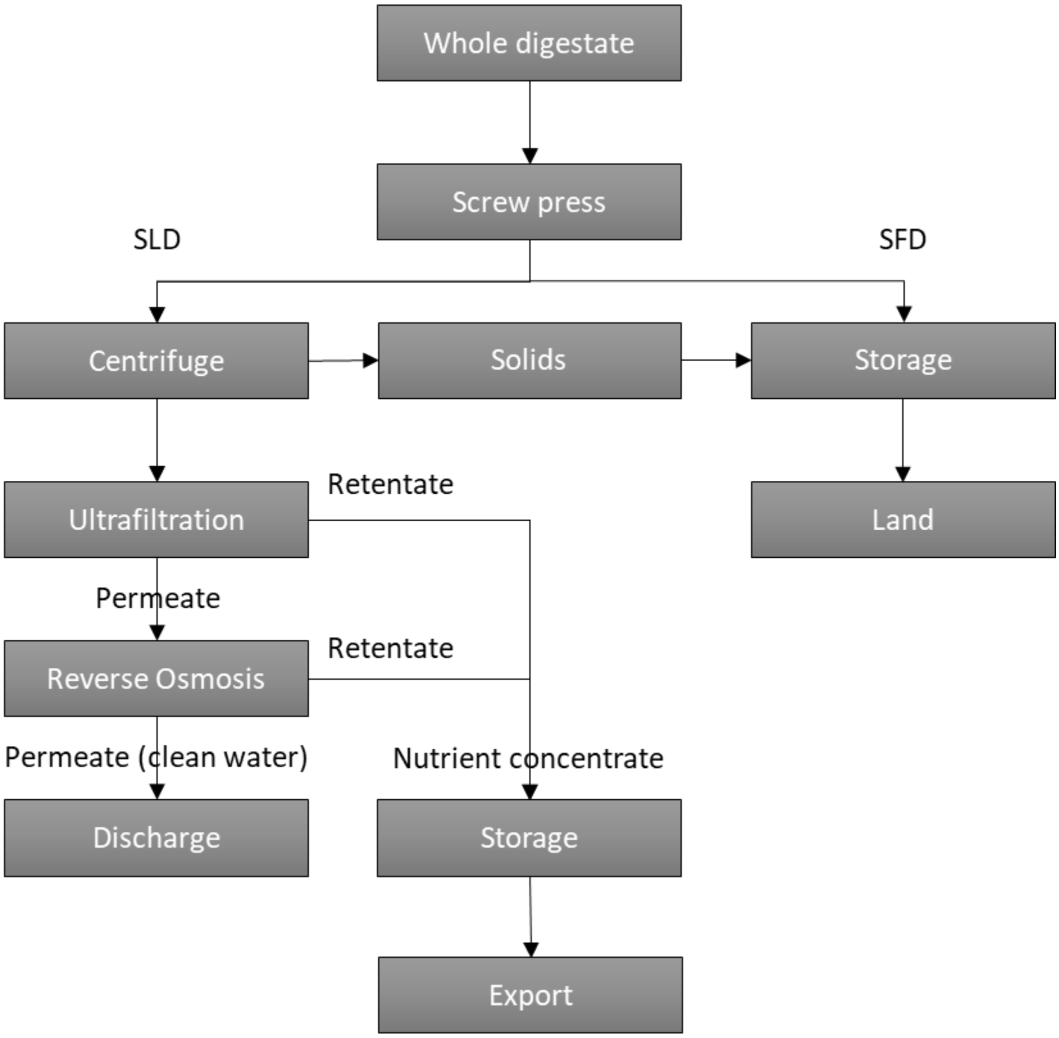
The variation in ammonium nitrate values changes the calculated value of nitrogen used in the model. For this valorisation process value is calculated as the value of the sale of ammonium sulphate which in the model is directly linked to the value of in ammonium nitrate. Therefore, as nitrogen prices rise the value of the exported product increases and vice versa if the price falls. This valorisation process is sensitive to the change in nitrogen prices. Revenue per tonne digestate treated and per MWh generated decreased by almost 70% with the low value and increased by over 45% with the high value. The low ammonium nitrate value makes the net cost for both factors more negative and therefore even further from profitability. Whilst the high prices bring the net cost closer to zero it is not enough to make the process profitable.

The variation in muriate of potash values changes the calculated value of potassium used in the model, but acidification has no impact on potash and does not therefore change the overall commercial position.

The variation in triple super phosphate values changes the calculated value of phosphorus used in the model but acidification has no impact on phosphate and does not therefore change the overall commercial position.

8.2.4 Archetype 4. Nutrient concentrate for export

Figure 34 Process flow for valorisation archetype 4



Nutrient concentrate modelling includes costs, mass balance and nutrient flows. The mass flows have been used to calculate the nutrient flow to calculate the value of exported materials. Additional costs and revenues of the valorisation process include:

- Screw press (CAPEX/OPEX)
- Centrifuge (CAPEX/OPEX)
- Ultrafiltration (CAPEX/OPEX)
- Reverse osmosis (CAPEX/OPEX)

- Spreading to land (OPEX)
- Nutrient concentrate storage (CAPEX)
- Nutrient concentrate export (Revenue)

The total costs have been modelled for small farm AD plants across their lifetime of 20 years. The CAPEX and OPEX of the valorisation process blocks have been combined with revenues to give an annual revenue per tonne of digestate processed. A positive revenue means the digestate as valorised delivers an income, while a negative revenue means that costs have increased compared to the relevant 'non valorisation' baseline.

Valorisation has been calculated as the value of the exported nutrient concentrate. To calculate value of the nutrient concentrate, the nutrient flows are tracked through each process block as a percentage, this is then combined with the mass flows to estimate the amount of nutrients in the exported nutrient concentrate and then given a value.

Table 54 Critical modelled data points for Archetype 4

Data	Figure			Source
Screw press CAPEX	£100,476			Supplier data
Screw press OPEX	£13,838 per year			Supplier data
Screw press separation rates and nutrient flows		partitions to fibre	partitions to liquor	SYSTEMIC, 2021
	Mass	30%	70%	
	Water	27%	73%	
	N-total	35%	65%	
	P-total	45%	55%	
	K-total	27%	73%	
Centrifuge CAPEX	£160,110			Verbeke, Van Dijk & Brienza, 2021
Centrifuge OPEX	£27,677 per year			Verbeke, Van Dijk & Brienza, 2021
Centrifuge separation rates and nutrient flows		partitions to fibre	partitions to liquor	SYSTEMIC, 2021
	Mass	28%	72%	
	Water	25%	75%	
	N-total	41%	59%	
	P-total	79%	21%	
	K-total	26%	74%	
Ultrafiltration CAPEX	£2,374,429			Verbeke, Van Dijk & Brienza, 2021
Ultrafiltration OPEX	£156,000 per year			Verbeke, Van Dijk & Brienza, 2021
Ultrafiltration separation rates and nutrient flows		partitions to retentate	partitions to permeate	Brienza et a., 2020 (Water from SYSTEMIC, 2021)
	Mass	27%	73%	

Data	Figure			Source
	Water	27%	73%	
	N-total	29%	71%	
	P-total	79%	21%	
	K-total	22%	78%	
Reverse osmosis CAPEX	£2,739,726			Verbeke, Van Dijk & Brienza, 2021
Reverse osmosis OPEX	£206,000 per year			Verbeke, Van Dijk & Brienza, 2021
Reverse osmosis separation rates and nutrient flows		partitions to retentate	partitions to permeate	SYSTEMIC, 2021
	Mass	46%	54%	
	Water	45%	55%	
	N-total	91%	9%	
	P-total	98%	2%	
	K-total	95%	5%	

Table 55 Table 2: Modelled data outputs Archetype 4

Technology step	Annual CAPEX (£)	Annual OPEX (£)	Revenue (£)
Screw press	-100,476	-13,838	0
Centrifuge	-160,110	-27,677	0
Ultrafiltration	-2,374,429	-156,000	0
Reverse osmosis	-2,739,726	-206,000	0
Spreading to land savings	0	104,437	0
Nutrient concentrate storage (35,200t)	-1,077,135	0	0
Nutrient concentrate export (35,200t)	0	0	524,845

Revenue per tonne digestate treated (£/t)	-0.84
Revenue per MWh generated (£/t)	-1.60

Negative modelled figures indicate a cost of £0.84 per tonne of digestate treated or £1.60 per MWh generated

Model sensitivity considerations

The sensitivity analysis for this scenario examined:

- A high and low value for ammonium nitrate of £283 and £839
- A high and low value for Muriate of potash of £254 and £626, and
- A high and low value for Triple super phosphate of £343 and £717

- Though not fully within the sensitivity analysis the sale of the concentrate at retail for £30 per 10L container was also considered

Results are presented for each of the different sensitivity factors considered and compared to the overall results from the model itself (Table 56).

Table 56 Nutrient concentrate for export - Sensitivity analysis results

Sensitivity factor	Plant type	Size	Revenue per tonne digestate treated (£/t)	Revenue per MWh generated (£/t)
Core model output:	**F**	**S**	**-0.84**	**-1.60**
Ammonium nitrate (AN), low, £283	F	S	-2.09	-3.98
Ammonium nitrate (AN), high, £839	F	S	-0.01	-0.01
Muriate of potash (MOP), low, £254	F	S	-1.90	-3.62
Muriate of potash (MOP), high, £626	F	S	-0.48	-0.92
Triple super phosphate (TSP), low, £343	F	S	-0.92	-1.75
Triple super phosphate (TSP), high, £717	F	S	-0.76	-1.45

The variation in ammonium nitrate values changes the calculated value of nitrogen used in the model. For this valorisation process value is calculated as the nutrient values of nitrogen, phosphorus and potassium (NPK). Therefore, as nitrogen prices rise the value of the exported product increases and vice versa. This valorisation process is very sensitive to the change in nitrogen prices. Revenues per tonne digestate treated and per MWh generated decreased by almost 2.5 times with the low value and increased by almost 100% with the high value. The low ammonium nitrate value makes the net revenue for both factors more negative and therefore even further from profitability. Whilst the high prices bring the net cost closer to zero it is not enough to make the process profitable, though it is very close.

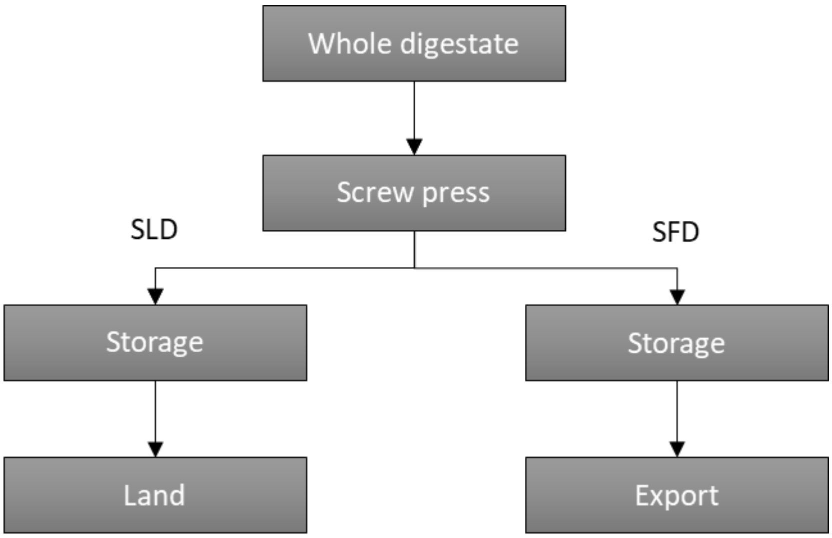
The variation in muriate of potash values changes the calculated value of potassium used in the model. For this valorisation process value is calculated as the nutrient values of NPK. Therefore, as potassium prices rise the value of the exported product increases and vice versa if the price falls. This valorisation process is very sensitive to the change in potassium prices. Revenues per tonne digestate treated and per MWh generated decreased by over 2 times with the low value and increased by just over 40% with the high value. The low muriate of potash value makes the net revenue for both factors more negative and therefore even further from profitability. Whilst the high prices bring the net cost closer to zero it is not enough to make the process profitable.

The variation in triple super phosphate values changes the calculated value of phosphorus used in the model. For this valorisation process value is calculated as the nutrient values of NPK. Therefore, as phosphorus prices rise the value of the exported product increases and vice versa if the price falls. This valorisation process is not very sensitive to the change in phosphorus prices. Revenues per tonne digestate treated and per MWh generated decreased by almost 10% with the low value and increased by almost 10% with the high value. The low triple super phosphate value makes the net revenue for both factors more negative and therefore even further from profitability. Whilst the high prices bring the net cost closer to zero it is not enough to make the process profitable.

For nutrient concentrate for export the sale of the concentrate at retail value was also considered. Annually this was found to have an extremely high value of over £105 million, far in excess of the £525,000 annually from sale for the nutrient value alone. This indicates large potential in this alternative revenue source, but this was not considered further in the sensitivity analysis.

8.2.5 Archetype 5. Fibre for export - farm plant

Figure 35 Process flow for valorisation archetype 5



Modelling in this scenario includes costs, mass balances and nutrient flows. The mass flows have been used to calculate the nutrient flow to calculate the value of exported materials. Additional costs and revenues of the valorisation process that have been modelled are:

- Screw press (CAPEX/OPEX)
- Spreading to land (OPEX)
- Fibre bagging line (CAPEX)

- Fibre export (Revenue)

The total costs have been modelled for small farm AD plants across their lifetime of 20 years. The CAPEX and OPEX of the valorisation process blocks have been combined with revenues to give an annual revenue per tonne of digestate processed. A positive revenue means the digestate as valorised delivers an income, while a negative revenue means that costs have increased compared to the relevant 'non valorisation' baseline.

Table 57 Critical modelled data points for Archetype 6

Data	**Figure**			**Source**
Screw press CAPEX	£100,476			Supplier data
Screw press OPEX	£13,838 per year			Supplier data
Screw press separation rates and nutrient flows		partitions to fibre	partitions to liquor	SYSTEMIC, 2021
	Mass	30%	70%	
	Water	27%	73%	
	N-total	35%	65%	
	P-total	45%	55%	
	K-total	27%	73%	
Hopper to fill bulk bag (CAPEX)	£600			website[22]

Valorisation has been calculated as the NPK value of the exported fibre. To calculate value of the exported fibre, the nutrient content is calculated after the screw press step as a percentage, this is then combined with the mass flows to estimate the amount of nutrients in the exported fibre and then given a value.

Table 58 Modelled data outputs – Archetype 6

Technology step	Annual CAPEX (£)	Annual OPEX (£)	Revenue (£)
Screw press	-100,476	-13,838	0
Spreading to land savings	0	129,610	0
Hopper for fibre bulking	-600	0	0
Fibre export (34,600t)	0	0	480,944
Revenue per tonne digestate treated (£/t)	5.14		
Revenue per MWh generated (£/t)	9.79		

[22] https://metalcagesandpallets.co.uk/products/free-standing-bulk-bag-tonne-bag-filling-hopper?variant=32823191273569

Positive modelled figures indicates that there will be a profit to the business of £5.14 per tonne of digestate treated or £9.79 per MWh generated.

Model sensitivity considerations

Sensitivity analysis for this scenario considered:

- A high and low value for Ammonium nitrate of £283 and £839
- A high and low value for Muriate of potash of £254 and £626, and
- A high and low value for Triple super phosphate of £343 and £717
- Additionally, the sale of fibre as a bulk soil improver for £0.21 per kg was considered

Results are presented for each of the different sensitivity factors considered and compared to the overall results from the model itself (Table 59).

Table 59 Fibre for export - Sensitivity analysis results

Sensitivity factor	Plant type	Size	Revenue per tonne digestate treated (£/t)	Revenue per MWh generated (£/t)
Core model output:	**F**	**S**	**5.14**	**9.79**
Ammonium nitrate (AN), low, £283	F	S	3.92	7.47
Ammonium nitrate (AN), high, £839	F	S	5.95	11.34
Muriate of potash (MOP), low, £254	F	S	4.59	8.74
Muriate of potash (MOP), high, £626	F	S	5.32	10.14
Triple super phosphate (TSP), low, £343	F	S	4.83	9.21
Triple super phosphate (TSP), high, £717	F	S	5.46	10.40

The variation in ammonium nitrate values changes the calculated value of nitrogen used in the model. For this valorisation process value is calculated as the nutrient values of nitrogen, phosphorus and potassium (NPK). Therefore, as nitrogen prices rise the value of the exported product increases and vice versa. This valorisation process is sensitive to the change in nitrogen prices. Revenues per tonne digestate treated and per MWh generated decreased by over 20% with the low value and increased by almost 15% with the high value. The low ammonium nitrate value makes the net revenue for both factors lower but still positive and therefore still profitable. Whilst the high price increases the processes' profitability even more.

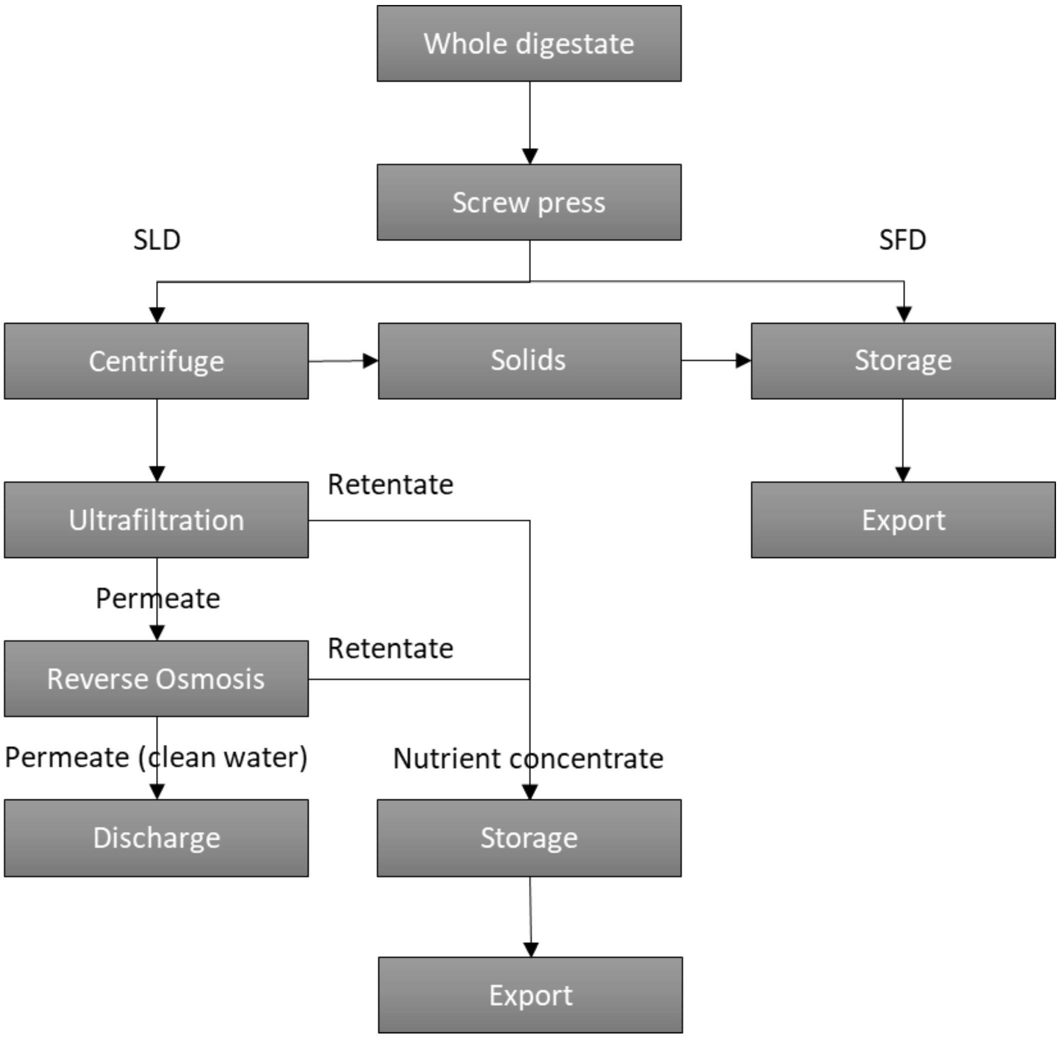
The variation in muriate of potash values changes the calculated value of potassium used in the model. For this valorisation process value is calculated as the nutrient values of NPK. Therefore, as potassium prices rise the value of the exported product increases and vice versa. This valorisation process is not very sensitive to the change in potassium prices. Revenues per tonne digestate treated and per MWh generated decreased by over 10% with the low value and increased by just over 3% with the high value. The low muriate of potash value makes the net revenue for both factors lower but still positive and therefore still profitable. Whilst the high price increases the processes’ profitability even more.

The variation in triple super phosphate values changes the calculated value of phosphorus used in the model. For this valorisation process value is calculated as the nutrient values of NPK. Therefore, as phosphorus prices rise the value of the exported product increases and vice versa. This valorisation process is also not very sensitive to the change in phosphorus prices. Revenues per tonne digestate treated and per MWh generated decreased by over 5% with the low value and increased by over 6% with the high value. The low triple super phosphate value makes the net revenue for both factors lower but still positive and therefore still profitable. Whilst the high price increases the processes’ profitability even more.

Where fibre is sold as a bulk soil improver (to amenity / domestic consumers) this was found to deliver an annual revenue of more than £7.3 million, far in excess of the £480,000 annually from sale for the nutrient value. This indicates large potential in this alternative revenue source, but this was not considered further in the sensitivity analysis.

8.2.6 Archetype 6. Nutrient concentrate and fibre for export - farm plant

Figure 36 Process flow for valorisation archetype 6



Modelling in this scenario includes costs, mass balances and nutrient flows. The mass flows have been used to calculate the nutrient flow to calculate the value of exported materials. Additional costs and revenues of the valorisation process that have been modelled are:

- Screw press (CAPEX/OPEX)
- Centrifuge (CAPEX/OPEX)
- Ultrafiltration (CAPEX/OPEX)
- Reverse osmosis (CAPEX/OPEX)
- Spreading to land (OPEX)
- Nutrient concentrate storage (CAPEX)
- Nutrient concentrate export (Revenue)
- Separated fibre export (Revenue)

The total costs have been modelled for small farm AD plants across their lifetime of 20 years. The CAPEX and OPEX of the valorisation process blocks have been combined with revenues to give an annual revenue per tonne of digestate processed. A positive revenue means the digestate as valorised delivers an income, while a negative revenue means that costs have increased compared to the relevant 'non valorisation' baseline.

Valorisation has been calculated as the value of the exported nutrient concentrate and separated fibre. To calculate value of the nutrient concentrate and separated fibre, the nutrient content is tracked through each of the process blocks as a percentage, for the nutrient concentrate this involves all steps including reverse osmosis, while for the separated fibre only the screw press and centrifuge have been applied. These nutrient contents are then combined with the mass flows to allow NPK values to be allocated to each output.

Table 60 Critical modelled data points for Archetype 5

Data	Figure			Source
Screw press CAPEX	£100,476			Supplier data
Screw press OPEX	£13,838 per year			Supplier data
Screw press separation rates and nutrient flows		partitions to fibre	partitions to liquor	SYSTEMIC, 2021
	Mass	30%	70%	
	Water	27%	73%	
	N-total	35%	65%	
	P-total	45%	55%	
	K-total	27%	73%	
Centrifuge CAPEX	£160,110			Verbeke, Van Dijk & Brienza, 2021
Centrifuge OPEX	£27,677 per year			Verbeke, Van Dijk & Brienza, 2021
Centrifuge separation rates and nutrient flows		partitions to fibre	partitions to liquor	SYSTEMIC, 2021
	Mass	28%	72%	
	Water	25%	75%	
	N-total	41%	59%	
	P-total	79%	21%	
	K-total	26%	74%	
Ultrafiltration CAPEX	£2,374,429			Verbeke, Van Dijk & Brienza, 2021
Ultrafiltration OPEX	£156,000 per year			Verbeke, Van Dijk & Brienza, 2021

Ultrafiltration separation rates and nutrient flows		partitions to retentate	partitions to permeate	Brienza et a., 2020 (water from SYSTEMIC, 2021)
	Mass	27%	73%	
	Water	27%	73%	
	N-total	29%	71%	
	P-total	79%	21%	
	K-total	22%	78%	
Reverse osmosis CAPEX	£2,739,726			Verbeke, Van Dijk & Brienza, 2021
Reverse osmosis OPEX	£206,000 per year			Verbeke, Van Dijk & Brienza, 2021
Reverse osmosis separation rates and nutrient flows		partitions to retentate	partitions to permeate	SYSTEMIC, 2021
	Mass	46%	54%	
	Water	45%	55%	
	N-total	91%	9%	
	P-total	98%	2%	
	K-total	95%	5%	
Hopper to fill bulk bag (CAPEX)	£600			website[23]

Table 61 Modelled data outputs – Archetype 5

Technology step	Annual CAPEX (£)	Annual OPEX (£)	Revenue (£)
Screw press	-100,476	-13,838	0
Centrifuge	-160,110	-27,677	0
Ultrafiltration	-2,374,429	-156,000	0
Reverse osmosis	-2,739,726	-206,000	0
Spreading to land savings	0	318,725	0
Nutrient concentrate storage (35,200t)	-1,077,135	0	0
Nutrient concentrate export (35,200t)	0	0	524,845
Fibre export	0	0	860,546
Revenue per tonne digestate treated (£/t)	8.49		
Revenue per MWh generated (£/t)	16.18		

Positive modelled figure indicates that there will be a profit to the business of £8.49 per tonne of digestate treated or £16.18 per MWh generated

[23] https://metalcagesandpallets.co.uk/products/free-standing-bulk-bag-tonne-bag-filling-hopper?variant=32823191273569

Model sensitivity considerations

A sensitivity analysis was conducted for the nutrient concentrate and fibre for export valorisation process. This consisted of:

- A high and low value for ammonium nitrate of £283 and £839
- A high and low value for Muriate of potash of £254 and £626, and
- A high and low value for Triple super phosphate of £343 and £717
- Though not fully within the sensitivity analysis the sale of the concentrate at retail value for £30 per 10L container was also considered
- Additionally, the sale of fibre as a bulk soil improver at retail values of £0.21 per kg was considered

Results are presented for each of the different sensitivity factors considered and compared to the overall results from the model itself (Table 62).

Table 62 Nutrient concentrate and fibre for export - Sensitivity analysis results

Sensitivity factor	Plant type	Size	Revenue per tonne digestate treated (£/t)	Revenue per MWh generated (£/t)
Core model output:	**F**	**S**	**8.49**	**16.18**
Ammonium nitrate (AN), low, £283	F	S	5.10	9.72
Ammonium nitrate (AN), high, £839	F	S	10.76	20.51
Muriate of potash (MOP), low, £254	F	S	6.49	12.38
Muriate of potash (MOP), high, £626	F	S	9.16	17.47
Triple super phosphate (TSP), low, £343	F	S	7.82	14.91
Triple super phosphate (TSP), high, £717	F	S	9.20	17.54

The variation in ammonium nitrate values changes the calculated value of nitrogen used in the model. For this valorisation process value is calculated as the nutrient values of nitrogen, phosphorous and potassium (NPK). Therefore, as nitrogen prices rise the value of the exported product increases and vice versa. This valorisation process is very sensitive to the change in nitrogen prices. Revenues per tonne digestate treated and per MWh generated decreased by almost 40% with the low value and increased by over 25% with the high value. The low ammonium nitrate value makes the net revenue for both factors lower but still positive and therefore still profitable. Whilst the high price increases the processes' profitability even more.

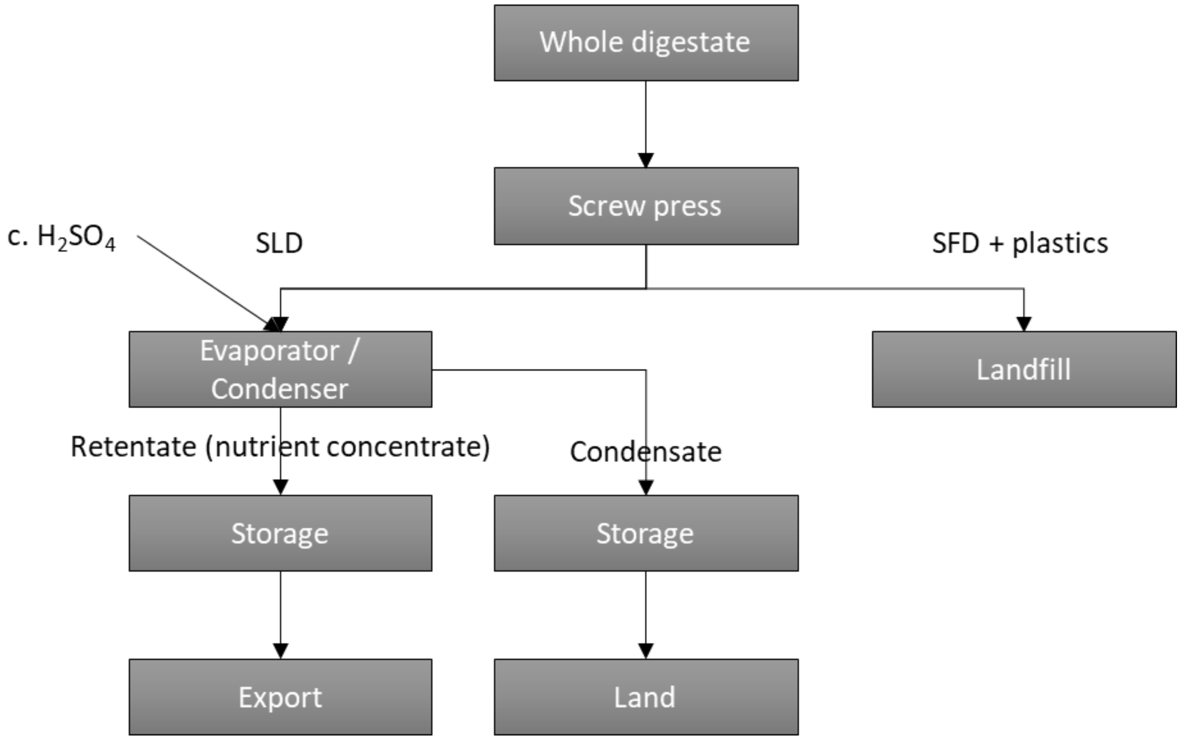
The variation in muriate of potash values changes the calculated value of potassium used in the model. For this valorisation process value is calculated as the nutrient values of NPK. Therefore, as potassium prices rise the value of the exported product increases and vice versa. This valorisation process is a bit less sensitive to the change in potassium prices. Revenues per tonne digestate treated and per MWh generated decreased by almost 25% with the low value and increased by almost 8% with the high value. The low muriate of potash value makes the net revenue for both factors lower but still positive and therefore still profitable. Whilst the high price increases the processes' profitability even more.

The variation in triple super phosphate values changes the calculated value of phosphorus used in the model. For this valorisation process value is calculated as the nutrient values of NPK. Therefore, as phosphorus prices rise the value of the exported product increases and vice versa. This valorisation process is not very sensitive to the change in phosphorus prices. Revenues per tonne digestate treated and per MWh generated decreased by almost 8% with the low value and increased by just over 8% with the high value. The low triple super phosphate value makes the net revenue for both factors lower but still positive and therefore still profitable. Whilst the high price increases the processes' profitability even more.

Sale of the concentrate at retail value was also considered. Annually this was found to have an extremely high value of over £105 million, far in excess of the £1.3 million annually from sale for the nutrient value. Sale of fibre as a bulk soil improver was also considered. Annually this was found to have a value of over £12 million, far in excess of the £1.3 million annually from sale for the nutrient value. This indicates large potential in both these alternative revenue source, but they were not considered further in the sensitivity analysis.

8.2.7 Archetype 7. Nutrient concentrate for export, commercial plant

Figure 37 Process flow for valorisation archetype 7



Modelling in this scenario includes costs, mass balances and nutrient flows. The mass flows have been used to calculate the nutrient flow to calculate the value of exported materials. Additional costs and revenues of the valorisation process that have been modelled are:

- Screw press (CAPEX/OPEX)
- Acidification (CAPEX/OPEX)
- Evaporator (CAPEX/OPEX)
- Spreading to land (OPEX)
- Disposal costs (OPEX)
- Nutrient concentrate storage (CAPEX)
- Nutrient concentrate export (Revenue)

The total costs have been modelled for small farm AD plants across their lifetime of 20 years. The CAPEX and OPEX of the valorisation process blocks have been combined with revenues to give an annual revenue per tonne of digestate processed. A positive revenue means the digestate as valorised delivers an income, while a negative revenue means that costs have increased compared to the relevant 'non valorisation' baseline.

Valorisation has been calculated as the value of the exported nutrient concentrate. To calculate value, nutrients are tracked through each of the process blocks as percentages, these are then combined with the mass flows to estimate the amount (and hence value) of nutrients in the nutrient concentrate.

Table 63 Critical modelled data points for Archetype 7

Data	Figure			Source
Screw press CAPEX	£100,476			Supplier data
Screw press OPEX	£13,838 per year			Suppler data
Screw press separation rates and nutrient flows		partitions to fibre	partitions to liquor	SYSTEMIC, 2021
	Mass	30%	70%	
	Water	27%	73%	
	N-total	35%	65%	
	P-total	45%	55%	
	K-total	27%	73%	
Store acidification CAPEX	£125,000			Foged et al., 2011
Acid requirements	16 litres per m^3 of digestate			Farming Forum[24]
Operation costs of field acidification	£0.94 per litre			Farming Forum[25]
Evaporator/condenser CAPEX	£2,394,936			Verbeke, Van Dijk & Brienza, 2021
Evaporator/condenser OPEX	£442,000 per year			Verbeke, Van Dijk & Brienza, 2021
Evaporator/condenser separation rates and nutrient flows		partitions to condensate	partitions to retentate	SYSTEMIC, 2021
	Mass	63%	37%	
	Water	71%	29%	
	N-total	3%	97%	
	P-total	0%	100%	
	K-total	0%	100%	
Plastic contaminated waste disposal costs via landfill	£113 per tonne			WRAP, 2021

Table 64 Modelled data outputs – archetype 7

Technology step	Annual CAPEX (£)	Annual OPEX (£)	Revenue (£)
Screw press	-100,476	-13,838	0
Acidification	-125,000	-451,279	0
Evaporator/condenser	-2,394,936	-442,000	0
Spreading to land savings	0	282,497	0
Disposal cost savings	0	0	0

[24] https://thefarmingforum.co.uk/index.php?threads/covering-slurry-lagoons-good-thing-or-not.298461/page-4
[25] https://thefarmingforum.co.uk/index.php?threads/covering-slurry-lagoons-good-thing-or-not.298461/page-4

Nutrient concentrate storage (18,800t)	-576,697	0	0
Nutrient concentrate export (18,800t)	0	0	326,539
Revenue per tonne digestate treated (£/t)	-10.72		
Revenue per MWh generated (£/t)	-7.58		

Negative modelled figures indicate a cost of £10.72 per tonne of digestate treated or £7.58 per MWh generated

Model sensitivity considerations

Sensitivity analysis for this scenario considered:

- A high and low value for Ammonium nitrate of £283 and £839
- A high and low value for Muriate of potash of £254 and £626, and
- A high and low value for Triple super phosphate of £343 and £717
- Though not fully within the sensitivity analysis the sale of the concentrate at retail for £30 per 10L container was also considered

Results are presented for each of the different sensitivity factors considered and compared to the overall results from the model itself (Table 65).

Table 65 Nutrient concentrate and for export, commercial plant - Sensitivity analysis results

Sensitivity factor	Plant type	Size	Revenue per tonne digestate treated (£/t)	Revenue per MWh generated (£/t)
Core model output:	**C**	**S**	**-10.72**	**-7.58**
Ammonium nitrate (AN), low, £283	C	S	-13.64	-9.64
Ammonium nitrate (AN), high, £839	C	S	-8.77	-6.19
Muriate of potash (MOP), low, £254	C	S	-11.53	-8.15
Muriate of potash (MOP), high, £626	C	S	-10.45	-7.38
Triple super phosphate (TSP), low, £343	C	S	-10.96	-7.74
Triple super phosphate (TSP), high, £717	C	S	-10.47	-7.40

The variation in ammonium nitrate values changes the calculated value of nitrogen used in the model. For this valorisation process value is calculated as the nutrient values of nitrogen, phosphorus and potassium (NPK). Therefore, as nitrogen prices rise the value of the exported product increases and vice versa. This valorisation process is sensitive to the change in nitrogen prices. Revenues per tonne digestate treated and per MWh generated decreased by over 25% with the low value and increased by almost 20% with the high value. The low ammonium nitrate value makes the net revenue for both factors more negative and therefore even further from profitability. Whilst the high prices bring the net cost closer to zero it is not enough to make the process profitable.

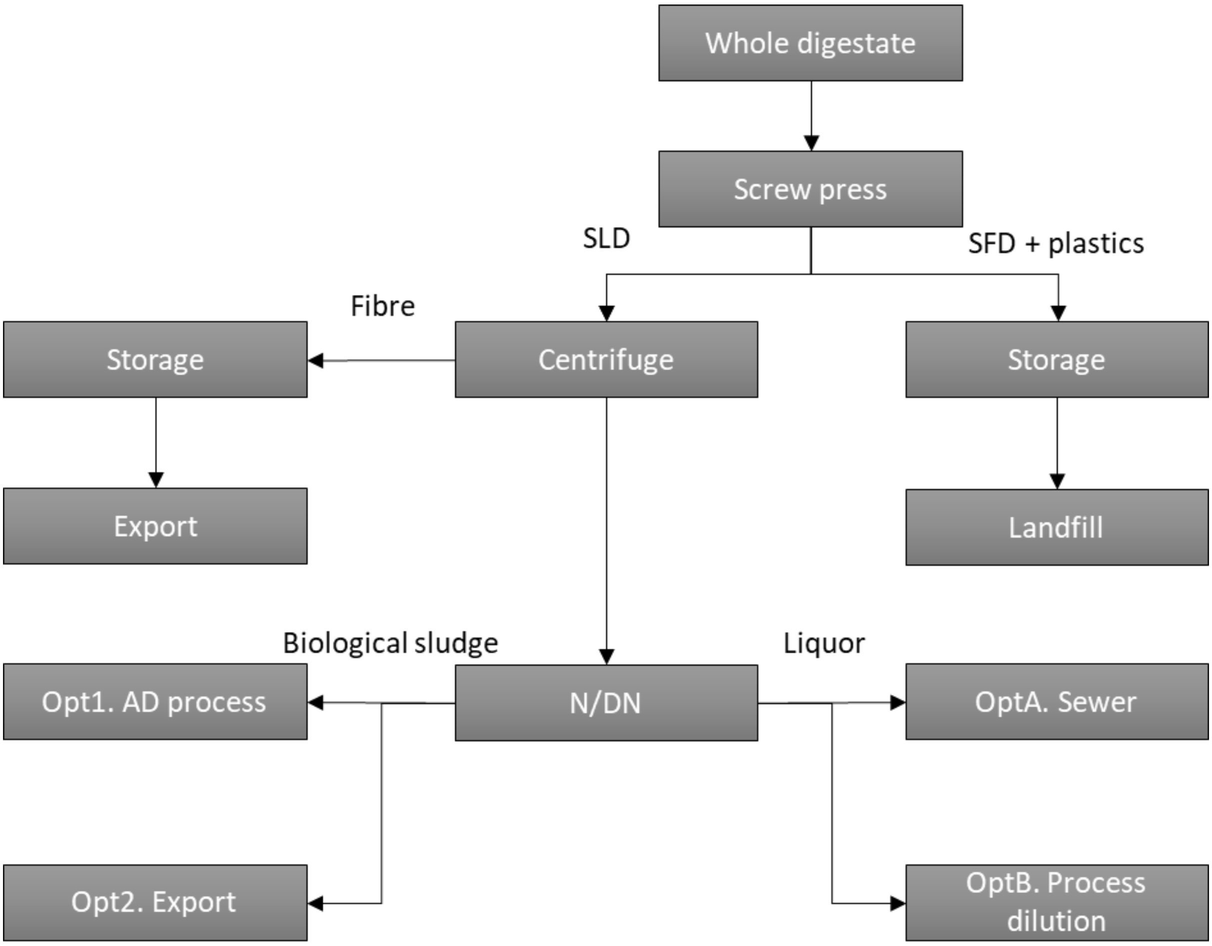
The variation in muriate of potash values changes the calculated value of potassium used in the model. For this valorisation process value is calculated as the nutrient values of NPK. Therefore, as potassium prices rise the value of the exported product increases and vice versa. This valorisation process is not very sensitive to the change in potassium prices. Revenues per tonne digestate treated and per MWh generated decreased by over 7% with the low value and increased by just over 2% with the high value. The low muriate of potash value makes the net revenue for both factors more negative and therefore even further from profitability. Whilst the high prices bring the net cost closer to zero it is not enough to make the process profitable.

The variation in triple super phosphate values changes the calculated value of phosphorus used in the model. For this valorisation process value is calculated as the nutrient values of NPK. Therefore, as phosphorus prices rise the value of the exported product increases and vice versa. This valorisation process is not very sensitive to the change in phosphorus prices. Revenues per tonne digestate treated and per MWh generated decreased by just over 2% with the low value and increased by a little over 2% with the high value. The low triple super phosphate value makes the net revenue for both factors more negative and therefore even further from profitability. Whilst the high prices bring the net cost closer to zero it is not enough to make the process profitable.

Selling fibre as a bulk soil improver was also considered. Annually this was found to have a value of over £7.3 million, far in excess of the £480,000 annually from sale for the nutrient value alone. This indicates large potential in this alternative revenue source, but this was not considered further in the sensitivity analysis.

8.2.8 Archetype 8. Discharge to sewer, commercial plant

Figure 38 Process flow for valorisation archetype 8



Modelling in this scenario includes costs, mass balances and nutrient flows. The mass flows have been used to calculate the nutrient flow to calculate the value of exported materials. After the nitrification/denitrification step there are multiple options: one of each of the biological sludge and liquor options must be taken, but they can be mixed and matched.

Additional costs and revenues of the valorisation process that have been modelled are:

- Screw press (CAPEX/OPEX)
- Centrifuge (CAPEX/OPEX)
- Nitrification/denitrification (CAPEX/OPEX)
- Spreading to land (OPEX)
- Disposal costs (OPEX)
- Export of fibre (Revenue)
- Option 1. Feed biological sludge back into the AD process (no cost)
- Option 2. Export of biological sludge (OPEX)
- Option A. Discharge liquor to sewer (OPEX)
- Option B. Use liquor as process dilution for the AD process (no cost)

The total costs have been modelled for small farm AD plants across their lifetime of 20 years. The CAPEX and OPEX of the valorisation process blocks have been combined with revenues to give an annual revenue per tonne of digestate processed. A positive revenue means the digestate as valorised delivers an income, while a negative revenue means that costs have increased compared to the relevant 'non valorisation' baseline.

The possible combinations are Option 1A, Option 1B, Option 2A and Options 2B. Each of these combinations has been modelled, in each combination of options there is no change before the nitrification/denitrification process.

Valorisation has been calculated as the NPK value of the exported fibre. To calculate this value, the nutrient contents are tracked through the screw press and centrifuge steps as percentages, these are then combined with the mass flows from the screw press and centrifuge processes to estimate the amount of nutrients and value in the exported fibre. For Option 2 the cost of disposing of the biological sludge is modelled at £15 per tonne disposed (in reality, recycled to land under waste regulatory controls).

Table 66 Critical modelled data points for Archetype 8

Data	Figure			Source
Screw press CAPEX	£100,476			Supplier data
Screw press OPEX	£13,838 per year			Supplier data
Screw press separation rates and nutrient flows		partitions to fibre	partitions to liquor	SYSTEMIC, 2021
	Mass	30%	70%	
	Water	27%	73%	
	N-total	35%	65%	
	P-total	45%	55%	
	K-total	27%	73%	
Centrifuge CAPEX	£160,110			Verbeke, Van Dijk & Brienza, 2021
Centrifuge OPEX	£27,677 per year			Verbeke, Van Dijk & Brienza, 2021
Centrifuge separation rates and nutrient flows		partitions to fibre	partitions to liquor	SYSTEMIC, 2021
	Mass	28%	72%	
	Water	25%	75%	
	N-total	41%	59%	
	P-total	79%	21%	
	K-total	26%	74%	
Nitrification / denitrification CAPEX	£1,500,000			DeVrieze et al., 2019
Nitrification / denitrification OPEX	£373,000 per year			DeVrieze et al., 2019
Nitrification / denitrification separation rates and nutrient flows		partitions to biological sludge	partitions to liquor	Lesschen et al., 2021 and Foged et al., 2011
	Mass	25%	75%	
	Water	25%	75%	
	N-total	23%	2%	
	P-total	81%	19%	
	K-total	25%	75%	
Plastic contaminated waste disposal costs via landfill	£113 per tonne			WRAP, 2021
Hopper to fill bulk bag (CAPEX)	£600			website[26]

[26] https://metalcagesandpallets.co.uk/products/free-standing-bulk-bag-tonne-bag-filling-hopper?variant=32823191273569

Table 67 Modelled data outputs – Archetype 8 Option 1A

Option 1A			
Technology step	**Annual CAPEX (£)**	**Annual OPEX (£)**	**Revenue (£)**
Screw press	-100,476	-13,838	0
Centrifuge	-160,110	-27,677	0
Nitrification/denitrification	-1,500,000	-373,000	0
Spreading to land savings	0	448,409	0
disposal saving	0	-190,570	0
Hopper for fibre bulking	-600	0	0
Fibre export (8,400t)	0	0	138,040
Revenue per tonne digestate treated (£/t)	-2.50		
Revenue per MWh generated (£/t)	-1.77		

Negative modelled figures indicate a cost of £2.50 per tonne of digestate treated or £1.77 per MWh generated

Table 68 Modelled data outputs – Archetype 8 Option 1B

Option 1B			
Technology step	**Annual CAPEX (£)**	**Annual OPEX (£)**	**Revenue (£)**
Screw press	-100,476	-13,838	0
Centrifuge	-160,110	-27,677	0
Nitrification/denitrification	-1,500,000	-373,000	0
Spreading to land savings	0	448,409	0
disposal saving	0	0	0
Hopper for fibre bulking	-600	0	0
Fibre export (8,400t)	0	0	138,040
Revenue per tonne digestate treated (£/t)	1.96		
Revenue per MWh generated (£/t)	1.39		

Positive modelled figure indicates that there will be a profit to the business of £1.96 per tonne of digestate treated or £1.39 per MWh generated

Table 69 Modelled data outputs – Archetype 8 Option 2A

Option 2A			
Technology step	**Annual CAPEX (£)**	**Annual OPEX (£)**	**Revenue (£)**
Screw press	-100,476	-13,838	0
Centrifuge	-160,110	-27,677	0
Nitrification/denitrification	-1,500,000	-373,000	0
Spreading to land savings	0	448,409	0
disposal saving	0	-268,055	0
Hopper for fibre bulking	-600	0	0
Fibre export (8,400t)	0	0	138,040
Revenue per tonne digestate treated (£/t)	-4.31		
Revenue per MWh generated (£/t)	-3.05		

Negative modelled figures indicate a cost of £4.31 per tonne of digestate treated or £3.05 per MWh generated

Table 70 Modelled data outputs Archetype 8 Option 2B

Option 2B			
Technology step	**Annual CAPEX (£)**	**Annual OPEX (£)**	**Revenue (£)**
Screw press	-100,476	-13,838	0
Centrifuge	-160,110	-27,677	0
Nitrification/denitrification	-1,500,000	-373,000	0
Spreading to land savings	0	448,409	0
disposal saving	0	-77,485	0
Hopper for fibre bulking	-600	0	0
Fibre export (8,400t)	0	0	138,040
Revenue per tonne digestate treated (£/t)	0.15		
Revenue per MWh generated (£/t)	0.11		

Positive modelled figure indicates that there will be a profit to the business of £0.15 per tonne of digestate treated or £0.11 per MWh generated

Model sensitivity considerations

The sensitivity analysis for this scenario considered:

- A high and low value for ammonium nitrate of £283 and £839
- A high and low value for Muriate of potash of £254 and £626, and
- A high and low value for Triple super phosphate of £343 and £717
- Though not fully within the sensitivity analysis the sale of the concentrate at retail for £30 per 10L container was also considered

Results are presented for each of the different sensitivity factors considered and compared to the overall results from the model itself (Table 71).

Table 71 Discharge to sewer, commercial plant - Sensitivity analysis results

Option 1A				
Sensitivity factor	Plant type	Size	Revenue per tonne digestate treated (£/t)	Revenue per MWh generated (£/t)
Core model output:	**C**	**S**	**-2.50**	**-1.77**
Ammonium nitrate (AN), low, £283	C	S	-3.73	-2.64
Ammonium nitrate (AN), high, £839	C	S	-1.67	-1.18
Muriate of potash (MOP), low, £254	C	S	-2.71	-1.91
Muriate of potash (MOP), high, £626	C	S	-2.43	-1.71
Triple super phosphate (TSP), low, £343	C	S	-2.69	-1.90
Triple super phosphate (TSP), high, £717	C	S	-2.30	-1.62

Option 1B				
Sensitivity factor	**Plant type**	**Size**	**Revenue per tonne digestate treated (£/t)**	**Revenue per MWh generated (£/t)**
Core model output:	**C**	**S**	**1.96**	**1.39**
Ammonium nitrate (AN), low, £283	C	S	0.73	0.52
Ammonium nitrate (AN), high, £839	C	S	2.79	1.97
Muriate of potash (MOP), low, £254	C	S	1.75	1.24
Muriate of potash (MOP), high, £626	C	S	2.04	1.44
Triple super phosphate (TSP), low, £343	C	S	1.78	1.25
Triple super phosphate (TSP), high, £717	C	S	2.16	1.53

Option 2A				
Sensitivity factor	Plant type	Size	Revenue per tonne digestate treated (£/t)	Revenue per MWh generated (£/t)
Core model output:	**C**	**S**	**-4.31**	**-3.05**
Ammonium nitrate (AN), low, £283	C	S	-5.55	-3.92
Ammonium nitrate (AN), high, £839	C	S	-3.49	-2.46
Muriate of potash (MOP), low, £254	C	S	-4.52	-3.20
Muriate of potash (MOP), high, £626	C	S	-4.24	-3.00
Triple super phosphate (TSP), low, £343	C	S	-4.50	-3.18
Triple super phosphate (TSP), high, £717	C	S	-4.11	-2.91

Option 2B				
Sensitivity factor	Plant type	Size	Revenue per tonne digestate treated (£/t)	Revenue per MWh generated (£/t)
Core model output:	**C**	**S**	**0.15**	**0.11**
Ammonium nitrate (AN), low, £283	C	S	-1.09	-0.77
Ammonium nitrate (AN), high, £839	C	S	0.98	0.69
Muriate of potash (MOP), low, £254	C	S	-0.06	-0.04
Muriate of potash (MOP), high, £626	C	S	0.22	0.16
Triple super phosphate (TSP), low, £343	C	S	-0.04	-0.03
Triple super phosphate (TSP), high, £717	C	S	0.35	0.25

The variation in ammonium nitrate values changes the calculated value of nitrogen used in the model. For this valorisation process value is calculated as the nutrient values of nitrogen, phosphorus and potassium (NPK). Therefore, as nitrogen prices rise the value of the exported product increases and vice versa. This valorisation process is sensitive to the change in nitrogen prices. Revenues per tonne digestate treated and per MWh vary for each option as indicated:

Option	Low price (decrease)	High price (increase)	Change from a negative result to positive?	Change from a positive result to negative?
1A	49%	33%	No	No
1B	60%	42%	No	No
2A	30%	20%	No	No
2B*	-625%	550%	No	Yes
***Due to very low modelled values in option 2B even small changes have dramatic results**				

Overall, with the exclusion of Options 2B this valorisation process is sensitive to changes in nitrogen values.

The variation in muriate of potash values changes the calculated value of potassium used in the model. For this valorisation process value is calculated as the nutrient values of NPK. Therefore, as potassium prices rise the value of the exported product increases and vice versa. This valorisation process is not very sensitive to the change in potassium prices, with the exception of option 2B due to the low values. Revenues per tonne digestate treated and per MWh vary for each option as indicated:

Option	Low price (decrease)	High price (increase)	Change from a negative result to positive?	Change from a positive result to negative?
1A	8%	3%	No	No
1B	10%	4%	No	No
2A	5%	2%	No	No
2B*	-140%	48%	No	Yes
***Due to very low modelled values in option 2B even small changes have dramatic results**				

Overall, with the exclusion of Option 2B this valorisation process is not very sensitive to changes in potassium values.

The variation in triple super phosphate values changes the calculated value of phosphorus used in the model. For this valorisation process value is calculated as the nutrient values of NPK. Therefore, as phosphorus prices rise the value of the exported product increases and vice versa. This valorisation process is not very sensitive to the change in phosphorus prices, with the exception of option 2B due to the low values. Revenues per tonne digestate treated and per MWh vary for each option as indicated:

Option	Low price (decrease)	High price (increase)	Change from a negative result to positive?	Change from a positive result to negative?
1A	8%	8%	No	No
1B	10%	10%	No	No
2A	4%	5%	No	No
2B*	-125%	134%	No	Yes
***Due to very low modelled values in option 2B even small changes have dramatic results**				

Overall, with the exclusion of Option 2B this valorisation process is not very sensitive to changes in phosphorus values.

Selling fibre as a bulk soil improver was also considered. Annually this was found to have a value of over £1.7 million, far in excess of the £138,000 annually from sale for its nutrient value. This indicates large potential in this alternative revenue source, but this was not considered further in the sensitivity analysis.

9.0 Summarised results

The results from the technoeconomic modelling have been summarised for presentation and improved accessibility in a Tableau format. This is available at:
https://public.tableau.com/shared/753H6HST6?:display_count=n&:origin=viz_share_link

The sections below include extracted screen grabs from the Tableau and are intended as illustrations of its content and functionality. It is advised that readers directly access the Tableau model to view the visualised data fully and to take advantage of the multiple comparisons that such visualisation enables.

The Tableau tool has 8 sections:

I. An introduction to using the tool
II. An overview of the mitigation options
III. Summary tables of cost data and qualitative data for each mitigation option
IV. Scatter plots for comparing data for each mitigation option
V. Individual summary dashboards for each mitigation option.
VI. An overview of the valorisation options
VII. A summary bar chart for valorisation option costs / revenues
VIII. A glossary of terms used to categorise various mitigation metrics

The TEA model has delivered outputs for three key metrics for the costs of mitigating each of the identified potential impacts of digestate. These are the cost per MWh generation, the cost per kg of impact abated and the cost per tonne of digestate treated. In addition, the assessment has collated information on the potential for pollution swapping, the regulatory complexity of all technology options, the TRL level and an assessment of the research team's confidence in the data that has been available for this work. Sensitivity analyses are not included in the Tableau visualisation.

9.1 Ammonia mitigation technologies

Illustration 1. Extracted Tableau table summarising all whole digestate ammonia mitigation options

Department for Business, Energy & Industrial Strategy

Mitigation Options for Whole Digestate: Ammonia

TRL	Regulatory Complexity	Pollution swapping potential	Data Quality
All	All	All	All

Mitigation Options	Plant type	Plant Size	TRL	Data Quality	Pollution swapping potential	Regulatory Complexity	Cost per MWh (WD)	Cost per kg ammonia abated	Cost per tonne (WD)
Acidification - Field	Commercial	Large	7	High	Amber	Amber	£2.05	£10.62	£2.91
		Medium	7	High	Amber	Amber	£2.05	£10.62	£2.91
		Small	7	High	Amber	Amber	£2.05	£10.62	£2.91
	Farm	Large	9	High	Amber	Amber	£5.27	£13.47	£2.77
		Medium	9	High	Amber	Amber	£5.27	£13.47	£2.77
		Small	9	High	Amber	Amber	£5.27	£13.47	£2.77
Acidification - Store (ammonia)	Commercial	Large	7	Medium	Amber	Amber	£3.36	£8.65	£4.76
		Medium	7	Medium	Amber	Amber	£3.43	£8.82	£4.85
		Small	7	Medium	Amber	Amber	£3.51	£9.04	£4.97
	Farm	Large	9	Medium	Amber	Amber	£10.24	£11.42	£4.71
		Medium	9	Medium	Amber	Amber	£10.31	£11.49	£4.74
		Small	9	Medium	Amber	Amber	£10.39	£11.59	£4.78
Gas tight cover (ammonia)	Commercial	Large	9	Low	Green	Green	£0.14	£1.44	£0.20
		Medium	9	Low	Green	Green	£0.14	£1.44	£0.20
		Small	9	Low	Green	Green	£0.14	£1.44	£0.20
	Farm	Large	9	Low	Green	Green	£0.38	£1.92	£0.20
		Medium	9	Low	Green	Green	£0.38	£1.92	£0.20
		Small	9	Low	Green	Green	£0.38	£1.92	£0.20
Injection spreading	Commercial	Large	9	Medium	Green	Green	£0.99	£2.24	£1.40
		Medium	9	Medium	Green	Green	£0.99	£2.24	£1.40
		Small	9	Medium	Green	Green	£0.99	£2.24	£1.40
	Farm	Large	9	Medium	Green	Green	£2.67	£2.98	£1.40
		Medium	9	Medium	Green	Green	£2.67	£2.98	£1.40
		Small	9	Medium	Green	Green	£2.67	£2.98	£1.40
Side stripping at 40%	Commercial	Large	9	Low	Amber	Red	£3.34	£28.26	£4.72
		Medium	9	Low	Amber	Red	£3.52	£29.78	£4.98
		Small	9	Low	Amber	Red	£3.75	£31.74	£5.31
	Farm	Large	9	Low	Amber	Red	£8.20	£30.07	£3.77
		Medium	9	Low	Amber	Red	£8.38	£30.75	£3.86
		Small	9	Low	Amber	Red	£7.72	£28.34	£3.55
Stripping and Scrubbing	Commercial	Large	9	Medium	Amber	Red	£6.89	£23.34	£9.75
		Medium	9	Medium	Amber	Red	£7.03	£23.81	£9.95
		Small	9	Medium	Amber	Red	£7.21	£24.41	£10.20
	Farm	Large	9	Medium	Amber	Red	£15.76	£23.13	£7.25
		Medium	9	Medium	Amber	Red	£15.91	£23.35	£7.32
		Small	9	Medium	Amber	Red	£16.09	£23.62	£7.40

Illustration 2. Extracted Tableau illustration summarising ammonia mitigation from use of separated liquor from digestate

Department for Business, Energy & Industrial Strategy

Mitigation Options for Separated Liquor: Ammonia

wrap

TRL	Regulatory Complexity	Pollution swapping potential	Data Quality
All	All	All	All

Mitigation Options	Plant type	Plant Size	TRL	Data Quality	Pollution swapping potential	Regulatory Complexity	Cost per MWh	Cost per kg ammonia abated (SL)	Cost per tonne
Acidification - Field	Commercial	Large	7	High	Amber	Amber	£1.83	£11.19	£2.87
		Medium	7	High	Amber	Amber	£1.83	£11.19	£2.87
		Small	7	High	Amber	Amber	£1.83	£11.19	£2.87
	Farm	Large	9	High	Amber	Amber	£4.40	£23.68	£2.57
		Medium	9	High	Amber	Amber	£4.40	£23.68	£2.57
		Small	9	High	Amber	Amber	£4.40	£23.68	£2.57
Acidification - Store (ammonia)	Commercial	Large	7	Medium	Amber	Amber	£3.03	£9.24	£4.77
		Medium	7	Medium	Amber	Amber	£3.10	£9.44	£4.87
		Small	7	Medium	Amber	Amber	£3.18	£9.70	£5.00
	Farm	Large	9	Medium	Amber	Amber	£9.22	£21.64	£4.71
		Medium	9	Medium	Amber	Amber	£9.29	£21.80	£4.75
		Small	9	Medium	Amber	Amber	£9.37	£22.00	£4.79
Gas tight cover (ammonia)	Commercial	Large	9	Low	Green	Green	£0.13	£1.54	£0.20
		Medium	9	Low	Green	Green	£0.13	£1.54	£0.20
		Small	9	Low	Green	Green	£0.13	£1.54	£0.20
	Farm	Large	9	Low	Green	Green	£0.34	£3.64	£0.20
		Medium	9	Low	Green	Green	£0.34	£3.64	£0.20
		Small	9	Low	Green	Green	£0.34	£3.64	£0.20
Injection spreading	Commercial	Large	9	Medium	Green	Green	£0.89	£2.39	£1.40
		Medium	9	Medium	Green	Green	£0.89	£2.39	£1.40
		Small	9	Medium	Green	Green	£0.89	£2.39	£1.40
	Farm	Large	9	Medium	Green	Green	£0.10	£0.23	£0.06
		Medium	9	Medium	Green	Green	£0.10	£0.23	£0.06
		Small	9	Medium	Green	Green	£0.10	£0.23	£0.06
Nitrification / Denitrification	Commercial	Large	9	Medium	Red	Red	£4.51	£11.51	£7.09
		Medium	9	Medium	Red	Red	£4.51	£11.51	£7.09
		Small	9	Medium	Red	Red	£4.51	£11.51	£7.09
	Farm	Large	9	Medium	Red	Red	£12.17	£27.25	£7.09
		Medium	9	Medium	Red	Red	£12.17	£27.25	£7.09
		Small	9	Medium	Red	Red	£12.17	£27.25	£7.09
Nitrification Only	Commercial	Large	9	Medium	Red	Red	£3.37	£12.16	£5.30
		Medium	9	Medium	Red	Red	£3.37	£12.16	£5.30
		Small	9	Medium	Red	Red	£3.37	£12.16	£5.30
	Farm	Large	9	Medium	Red	Red	£9.09	£28.79	£5.30
		Medium	9	Medium	Red	Red	£9.09	£28.79	£5.30
		Small	9	Medium	Red	Red	£9.09	£28.79	£5.30
Stripping and Scrubbing	Commercial	Large	9	Medium	Amber	Red	£6.20	£24.90	£9.76
		Medium	9	Medium	Amber	Red	£6.34	£25.46	£9.97
		Small	9	Medium	Amber	Red	£6.52	£26.16	£10.25
	Farm	Large	9	Medium	Amber	Red	£7.56	£23.35	£3.86
		Medium	9	Medium	Amber	Red	£7.70	£23.80	£3.94
		Small	9	Medium	Amber	Red	£7.88	£24.36	£4.03

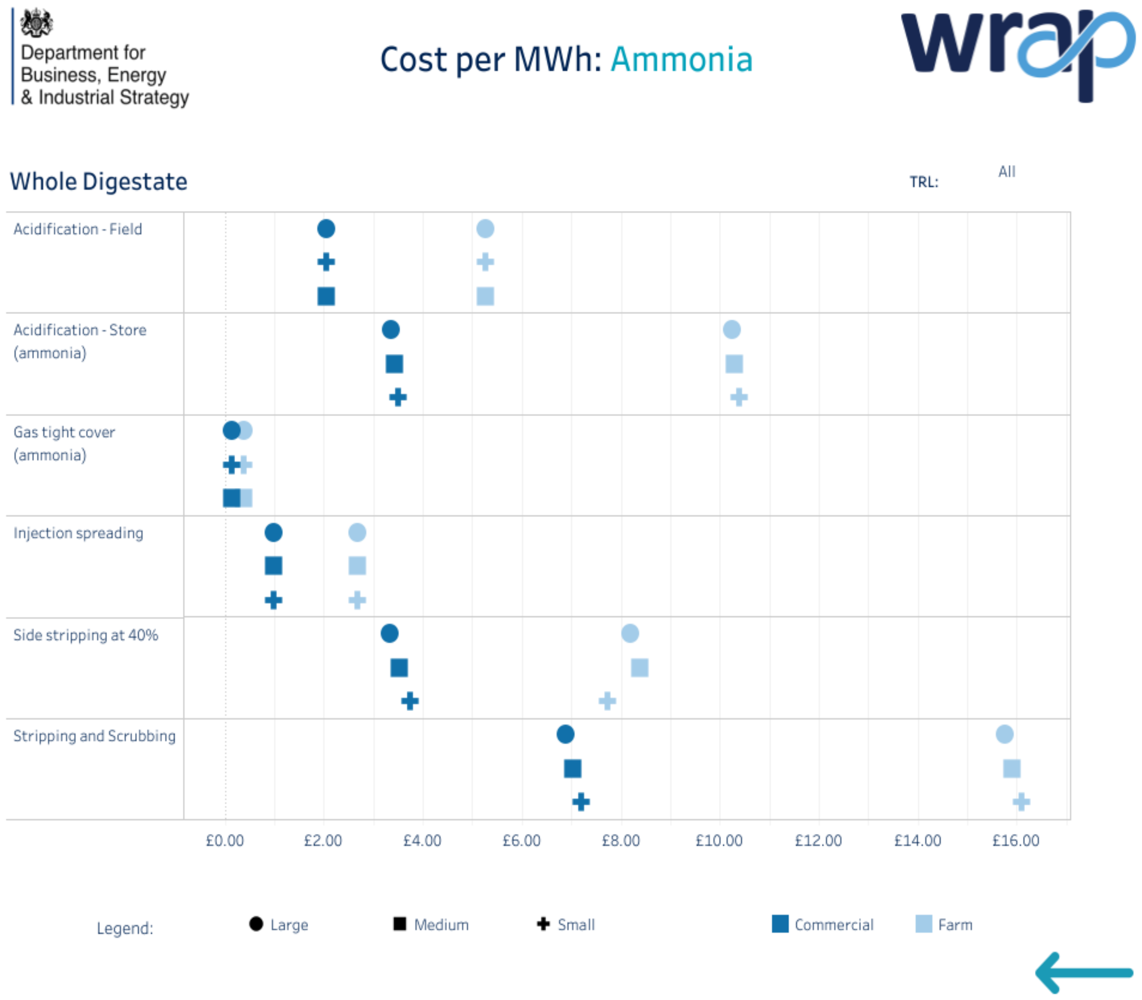
Illustration 3. Extracted Tableau illustration summarising ammonia mitigation from use of separated fibre from digestate

Department for Business, Energy & Industrial Strategy

Mitigation Options for Separated Fibre: Ammonia

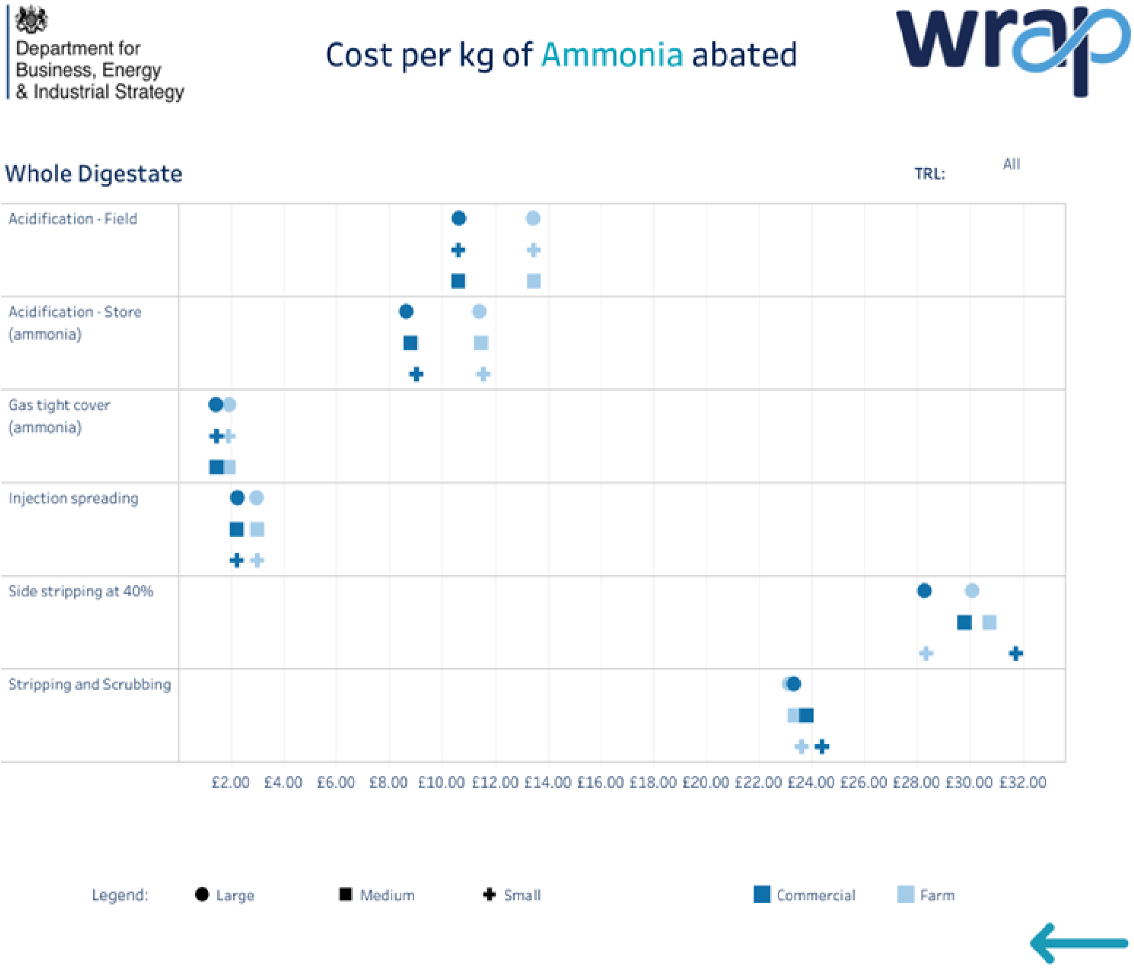
Mitigation Options	Plant type	Plant Size	TRL	Data Quality	Regulatory Complexity	Pollution swapping potential	Cost per MWh (SF)	Cost per kg of ammonia abated (SF)	Cost per tonne (SF)
Acidification - Alum	Commercial	Large	7	Low	Amber	Amber	£4.35	£27.98	£61.50
		Medium	7	Low	Amber	Amber	£4.35	£27.98	£61.50
		Small	7	Low	Amber	Amber	£4.35	£27.98	£61.50
	Farm	Large	9	Low	Amber	Amber	£13.37	£44.47	£61.50
		Medium	9	Low	Amber	Amber	£13.37	£44.47	£61.50
		Small	9	Low	Amber	Amber	£13.37	£44.47	£61.50

Illustration 4. The modelled cost per MWh of ammonia mitigation from the use of whole digestate



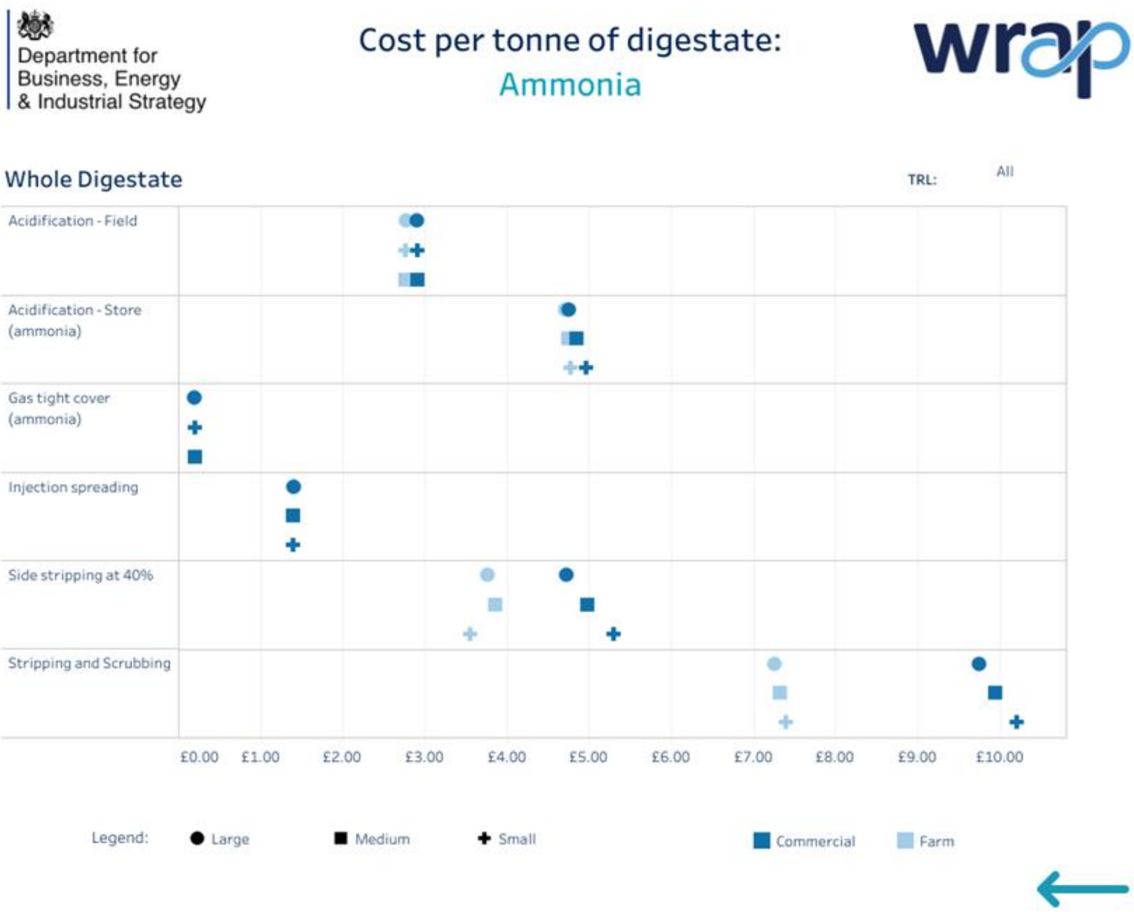
Modelled costs range from £0.14 / MWh for the cost of using a gas-tight cover on a store on a commercial plant through to over £16.00 / MWh when stripping and scrubbing technology is used on a farm plant. As with the majority of these model illustrations, use of technology to mitigate ammonia on a farm scale is more costly than its use on a commercial plant and in all cases, there is very little variation in modelled costs with the changing scale of the plant. This reflects the lower energy yield from farm materials (compared with food wastes).

Illustration 5. Modelled cost per kg of ammonia removed from whole digestate



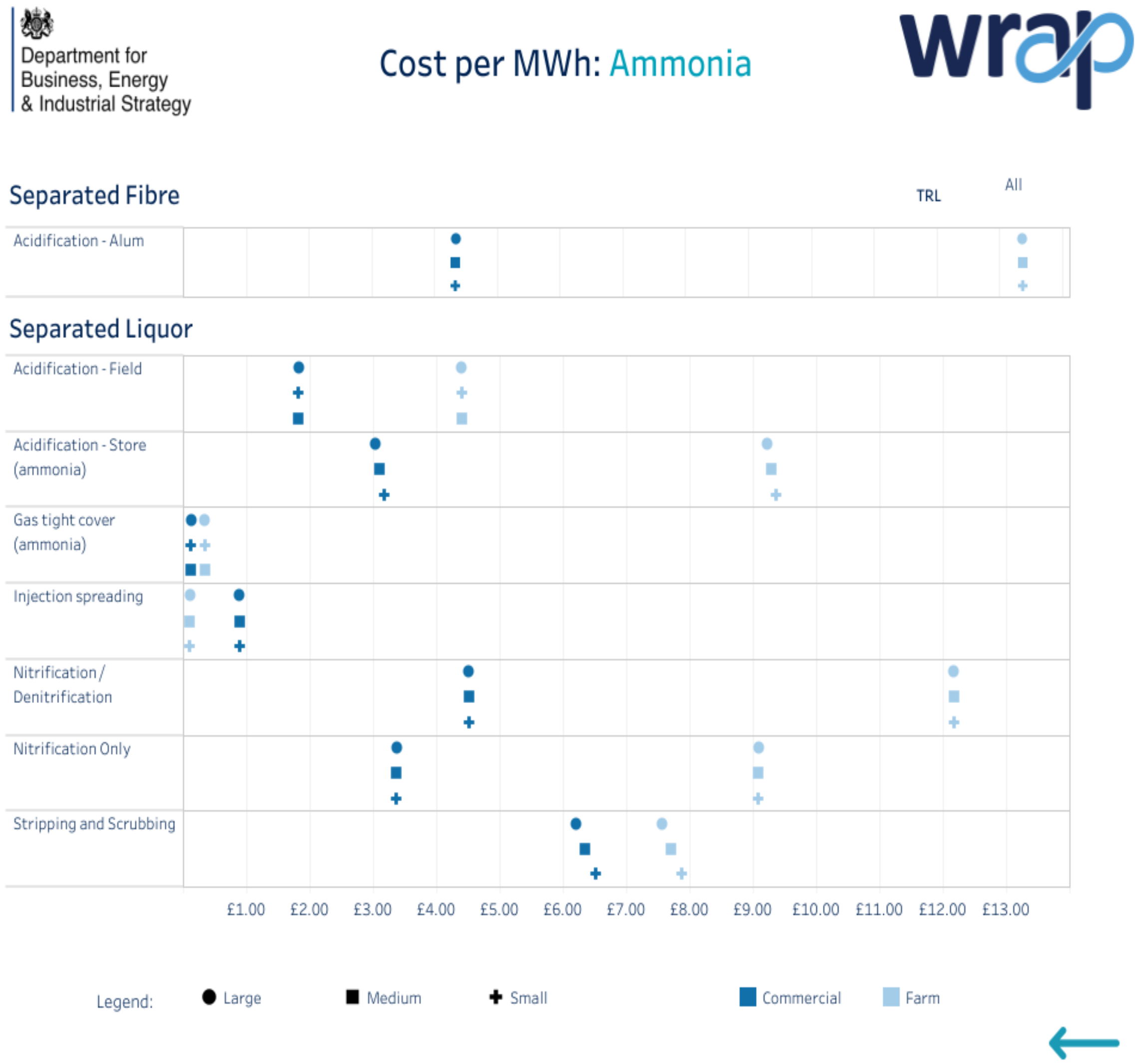
These costs mirror the modelled costs per MWh, showing a similar lack of variation with plant scale and a similar increase in costs for farm scale operations. The latter reflects the lower levels of ammonia present in the whole digestate prior to mitigation intervention. Costs range from £1.44 /kg ammonia mitigated through the use of a gas-tight covered store on a commercial plant through to £31.74 where a side stripping technology is used on a large-scale commercial plant.

Illustration 6. Modelled cost of ammonia mitigation expressed as cost per tonne of digestate treated for whole digestate



The costs range from £0.20 for the installation of a gas-tight cover on either farm or commercial plants through to £10.20 where stripping and scrubbing is used on commercial plants.

Illustration 7. Modelled cost of ammonia mitigation expressed as cost per MWh for separated liquor and fibre from digestate



When the digestate is split into liquor and fibre fractions the use of alum treatment for acidification of the fibre fraction can be included. The modelled costs for this show a large difference between commercial and farm systems where the costs for farm systems are much higher reflecting the lower ammonia content of the system. The lower energy yield per unit feedstock for farm compared to commercial is driving the cost difference as due to the lower energy yield a greater amount of digestate is required which incurs higher alum costs.

The cost per MWh across the technologies is similar to those modelled for whole digestate with the lowest costs associated with gas-tight covered storage and with the use of injection equipment to spread digestates. Costs per MWh for acidification (in field or in store) and for stripping and scrubbing are in line with costs per MWh for whole digestate.

Illustration 8. Modelled cost of ammonia mitigation expressed as cost per kg ammonia abated for separated liquor and fibre from digestate

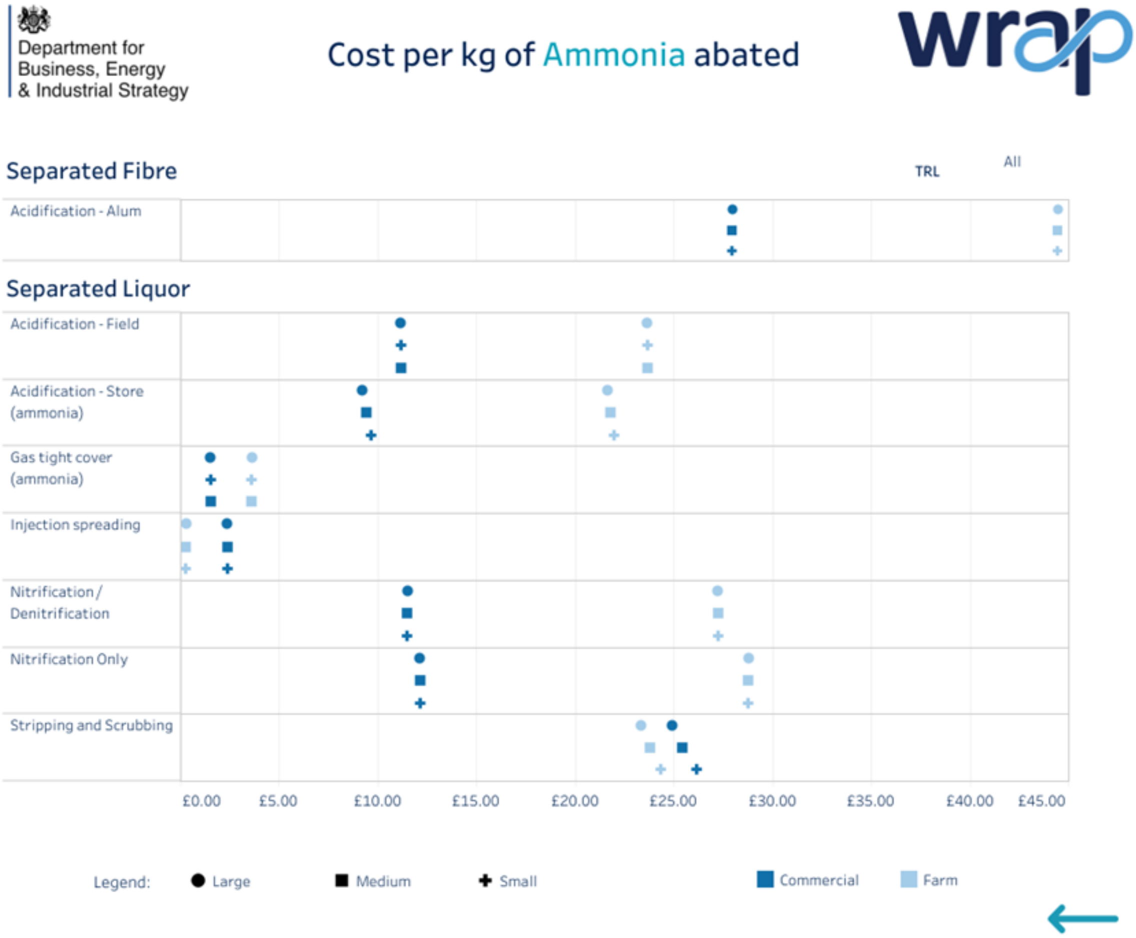
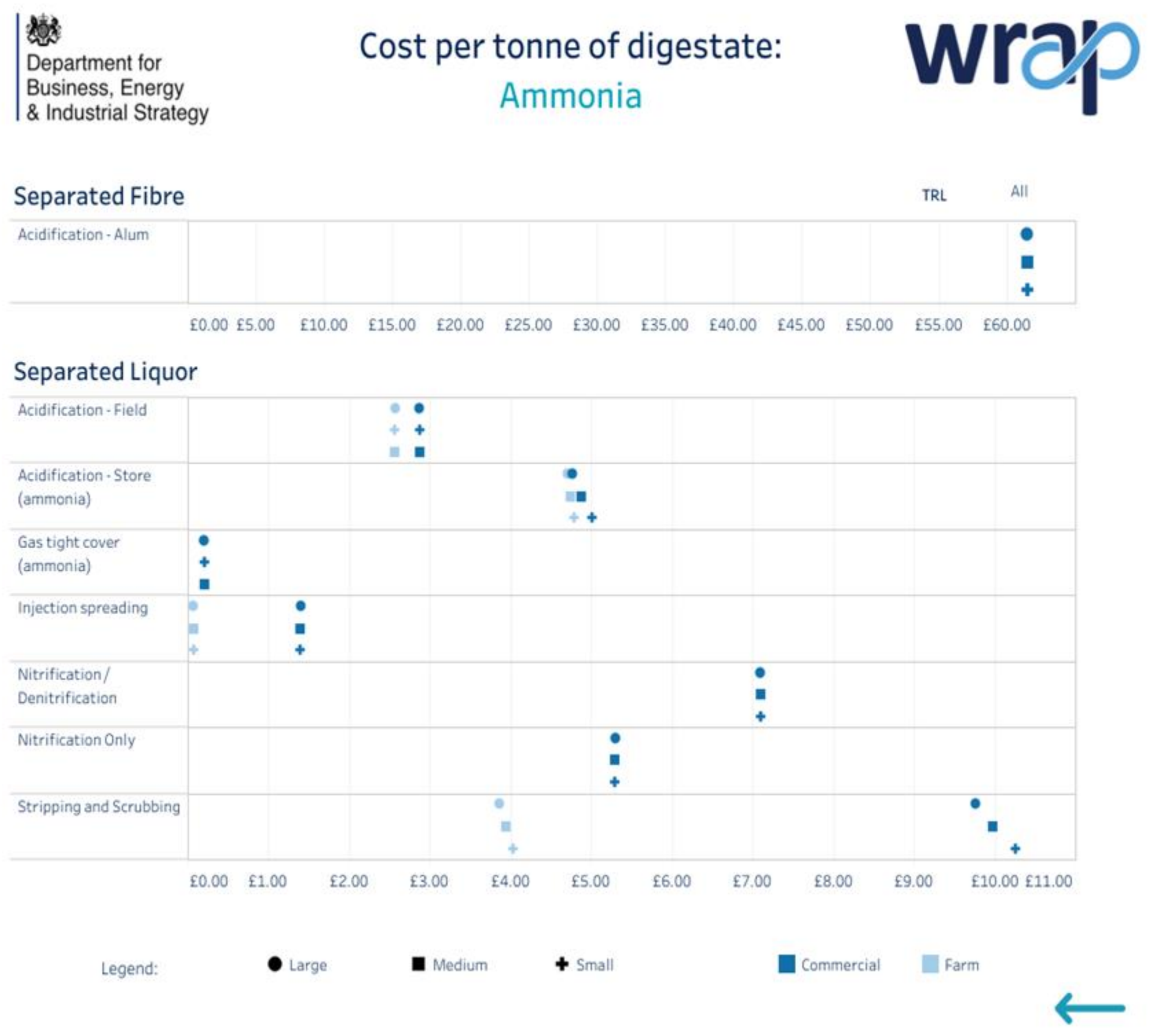


Illustration 9. Modelled cost of ammonia mitigation expressed as cost per tonne of digestate treated for separated liquor and fibre



Summary – ammonia mitigation

The modelled data shows some consistent patterns in terms of all three of the cost metrics. Generally speaking, there is little variation in cost with scale for any of the modelled options. The use of stripping and scrubbing technology show some increase in costs with decreasing plant size, but in general, for the other technologies all three cost metrics do not appear to vary with plant size. The key reasons for this are the lack of economies of scale and / or OPEX-centric solutions. For example, acidification in store modelled a single price for the acidification equipment while the costs were dominated by price and quantity of acid used. Data for nitrification / denitrification costs were limited and might reveal some scaling if put to the market – as is seen with stripping and scrubbing. The apparently lower costs for in field acidification vs in store may be deceptive since the former uses smaller volumes of acid to deliver lower ammonia mitigation, but contributes to improved nutrient use efficiency at a farm scale. In field acidification may also require no CAPEX, relying instead on a contracted service that will charge for the use of the equipment and acid used.

The use of a gas-tight cover on the digestate storage tank is clearly the cheapest technology option across all three metrics. Given that it is also a commercially available technology, with a clear regulatory framework for implementation, it would therefore appear to be the best available option for installation at new plants to mitigate ammonia losses. The modelling exercise does however reveal some uncertainty in the data that is available. As discussed previously, the model uses the best data available to the research team at the time, but it is recommended that this potential data weakness or gap is addressed to verify the model outputs.

The use of precision spreading equipment (injection) is the second cheapest option. There will be advantages in both the installation of a gas-tight cover and use of precision spreading technology, but the additive costs and environmental benefits have not been modelled at this stage.

The other modelled options present larger modelled costs and higher degrees of uncertainty in terms of regulatory framework, TRL level or general confidence in the data that was used for the modelling. The use of stripping and scrubbing technology or side stripping options are particularly challenging in regulatory terms where the waste status of both the input acid and of the output that will then need to be spread to land need to be determined and dealt with under the appropriate regulatory mechanism.

The use of acidification techniques for ammonia mitigation is currently being developed at scale in continental Europe but is not a common technology here in the UK. It is particularly common in Denmark where it is applied to pig slurries – and provides an alternative to covered storage of this material. It is not commonly applied to digestates in any country. The modelled costs for acidification in store are in the middle of the technology ranges that have been calculated and of the technologies that have been modelled, acidification options have a lower TRL level combined with some potential for pollution. There is also some regulatory uncertainty that would need to be clarified if acidification technologies were to be adopted.

9.2 Methane mitigation technologies

Illustration 10. Summary modelled data for methane mitigation from the treatment of whole digestate

Department for Business, Energy & Industrial Strategy

Mitigation Options for Whole Digestate:
Methane

wrap

TRL	Regulatory Complexity	Pollution swapping potential
All	All	All

Mitigation Options	Plant type	Plant Size	TRL	Data Quality	Pollution swapping potential	Regulatory Complexity	Cost per MWh (WD)	Cost per kg of methane abated (WD)	Cost per tonne (WD)
Acidification - Store (methane)	Commercial	Small	7	Low	Amber	Amber	£0.84	£0.09	£1.18
		Medium	7	Low	Amber	Amber	£0.75	£0.08	£1.06
		Large	7	Low	Amber	Amber	£0.69	£0.07	£0.97
	Farm	Small	9	Low	Amber	Amber	£1.92	£0.21	£1.01
		Medium	9	Low	Amber	Amber	£1.83	£0.20	£0.96
		Large	9	Low	Amber	Amber	£1.77	£0.19	£0.93
Gas tight cover (methane)	Commercial	Small	9	Low	Green	Green	£0.14	£0.01	£0.20
		Medium	9	Low	Green	Green	£0.14	£0.01	£0.20
		Large	9	Low	Green	Green	£0.14	£0.01	£0.20
	Farm	Small	9	Low	Green	Green	£0.38	£0.03	£0.20
		Medium	9	Low	Green	Green	£0.38	£0.03	£0.20
		Large	9	Low	Green	Green	£0.38	£0.03	£0.20

Illustration 11. Summary modelled data for methane mitigation from the treatment of separated liquor

Department for Business, Energy & Industrial Strategy

Mitigation Options for Separated Liquor:
Methane

wrap

TRL	Regulatory Complexity	Pollution swapping potential
All	All	All

Mitigation Options	Plant type	Plant Size	TRL	Data Quality	Pollution swapping potential	Regulatory Complexity	Cost per MWh	£ per kg of methane abated	Cost per tonne
Acidification - Store (methane)	Commercial	Small	7	Low	Amber	Amber	£0.77	£2.01	£1.22
		Medium	7	Low	Amber	Amber	£0.69	£1.79	£1.08
		Large	7	Low	Amber	Amber	£0.62	£1.62	£0.98
	Farm	Small	9	Low	Amber	Amber	£1.75	£1.68	£1.02
		Medium	9	Low	Amber	Amber	£1.66	£1.60	£0.97
		Large	9	Low	Amber	Amber	£1.59	£1.53	£0.93
Gas tight cover (methane)	Commercial	Small	9	Low	Green	Green	£0.13	£0.26	£0.20
		Medium	9	Low	Green	Green	£0.13	£0.26	£0.20
		Large	9	Low	Green	Green	£0.13	£0.26	£0.20
	Farm	Small	9	Low	Green	Green	£0.34	£0.26	£0.20
		Medium	9	Low	Green	Green	£0.34	£0.26	£0.20
		Large	9	Low	Green	Green	£0.34	£0.26	£0.20

Illustration 12. Summary modelled cost of methane abatement expressed as cost per MWh for whole digestate and separated liquor

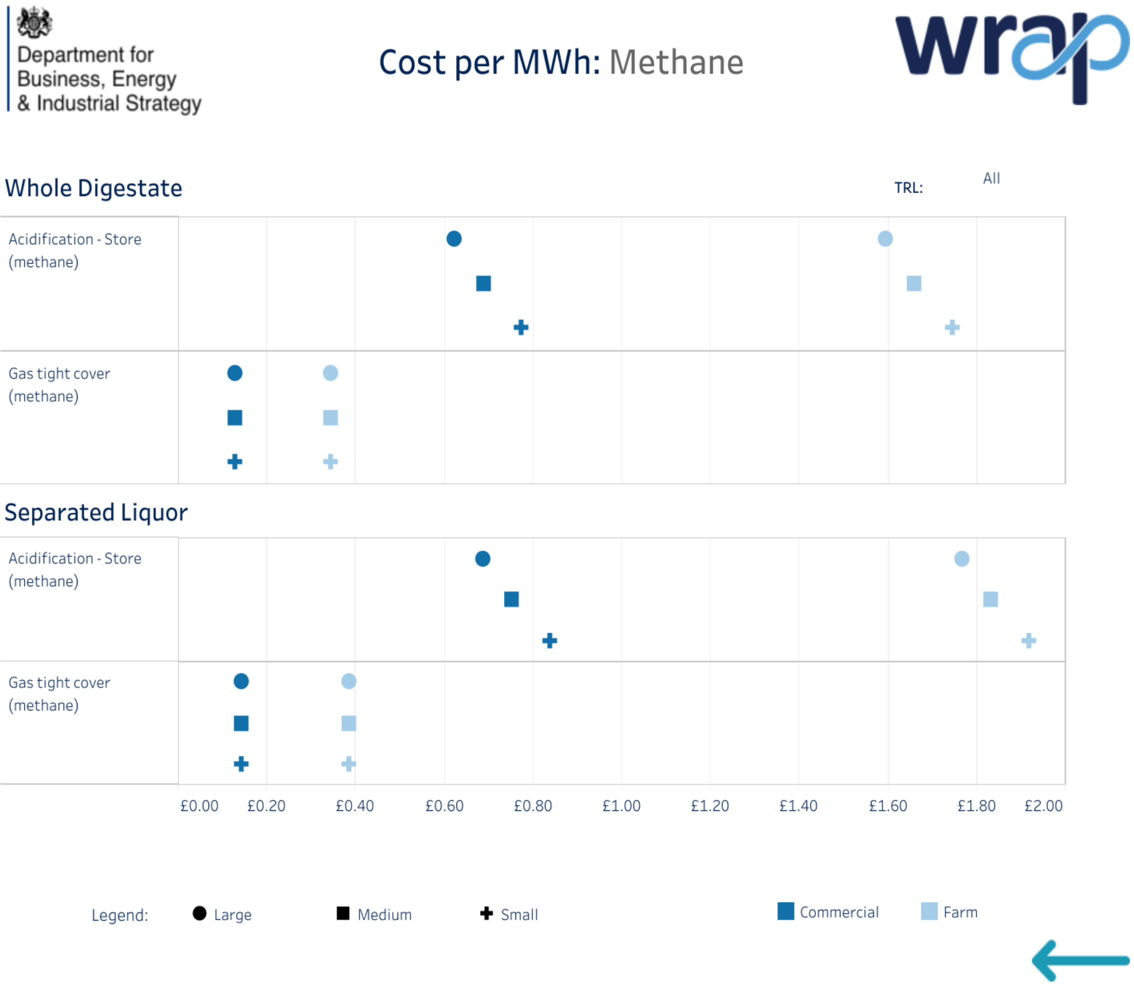


Illustration 13. Modelled cost of methane abatement expressed as cost per kg methane abated for whole digestate and separated liquor

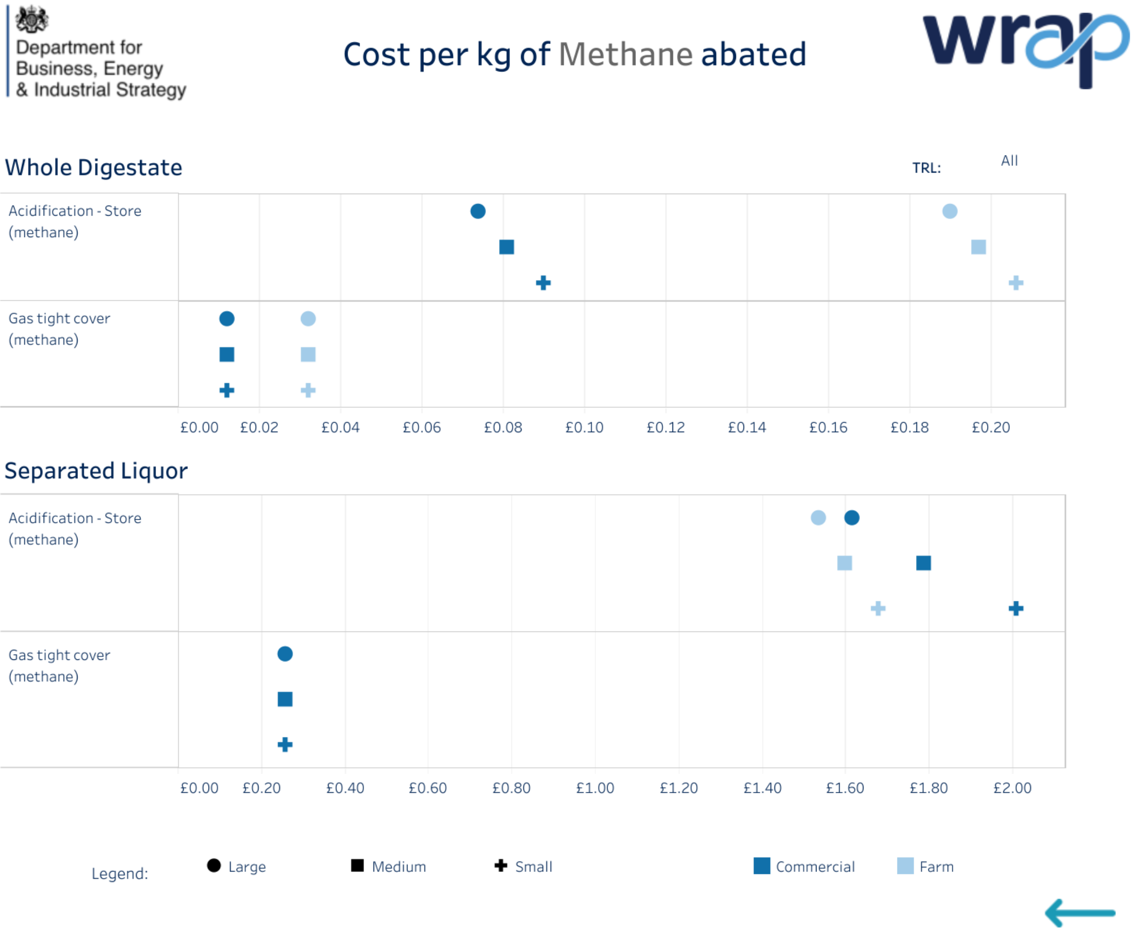
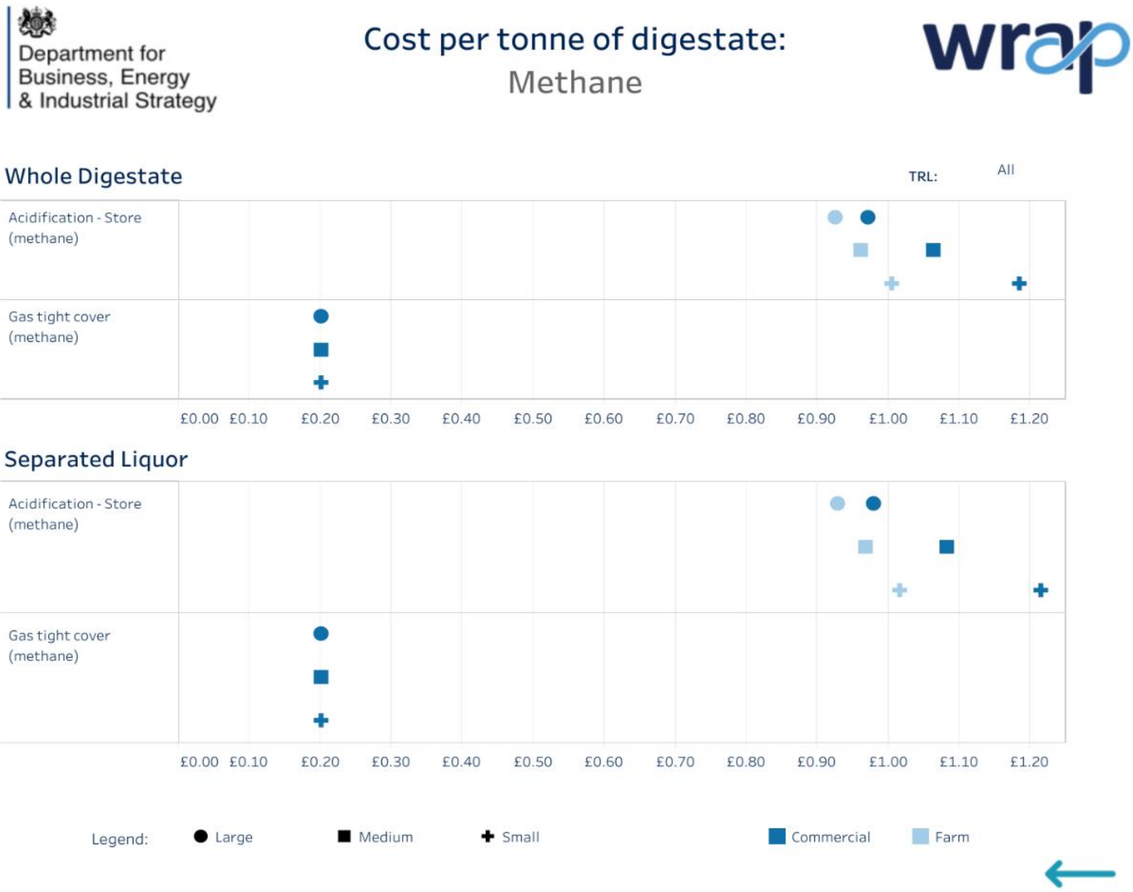


Illustration 14. Modelled cost of methane abatement expressed as cost per tonne of digestate treated for whole digestate and separated liquor



Summary – methane mitigation

Only two options were modelled for mitigation of methane impact from the storage of digestate, the use of acidification in store and the use of gas-tight store covers.

Many of the same conclusions that were arrived at when these technologies were modelled for ammonia abatement apply to their use for mitigating the impact of methane. As before, the use of a gas-tight cover on the digestate storage tank is the cheapest option when measured by all three metrics. There are, however, clearer differences in cost between farm and commercial systems, and for acidification clear difference with costs increasing with decreasing scale.

There is a similar lack of robust cost data for the use of gas-tight stores for methane mitigation and this is a weakness in the modelling. This should be addressed by the EA and Defra if further work or improved modelling is to be undertaken.

The same comments about TRL level, regulatory complexity and pollution swapping apply as they did with ammonia mitigation. The understanding and use of gas-tight stores is further advanced than the use of acidification technology. Since it what not possible to determine consensus values for methane emission during the application of digestate no specific mitigations for this were sought. However, readers should consider that acidification has the benefit of reducing ammonia emissions in both storage and then during subsequent spreading of digestate. This is not the case with gas-tight covers, which do not change digestate chemistry and would need to be combined with a separate mitigation technique during spreading to deliver maximum mitigation. It is possible that these constraints would also apply to methane.

9.3 Plastic mitigation technologies

Illustration 15. Summarised modelled data for plastics removal from whole digestate

Department for Business, Energy & Industrial Strategy

Mitigation Options for Whole Digestate: Plastics Removal

wrap

Mitigation Options	Plant type	Plant Size	TRL	Data Quality	Pollution swapping potential	Regulatory Complexity	Cost per MWh (WD)	Cost per kg of plastics abated (WD)	Cost per tonne (WD)
Plastics Removal (Downstream)	Commercial plant (PAS110)	Large	9	High	Red	Green	£0.05	£0.57	£0.07
		Medium	9	High	Red	Green	£0.05	£0.57	£0.07
		Small	9	High	Red	Green	£0.05	£0.57	£0.07
	Commercial plant (Scotland)	Large	9	High	Red	Green	£0.05	£7.03	£0.07
		Medium	9	High	Red	Green	£0.05	£7.03	£0.07
		Small	9	High	Red	Green	£0.05	£7.03	£0.07

Summary – plastic mitigation

The modelling focussed on commercial plants only. Farm plants were not included as they should not be utilising feedstocks that will be contaminated with plastics. The modelling assumes that an AD plant will have an existing depackaging plant and that additional costs are incurred through the use of a screw press at the end of the digestate processing stage.

As there is no agreed figure for a baseline amount of plastic left in the feedstock after depackaging, starting points were back-calculated assuming that one plant was exactly meeting the PAS110 standard, one exactly meeting the Scottish limits. A third starting point assumed 5% contamination before depackaging.

The overall cost of plastic removal is low in terms of the cost per MWh generated or the cost in terms of the tonnage of digestate treated. The modelling also calculated the cost in terms of the kg of plastic that is removed in line with other impact mitigation technologies covered by this work. The modelling shows a sharp increase in unit cost per kg plastic removed when a lower plastic contamination level is set.

The technology that can be used to remove plastics is readily available to the AD industry and widely used in the UK, giving a high level of confidence in the data that has been used in the modelling. However, the process of removing plastic from the final digestate stream will result in a contaminated stream that cannot be spread to land due to high levels of plastic. This means that the material will have to be disposed of via energy from waste or landfill and will thus result in pollution swapping via losses of carbon dioxide or methane.

WRAP has recently undertaken a separate piece of work on plastic contamination in digestate. That work has revealed the full extent of the lack of measured data that is available for actual levels of plastic contamination that are present in either digestate or compost. It has also shown that there is little measured data on plastic inputs to these treatment systems or realistic evidence that gives an indication of environmental impacts of plastics in digestates when the contaminated materials are spread to land. So, whilst the modelling outputs that are reported here indicate that clean-up of contamination levels is possible using current technology at reasonable cost, there is further work to be done in this area if future regulatory limit values or environmental permit requirements are to be based on sound evidence. Put simply, this means that existing technology is capable of achieving current limit values and can also achieve stricter limit values if required, but there will be an economic cost in doing this together with a yet to be determined increase in GHG emissions through the disposal of the contaminated residue. Much lower limits on plastics have been applied to digestates in Scotland since December 2019 (compared with the limits which pertain in England, Wales and Northern Ireland), and AD operators have been forced to invest to meet these requirements. Incentivising AD plants outside Scotland to achieve these lower limits under the GGSS may not be appropriate.

9.4 Valorisation archetypes

The technoeconomic modelling for valorisation processes differed from that for impact mitigation technologies in that each of the valorisation archetypes modelled were theoretical examples rather than technologies that are proven at high TRL levels. This means that the calculated costs are indicative only and should be viewed and used carefully. Actual installation of an archetype model at an AD site will mean that the configuration and efficiency of each step will need to be tailored to site requirements which will result in different economic outcomes for each site.

As described previously, archetypes have been modelled on small plants only. An overview of modelled revenues is provided in Table 72, which is also presented in Illustration 16. These clearly show the revenue potential of selling digestate concentrates and fibre to amenity (professional and amateur horticulturist) users since the attainable retail prices are significantly divorced from the base fertiliser values of the materials in these uses. Current regulatory barriers (particularly waste) currently prevent the development of such supply chains outside the crop-only AD sector. Capturing phosphorus in the fine solids and exporting the P-enriched fibre also appears more attractive than applying (non-enriched) fibre to farm land. For commercial AD plants, use of nitrification / denitrification and downstream liquor treatment is more attractive than simply exporting digestates as wastes – particularly where the treated liquor is used for feedstock dilution and the biological sludge from the nitrification / denitrification system is returned to the AD plant as an additional feedstock. Creating a nutrient concentrate for export from commercial plants incurs overall cost, as do the other valorisation options considered.

Illustration 16 Bar chart showing revenue per MWh generated and per tonne of digestate treated for different valorisation archetypes

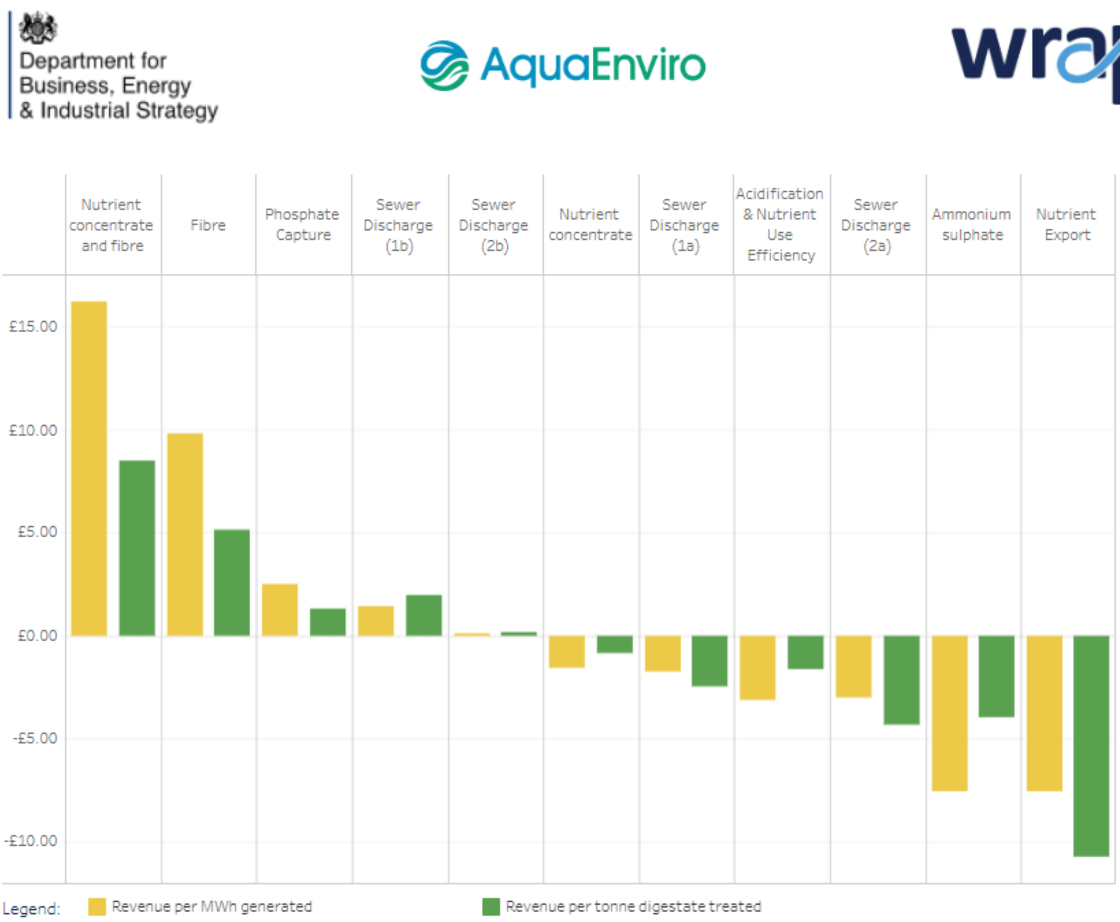


Table 72 Summary revenue metrics for valorisation archetypes

	Archetype	Revenue per tonne of digestate treated (£/tonne)	Revenue per MWh generated (£/MWh)	Type of AD plant
1	Injection, acidification and increased nutrient use efficiency	-£1.65	-£3.15	Farm
2	Capture of phosphorus for export	£1.31	£2.49	Farm
3	Nitrogen capture as ammonium sulphate	-£3.96	-£7.55	Farm
4	Nutrient concentrate for export	-£0.84	-£1.60	Farm
5	Nutrient concentrate and fibre for export	£8.49	£16.18	Farm
6	Fibre for export	£5.14	£9.79	Farm
7	Nutrient concentrate for export – commercial plant	-£10.72	-£7.58	Commercial
8	Discharge to sewer – commercial plant			Commercial
	Option 1A	-£2.50	-£1.77	
	Option 1B	£1.96	£1.39	
	Option 2A	-£4.31	-£3.05	
	Option 2B	£0.15	£0.11	

10.0 Case studies

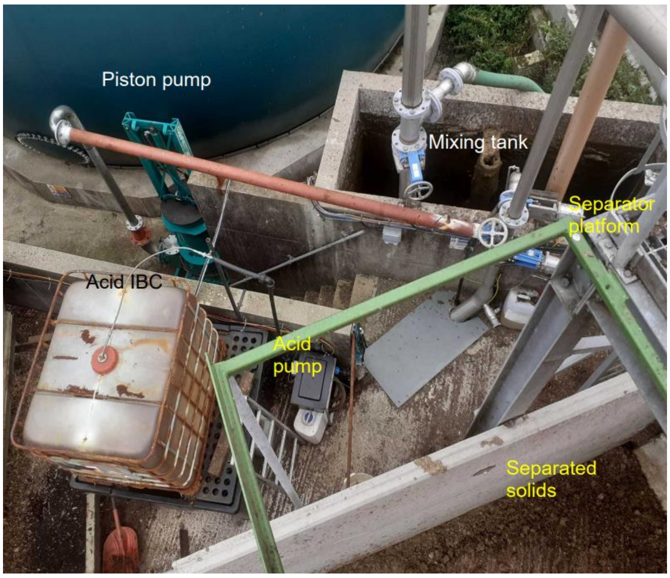
This section includes a number of case studies for digestate processing – which are either available in the UK or elsewhere in Europe. The authors acknowledge the assistance of those suppliers who provided the cost and performance data reproduced here. Links to additional processing options are provided for interest.

10.1 Acidification of digestate in store

1 What is the issue being addressed?
Stephen Temple is a dairy farmer and AD owner / operator, who has built his own system to acidify whole digestate before separation. He expects the process to improve nitrogen retention in his digestate and reduce his reliance on conventional fertilisers.

2 What is the solution?
Whole digestate is acidified by mixing with concentrated sulphuric acid prior to separation in a screw press.

Figure 39 Overview of acidification system. From https://www.angliaruralconsultants.com/wp-content/uploads/Copys-Green-ammonia-reductions-revised-1.pdf



3 Matrix applicability and commercial status?
Acidification is commercially applied to pig and cattle slurries and has been demonstrated on digestates, but as yet the technology is not commercially applied to this matrix. In this case a farmer and AD operator has developed his own acidification equipment to explore the costs and benefits. In theory, acidification of digestate before separation can obviate the need to cover (liquor or fibre) digestate stores. This is a bespoke system which is not intended for commercial reproduction.

4. Performance

Whole digestate pH reduced from 8.3 to 6.1 in trials, with an estimated saving of 20% of ammoniacal nitrogen.

5. Cost

The AD plant at Copys Green Farm processes approximately 5,000 tonnes per year of dairy manure and silage. The farmer was quote £35,000 for a commercial acidification system, but instead invested in the following:

- Bunded stand for the acid container (£500 to £1000)
- Acid dosing pump (£400)
- Continuous reading pH meter (£1200)
- Dosing and mixing tank
- Mixing and discharge pump (£7000)
- Remote operating valves (£1000)
- Level sensors (£100)
- Pipework (25mm for acid; 75mm for digestate)
- Safety shower and water supply for wash-down etc
- Based on reduced fertiliser costs, the farmer estimates payback from this system within five years – where second user acid is available at ~ £110 per tonne

6. Scalability

In principle this approach can be applied to digestate at any volume.

7. Are there any particular regulatory issues to be aware of?

In addition to Health and Safety considerations (which are relevant to the use of a system which handles concentrated sulphuric acid) it is possible that the use of acid would constitute a treatment process, requiring additional approval from the environmental regulators when used for either farm or commercial digestates. This is irrespective of the waste status of the acid used.

Clarification on the above is required from the environmental regulators.

8. Link(s) to further information

https://www.angliaruralconsultants.com/wp-content/uploads/Copys-Green-ammonia-reductions-revised-1.pdf

10.2 SyreN

1. What is the issue being addressed?
   In-field acidification of digestate reduces ammonia emissions at the point of application. By acidifying with sulphuric acid, this system also contributes agronomically useful sulphur. This creates an overall improvement in nutrient use efficiency, which can be estimated and costed using both financial and carbon metrics.
2. What is the solution?
   An acid-dosing unit is front-mounted onto the tractor unit for digestate application. The use of in-line pH sensing and digestate flow-rate monitoring means that acid can be dosed to achieve a target pH in the digestate. Alternatively, acid can be dosed at a predetermined rate. The dosing unit is also designed to accommodate other additives, such as nitrification inhibitors.

   Figure 40 SyreN system in use. From: http://www.biocover.dk/galleri.aspx

3. Matrix applicability and commercial status?
   Commercialised for pig and cattle slurries, but also sold for use with digestates. References are available for the former, but not the latter.
4. Performance
   For pig and cattle slurries, ammonia abatement of between 50 and 70% can be delivered with a target pH of between 6.4 and 6.0. Although VERA-certified[1] for slurries, certification for use on digestates has not been possible due to their variability and higher buffering capacities. While the system can be operated in the same way with either digestates or slurries, the supplier recommends fixed dosing at a rate of approximately 2.5 litres of c.H_2SO_4 per m^3 of digestate, to deliver a 30% reduction in ammonia emissions.
5. Cost
   The unit costs approximately €20 per hectare to use, excluding acid. The suppliers have developed a tool which estimates improved nutrient use efficiency from the system[2].

6. Scalability

The unit is tractor-mounted, with one required for each set of digestate application equipment. It is compatible with dribble bar, trailing shoe and injection applicators operating at widths of up to 36m. More than 130 units are in use and the technique is considered BAT.

7. Are there any particular regulatory issues to be aware of?

In addition to Health and Safety considerations (which are relevant to the use of a system which handles concentrated sulphuric acid) it is possible that the use of acid would constitute a treatment process for the digestate, requiring additional approval from the environmental regulators when used for either farm or commercial digestates. This is irrespective of the waste status of the acid used.

Clarification on the above is required from the environmental regulators.

8. Link(s) to further information

[1] http://www.biocover.dk/uk/counseling/vera-verifikation.aspx

[2] http://www.biocover.dk/uk/counseling/syren-estimator.aspx

10.3 Arnold / Swiss Combi

1. What is the issue being addressed?
   This is a 'zero liquid export' solution that reduces digestate volumes whilst retaining and concentrating nutrients within a dry granule.
2. What is the solution?
   Whole digestate is first separated into liquor and fibre fractions. The liquor fraction is acidified prior to vacuum evaporation, retaining nitrogen within the resulting concentrate. The distillate is separately condensed and then (depending on digestate characteristics, process conditions and regulatory requirements) discharged to water course. The concentrate is mixed with the separated fibre digestate and passed into a rotary drier in which fertiliser granules are created. Additional mineral nutrients can be added during the drying phase to create bespoke fertilisers.
3. Matrix applicability and commercial status?
   This solution combines technologies from two suppliers: the Arnold multi-effect evaporator[1] and Swiss Combi ecoDry drier[2]. References are available for both separately, but not as an integrated solution. Since the end product is a fertiliser granule, this solution requires efficient phase-separation of whole digestates to deliver a separated fibre digestate of ~25% dry matter. This may favour farm digestates, rather than commercial digestates.
4. Performance
   Performance data have been provided by the supplier below.
5. Cost
   Indicative cost data have been provided by the supplier below.
6. Scalability
   The solution can be scaled across all sizes of AD facility within scope.

7. Are there any particular regulatory issues to be aware of?

There are two outputs from this solution: condensate and granules.

Anaerobic digestion of both farm and commercial materials is a regulated (waste) activity and these outputs are therefore likely to be classified as wastes. The pellets represent a physically transformed variant of digestate and could benefit from current low-risk regulatory approaches that apply to farm digestates. Likewise, although not explicitly covered by current end of waste approaches for commercial digestates, it might be possible to include the pellets within these approaches.

Discharge of the condensate is likely to require authorisation from the environmental regulators.

Clarification on the above would be required from the environmental regulators.

8. Link(s) to further information

[1]https://arnold-partner.ch/index.php/en/products/evaporator

[2]https://www.swisscombi.ch/en/downloads.html

Table 73 Indicative costs for processing commercial and farm digestates at small, medium and large AD facilities. Courtesy of Oliver Arnold

	kt/year	43	74	131	171	228	526
DM-content	%	7.0	7.0	7.0	7.0	7.0	7.0
NH_4-N	g/litre	5.0	5.0	5.0	5.0	5.0	5.0
Annual water evaporation (evaporator + dryer)	kt	39.6	68.2	121	158	210	484
electrical consumption total (evaporator + dryer)	kW	115	230	390	520	680	1,400
Annual hours of production	h	8,322	8,322	8,322	8,322	8,322	8,322
Heat requirement (from gas boiler)	kW	1,426	2,454	4,344	5,670	7,560	17,441
Annual heat consumption	MWh	11,867	20,422	36,151	47,186	62,914	145,144
Annual sulphuric acid consumption*	t	865	1,488	2,563	3,439	4,585	10,578

	kt/year	43	74	131	171	228	526
Annual pellet production	t	4,267	7,343	13,000	16,968	22,624	52,194
Fertiliser value of granules (2020 prices)	€M	0.55	0.95	1.7	2.25	3.0	7.0
Price for evaporator	€M	1.85	2.80	4.30	5.40	6.80	13.0
Evaporator installation	€M	0.15	0.18	0.23	0.26	0.35	0.55
Price for dryer	€M	2.538	3.341	4.605	6.505	9.210	18.93
Dryer installation	€M	0.5	0.6	0.65	0.7	0.75	2.1
Price for additional tanks (acid etc)	€M	0.18	0.18	0.24	0.24	0.40	0.75
Pellet Press**							

*Depends on NH_4-N concentration in digestates
**Not required, since dryer action creates pellets

Figure 41 Overview of digestate processing cascade, process points are labelled for reference in Table 74

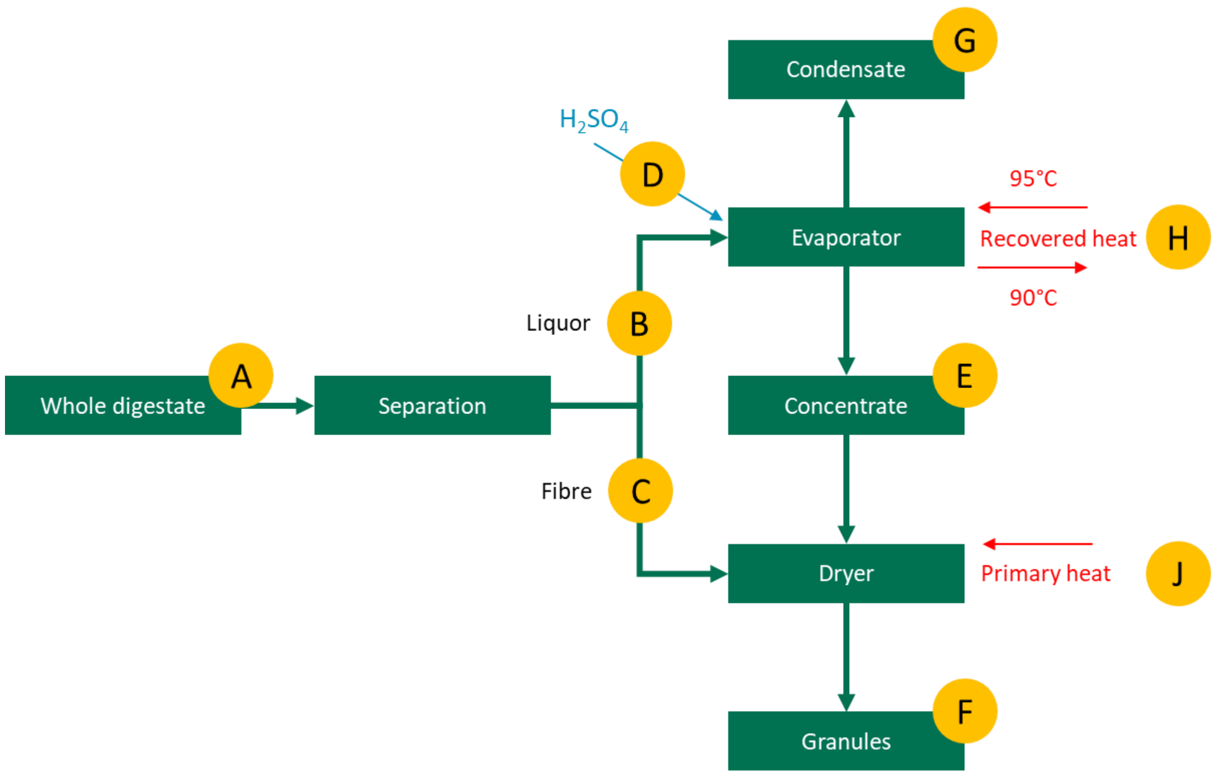


Table 74 Indicative material flows at small, medium and large scale for farm and commercial AD sites. Courtesy of Oliver Arnold

		kt/year	43	74	131	171	228	526
Whole digestate	A	kg/h @ 7%DS	5,167	8,892	15,741	20,548	27,397	63,206
Separated liquor	B	kg/h @ 3.5%DS	4,326	7,445	13,179	17,203	22,937	52,917
Separated fibre	C	kg/h @ 25%DS	841	1,448	2,563	3,345	4,460	10,289
Sulphuric acid	D	kg/h	104	179	317	413	551	1,271
Concentrate	E	kg/h @ 20%DS	1,256	2,161	3,826	4,994	6,659	15,361
Granules	F	kg/h @ 90%DS	513	882	1,562	2,039	2,719	6,272
Condensate	G	kg/h	3,174	5,462	9,670	12,622	16,830	38,826
Heat (recovered)	H	kW	839	1,444	2,556	3,337	4,449	10,264
Heat (primary)	J	kW	1,426	2,454	4,344	5,670	7,560	17,441

10.4 Other options

The following digestate processing options were compiled during evidence assessment for other project tasks and should neither be inferred as comprehensive nor as an endorsement of any particular approach. Brief descriptions and (where possible) links to digestate processing references are provided for information. The options are grouped according to the following categories:

1. Ammonia stripping / scrubbing
2. Evaporation
3. Membrane
4. Drying

Ammonia stripping/scrubbing	
Gas-permeable membranes	Ammonia stripping / scrubbing
These represent an alternative to conventional ammonia stripping and scrubbing, with membranes immersed in liquor digestate and ammonia captured in a sulphuric acid solution on the lumen (internal) side as ammonium sulphate. Although these membranes are sold commercially, there is limited evidence for their use in this application. Reference in Switzerland: https://www.membratec.ch/eau/stripping-membranaire-production-engrais-azote-670.html	
Nijhuis	Ammonia stripping / scrubbing
CO_2 is air-stripped from separated liquor digestate that has been pre-heated to around 70°C, increasing its pH. Sodium hydroxide is then added to further increase the digestate pH to around 9. The digestate is then passed through a stripping column to remove ammonia in a counter-current air stream, which is passed into an acid scrubbing column to recover nitrogen as ammonium sulphate solution. A heat exchanger is used to recover energy from the stripped digestate, which may be used for AD feedstock or process dilution. Reference in England: https://www.nijhuisindustries.com/assets/uploads/Product-Sheet_AECO-NAR_ENG-2021_2021-12-01-065829.pdf	

Colsen	Ammonia stripping / scrubbing
Ammonia is stripped from separated liquor digestate and recovered as an ammonium sulphate solution, following acid-scrubbing. The residual digestate may then be further treated via nitrification / denitrification to produce water suitable for AD process or feedstock dilution. UK reference: https://www.colsen.nl/en/publications/construction-first-amfer-uk-has-started	
Ecochimica and Eliopig	Ammonia stripping / scrubbing
Italian suppliers https://www.ecochimica.com/ https://www.eliopig.com/en/products/nitrogen-reduction	
CMI Environment	Ammonia stripping / scrubbing
Belgian supplier http://www.europe-environnement.com/wp-content/uploads/2017/06/Stripping-EN.pdf	
Byosis	Side-stream ammonia stripping / scrubbing
This technique allows high ammonia poultry litter to be digested, creating a separate ammonium sulphate fertiliser. Reference in Northern Ireland: https://byosis.com/case-studies/ballymena-plant	
Evaporation	
EPCON	Vacuum-assisted digestate thickening and ammonia recovery
Separated liquor digestate is evaporated under vacuum in an MVR (mechanical vapour recompression) system with ammonia recovered in the condensate. The system can also be configured to evaporate pre-acidified digestate (to create a nutrient concentrate). References from Scandinavia: https://www.epcon.org/uploads/4/6/3/5/46351051/epcon_biogas_brochure.pdf	
France Evaporation	Vacuum-assisted digestate thickening and ammonia recovery
French supplier https://www.evaporation.fr/en/industries/energy-biogas-and-biofuels	
Evaled	Vacuum-assisted digestate thickening and ammonia recovery
Italian supplier https://www.evaled.com/biogas-and-biofuels/	
Agri-Fer	Vacuum-assisted digestate thickening and ammonia recovery
Separated liquor digestate is evaporated under vacuum, with the distillate then rectified to create separate ammonia and water streams. The water stream is then polished via	

reverse osmosis prior to discharge or reuse. The ammonia stream can be used for a number of industrial processes. References in Germany: https://agrikomp.com/utilisation/digestate/	
K-RÉVERT	Vacuum-assisted digestate thickening and clean water
Separated liquor digestate is evaporated (following initial acidification?), with the condensate potentially suitable for environmental discharge with or without further treatment via reverse osmosis. Alternatively, the liquor digestate can be processed via ultrafiltration and reverse osmosis – with the retentate from the latter then thickened through evaporation. The condensate can be combined with the RO permeate to produce water of (potentially) discharge quality. Multiple references in France: http://www.k-revert.fr/installations_en.html	
HRS	Digestate thickening
Scraped-surface heat-exchangers are used within a vacuum evaporation system to thicken digestates, with the resulting condensate used for AD feedstock or process dilution. Reference in Scotland: https://www.hrs-heatexchangers.com/case-study/digestate-processing/	
Membrane	
ESMIL	Vibrating membrane treatment to produce clean water and nutrient concentrate
Separated liquor digestates are processed in a proprietary VSEP RO (Vibratory Shear Enhanced Process Reverse Osmosis) membrane system to produce a retentate in the form of a concentrated nutrient solution. The permeate is passed forwards to a conventional RO membrane system which produces a further concentrate and clean water – the latter suitable for process use or (where regulations allow) discharge to the environment. The RO retentate is passed back to the VSEP inlet. The UK supplier provides links to references in the USA and elsewhere: https://esmil.co.uk/wp-content/uploads/2021/01/ESMIL_Digestate-Treatment-Application_ENG.pdf	

WELTEC Kumac	Belt press and DAF removal of solids, followed by membrane treatment and ion exchange to produce a nutrient concentrate and clean water
Whole (farm) digestate is mixed with flocculants and separated into liquor and fibre fractions using a belt press. Solids can be used as a soil improver. Fine solids are removed from the liquor fraction in a DAF / filter system and returned to the front of the treatment process. The clarified liquor digestate is then processed via reverse osmosis and ion exchange to create separate nutrient concentrate and clean water streams. Possible references in Germany: https://www.weltec-biopower.com/technology/kumac-processing.html	
Digested Organics	Membrane treatment to produce clean water and nutrient concentrate
American supplier with one UK digestate reference, which processes separated liquor digestate in ultrafiltration (to remove fine solids) and then reverse osmosis (to produce clean water). Retentates from both steps can be used as fertilisers. https://digestedorganics.com/manure-and-digestate-management/	
TDL Energie	Membrane treatment to produce clean water and nutrient concentrate
Separated liquor digestate is processed via ultrafiltration (to remove fine solids) and then reverse osmosis (to produce clean water). This is claimed to be a containerised solution. https://www.tdl-energie.de/en/water-treatment/digestate	
A3 water solutions	Membrane treatment to produce clean water and nutrient concentrate
Separated liquor digestate is processed via ultrafiltration (to remove fine solids) and then reverse osmosis (to produce clean water). One UK reference (not currently operational): http://www.a3-gmbh.com/NewsBASE/content_a3/frame_english.php	

WEHRLE	Nitrification / Denitrification and membrane treatment to produce clean water and nutrient concentrate
Separated liquor digestate is processed via nitrification / denitrification in a membrane bioreactor (MBR) to remove nitrogen, with optional reverse osmosis to produce clean water for discharge as a final process. The MBR effluent may be used for AD feedstock or process dilution, while the RO permeate may be suitable for environmental discharge (where local regulatory conditions allow). Installations are bespoke, but indicative performance data are provided for some applications: https://www.wehrle-werk.de/sites/default/files/pr_wehrle_mbt-digestate-manure_-_short_introduction_en.pdf	
Drying	
Dorset Green Machines	Dried and pelletised digestate
Dutch supplier, uses Arnold evaporator (see above) as part of a thickening, drying and pelletising process train. https://www.dorset.nu/wp-content/uploads/2018/06/GM-EN-Full-nutrient-recovery.pdf	

11.0 Conclusions and recommendations

The initial scope of this project included consideration of the following impacts associated with commercial and farm digestates:

- Ammonia emissions from digestate during storage and use
- Methane emissions from digestate during storage and use
- Nitrate emissions from digestate following application
- Plastic contamination of digestates
- Handling costs and lack of digestate value

Before determining and modelling options to address these impacts, evidence was assessed for additional impacts. A number of these were discussed and discarded during a steering group meeting due either to evidence of a lack of harm, an absence of consistent evidence suggesting likelihood of harm – or evidence that the impact under consideration was likely to be attenuated during anaerobic digestion. Dismissed impacts included:

- N_2O from stored digestate
- CH_4 and N_2O (fugitive) emissions during AD
- Earthworm mortality
- Plant pathogens
- Combined biological, physical and chemical hazards
- Veterinary medicines
- Organic compound contaminants
- Antibiotic resistance genes
- Bacteria of relevance to human health
- Potentially Toxic Elements
- Soil microbial activity
- Weed seeds
- Botulinum toxin
- N_2O from digestate amended soils
- P transformation in soils
- Salinity

The project did not aim to undertake risk assessment for these additional hazards / impacts but there are nonetheless additional harms potentially associated with digestates: ammonia impacts on earthworm mortality under certain soil conditions; the potential for veterinary residues to be introduced to AD systems in livestock manures and slurries; the potential for specific pathogens or plant propagules to survive anaerobic digestion.

Recommendation 1. Implement a strategic approach to the surveillance and understanding of emerging hazards of concern in food and farm digestates

Following confirmation of the digestate impacts within scope it was then necessary to identify impact mitigation options and to determine baselines for impacts against which mitigations might be assessed. This research highlighted a lack of evidence for nitrate leaching following digestate application – when digestates were applied to soil in Spring, to coincide with maximum crop nutrient demand. The evidence suggests that potential nitrate losses when digestate is used in such a way are lower than might be expected for conventional fertilisers. Nitrate leaching would certainly be expected were digestates to be applied at times of minimal or no crop demand, but this is not good practice and would contravene the Farming Rules for Water. Nitrification inhibitors were identified as potentially capable of mitigating such losses but not subjected to techno-economic assessment in the absence of identified harm from digestates used in the correct way.

Attempts to develop baselines also highlighted additional evidence gaps – particularly with respect to methane emissions from digestates during / after application and for levels of plastic contamination in digestates. Evidence suggests that methane emissions from digested manures will be lower than manures that have not been subject to anaerobic digestion, whilst evidence for other types of digestate was inconclusive. In the absence of a clear baseline for methane emissions during / after digestate application no specific mitigation methods were sought. Nonetheless, acidification of digestate (in store or in field) would likely eliminate methane emissions at this point.

Recommendation 2. Determine the potential methane emissions from commercial and farm digestates during / after application within the context of undigested manures and slurries. Where relevant, investigate the potential for acidification and/or precision application techniques to mitigate such emissions

In the absence of evidence for plastics in digestates, a range of contamination levels was modelled. The understanding of the extent of contamination and potential to use known techniques to mitigate this contamination would be improved with additional evidence.

Recommendation 3. Develop a dataset for plastic contamination in UK commercial digestates. Consider collecting data for farm digestates to confirm research assumptions that these materials are not a relevant vector for plastics in soils

A number of mitigation options were identified for the remaining digestate impacts: ammonia emissions during storage and application; methane emissions during storage; and plastic contamination of the final digestate product. The research methodology was targeted at commercial and near-commercial options, which for the purposes of this project were considered to be those at a Technology Readiness Level of 7 or above. Where lower TRL options were identified these were catalogued but not considered any further.

Recommendation 4. Engage with the research community to develop understanding of the potential of lower TRL and under-represented potential mitigation options such as gas-permeable membrane recovery of ammonia and hot microbubble ammonia stripping

The research also categorised options according to whether they had been demonstrated on 'in scope' digestates (Tier 1 options) or 'similar' substrates such as livestock manures and digested sewage sludges (Tier 2 options). Alum treatment of separated fibre digestate was the only Tier 2 option modelled in detail. This treatment is intended to acidify the substrate – an outcome that can be delivered through the use of concentrated sulphuric acid when treating whole and separated liquor digestates. This latter technique is considered fully commercialised and Tier 1 – but such a designation is misleading. Acidification is commercially available and commonly applied to pig slurries (specifically in Denmark) and has been demonstrated on ‘in scope’ digestates – but without yet being commercially demonstrated on these materials. A UK farmer case study suggests that the technique might be feasibly applied to digestates but there are a number of process uncertainties. Evidence for mitigation of both ammonia and methane from stored fibre digestates is limited, and it is possible that a simple plastic sheet cover may suffice – although the evidence also suggests that this might exacerbate potential methane emissions. Further work is necessary.

Recommendation 5. Determine the potential for methane emissions and abatement for separated fibre digestates in storage. Options for mitigation could include alum treatment and covering with plastic sheeting

A wide range of valorisation end points was identified, but the process of evidence gathering highlighted a number of points that make it difficult (or indeed, inappropriate) to generalize about the applicability of one or any of these end points to all possible commercial and farm AD businesses within the scope of this project. To overcome these a shortlist of valorisation ‘archetypes’ was developed to explore some common AD market drivers, including the need to minimize digestate exports, need to export specific nutrients and a need to reduce reliance on conventional fertilisers. Several of these archetypes mirror commercial process cascades, to give a sense of the order of magnitude of costs and benefits associated with these. An extensive programme of supplier engagement was undertaken to gather cost and performance data for both valorisation and mitigation solutions. Supplier response to this was varied and in some cases extremely limited. This impacted on the quality of data available for investigating nitrification and nitrification / denitrification as well as the use of gas-tight store covers.

Recommendation 6. Develop a mechanism for information exchange between GB users of digestate mitigation and valorisation techniques to facilitate understanding of costs, performance and applicability across different types of digestate

Based on all evidence gather from suppliers and published data, technoeconomic assessment models were separately developed for mitigation and valorisation techniques. Both models are based on the installation of technologies at new build plants. This means that results are not applicable for the retrofitting or the replacement of existing technology with new versions at existing plants.

The main outputs of the mitigation model are the costs per kg abatement, cost per tonne of digestate, and cost per MWh of energy produced. The valorisation model focuses on the valorisation of digestate, modelling the revenue derived from valorisation processes and associated costs of multiple valorisation archetypes. The main outputs of the valorisation model are the net revenue per tonne of digestate treated and net revenue per MWh of energy generated.

For ammonia the modelled data shows some consistent patterns in terms of all three of the cost metrics. Generally speaking, there is little variation in cost with scale for any of the modelled options. The use of stripping and scrubbing technology show some increase in costs with decreasing plant size, but in general, for the other technologies all three cost metrics do not appear to vary with plant size. The use of a gas-tight cover on the digestate storage tank is clearly the cheapest technology option across all three metrics for whole and separated liquor digestates (commercial and farm). Given that it is also a commercially available technology, with a clear regulatory framework for implementation, it would therefore appear to be the best available option for installation at new plants to mitigate ammonia losses. There is however a significant issue with the data that has been used in the modelling exercise for use of gas-tight covers. The data was difficult to obtain and there is a lack of confidence in its robustness. Further work is recommended to address this.

Recommendation 7. Engage with suppliers and operators to understand the true costs and implications of using gas-tight store covers to mitigate ammonia and methane emissions during storage of whole and separated liquor digestates

The use of injection application equipment is the second cheapest option. There will be advantages in both installing a gas-tight cover and using precision spreading technology, but the additive costs and environmental benefit have not been modelled at this stage. Since ammonia emissions during application / use are more significant than emissions during storage, precision spreading might become a preferred option. Although less cost-effective, acidification provides the advantage of mitigating ammonia in both storage and use. There is also evidence that it will mitigate methane during storage (for whole and separated liquor digestates in all cases). Further analysis would be required to understand the benefits and costs associated with integration of different mitigation techniques during storage and use, compared with techniques that may confer benefit at both points.

Recommendation 8. Investigate the costs and benefits of combining mitigation techniques during storage and use of whole and separated liquor digestates, as compared with techniques that may confer benefit at both process points

The other modelled options present larger modelled costs and higher degrees of uncertainty in terms of regulatory framework, TRL level or general confidence in the data that was used for the modelling. The use of stripping and scrubbing technology or side stripping options are particularly challenging in regulatory terms where the waste status of both the input acid necessary and of the output that will then need to be spread to land need to be determined and dealt with under the appropriate regulatory mechanism.

The use of acidification techniques for ammonia mitigation is currently being developed at scale in continental Europe for separated pig slurries (<u>not</u> digestates) but is not a common technology in the UK. The modelled costs from this exercise are in the middle of the technology ranges that have been calculated and of the technologies that have been modelled, acidification options have a lower TRL level combined with some potential for pollution swapping to occur. There is some regulatory uncertainty that would need to be clarified if acidification technologies were to be adopted by more plants.

Recommendation 9. Engage with suppliers and operators to understand the potential for acidification of separated liquor digestates alongside options for mitigation of ammonia and methane emissions from separated fibre digestates

Only two technology options were modelled for mitigation of methane emissions during digestate storage: the use of acidification in store and the use of gas-tight store covers.

Many of the same conclusions that were arrived at when these technologies were modelled for ammonia abatement apply to their use for mitigating the impact of methane. As before, the use of a gas-tight cover on the digestate storage tank is the cheapest option when measured by all three metrics. There are, however, clearer differences in cost between farm and commercial systems, and for acidification clear differences with costs increasing with decreasing scale. There is a similar lack of robust data for the use of gas-tight stores for methane mitigation and this is a weakness in the modelling. This should be addressed by the EA and Defra if further work or improved modelling is to be undertaken.

The same comments about TRL level, regulatory complexity and pollution swapping apply as they did with ammonia mitigation. The understanding and use of gas-tight stores is further advanced than the use of acidification technology which would benefit from further work to derive a robust evidence base.

Modelling of plastic mitigation was hampered by the lack of evidence for baseline contamination levels and the absence of industry data on the current use of screening techniques (such as screw presses and similar separators). Farm plants were not considered for plastic mitigation since they should not be utilising feedstocks that will be contaminated with plastics. Costs and performance for screens were modelled (based on data for screw presses) and clearly effective. However, the modelling highlighted that screening costs increased in step with contamination levels due to the production of a plastic-contaminated reject fraction which is disposed via landfill or energy from waste. This is clearly undesirable. Operators in Scotland have been required to comply with much lower contamination levels that operators elsewhere in GB since December 2019 and could be commercially disadvantaged if new plants were incentivised to include screening equipment which they have already installed.

Recommendation 10. Engage with suppliers, operators and the research community to understand and develop options for improved depackaging techniques which recover contaminants for recycling and obviate the need for downstream digestate screening

Eight valorisation archetypes were modelled, revealing that several techniques might be commercially attractive. In particular where digestates could be transformed into a nutrient concentrate for retail sale or where separated fibre could be supplied for landscaping / horticultural uses. In both cases the potential revenue for each stream was estimated to be many millions of £. Perhaps more realistically the use of DAF to capture fine solids and increase the phosphorus value of fibre digestate was also attractive purely from a nutrient management perspective. Regulatory barriers currently prevent the use of digestate concentrates or soil improvers for landscaping / amenity purposes as products. The physical characteristics of commercial digestates make phase separation challenging, but their conversion to nutrient concentrates is feasible via several process routes.

Recommendation 11. Engage with regulators and operators to develop end of waste positions for specific digestate-derived materials, particularly for farm digestates. These include nutrient concentrates and soil improvers.

Sensitivity analyses were performed for both mitigation and valorisation scenarios. In most cases significant model impacts were linked to the nutrient contents of digestates and to the volumes of digestate processed (which varies according to the mix of farm materials processed in AD). Many of the mitigation scenarios are OPEX-dominated and consequently sensitive to the costs of consumables such as sulphuric acid and alum. Mitigations are also very sensitive to the % abatement allocated, and in some cases (for example, stripping and scrubbing, nitrification, nitrification / denitrification) evidence for abatement was extremely variable. Fertiliser prices impacted several valorisation scenarios where revenue is associated with nutrients – particularly nitrogen. However, even very high fertiliser prices (March 2022) were insufficient in most cases to transform negative valorisation business cases in positive cases.

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Appendix 1: REA Search Structures

Table 75 Task 1 search results (digestate impacts)

Number	Date	Database	Search logic	Limiters	Number of hits	Number reviewed	Number saved for full evaluation
1	18/10/2021	Science Direct	"digestate" AND "risk assessment" NOT sewage	2011-2021	177	177	5
2	18/10/2021	ResearchGate	"digestate" AND "risk assessment" NOT sewage	none	n/a	200	9
3	19/10/2021	EU Science hub	"digestate" AND "risk assessment" NOT sewage	none	55	55	0
4	19/10/2021	EU Science hub	digestate	agriculture and food security	64	64	0
5	19/10/2021	EU Science hub	digestate	environment and climate change	35	35	3
6	19/10/2021	EU Science hub	digestate AND risk	none	75	75	0
7	19/10/2021	google	technical proposals EU fertilising products digestate	none	61,600	100	7
8	19/10/2021	EthOS	digestate AND risk	none	186	186	0
9	19/10/2021	CORDIS	digestate' AND 'risk' AND NOT 'sewage'	report summaries	353	100	0
10	19/10/2021	keep.eu	digestate	Description and Delivered Outputs	8	8	0
11	19/10/2021	Defra science search	digestate AND risk NOT sewage	none	0	0	0
12	19/10/2021	Defra science search	digestate AND risk	none	0	0	0
13	19/10/2021	Defra science search	digestate	none	1	1	0
14	19/10/2021	Science Direct	"digestate" AND "environment" and "harm" NOT "sewage"	2011-2021	139	139	0
15	19/10/2021	Science Direct	"digestate" AND "soil" and "risk" NOT "sewage"	2011-2021	1153	200	4

16	19/10/2021	Science Direct	"digestate" AND "air quality" and "impact" NOT "sewage"	2011-2021	165	165	3
17	19/10/2021	Science Direct	"digestate" AND "soil quality" and "impact" NOT "sewage"	2011-2021	227	227	1
18	19/10/2021	google scholar	digestate environment risk	2011-2021; without 'sewage'	7790	200	5
19	19/10/2021	google scholar	digestate risk assessment	2011-2021; without 'sewage'	7150	200	2
20	20/10/2021	google	digestate risk assessment	2011-2021	108	108	12
21	20/10/2021	Wageningen University	digestate and risk	none	65	65	3
22	20/10/2021	Open Grey	digestate	none	7	7	0
23	20/10/2021	IWA publishing	digestate AND risk NOT sewage	Journal articles	264	100	0
24	20/10/2021	VCM (Flemish centre for manure processing)	risk	none	0	0	0
25	21/10/2021	Science Direct	digestate storage impact -sewage	2011-2021	1650	200	7
26	21/10/2021	google scholar	digestate storage impact -sewage	2011-2021	9560	200	11

Table 76 Task 2 search results (mitigation)

Number	Date	Database	Search logic	Limiters	Number of hits	Number reviewed	Number saved for full evaluation
1	09/11/2021	google	digestate ammonia mitigation	none	162,000	200	10
2	10/11/2021	Finzi et al., 2020 (on google scholar)	Citations of this paper	none	13	13	1
3	10/11/2021	Sánchez-Rodríguez et al., 2018 (on google scholar)	Citations of this paper	none	17	17	2
4	10/11/2021	Bittman et al., 2014 (on google scholar)	Citations of this paper	none	135	135	12
5	10/11/2021	Engineering Village	digestate and plastic and removal	none	187	187	2
6	11/11/2021	Alessi et al., 2020 (on google scholar)	Citations of this paper	none	8	8	1
7	11/11/2021	Lopes et al., 2019 (on google scholar)	Citations of this paper	none	5	5	1
8	11/11/2021	Alessi et al., 2020	Citations of interest within this paper	none	5	5	5
9	11/11/2021	Jank et al., 2015 (on google scholar)	Citations of this paper	none	30	30	3
10	11/11/2021	Hansen et al., 2007 (on google scholar)	Citations of this paper	none	112	112	6
11	11/11/2021	Bernstad et al., 2013 (on google scholar)	Citations of this paper	none	112	112	6
12	11/11/2021	Science Direct	"plastic contamination" and removal and biowaste	none	5	5	0
13	11/11/2021	Science Direct	microplastic and removal and biowaste	none	62	62	1
14	11/11/2021	Science Direct	plastic and removal and biowaste	2020 - 2022	354	200	1
15	11/11/2021	Science Direct	plastic and removal and food waste	Title, abstract, keywords	18	18	0
16	11/11/2021	Engineering Village	plastic and removal and "food waste"	Abstract	13	13	0
17	11/11/2021	Engineering Village	plastic and removal and biowaste	Abstract	7	7	0

18	11/11/2021	Engineering Village	plastic and removal and digestate	Abstract	93	93	1
19	11/11/2021	Engineering Village	depackaging and waste	Abstract	3	3	1
20	12/11/2021	AHDB knowledge library	nitrate leaching	crops and grassland	44	44	1
21	22/11/2021	Science Direct	ammonia and digestate and recovery NOT sewage	2012-2022	1,244	200	40
22	22/11/2021	Science Direct	nitrogen and digestate and removal NOT sewage	2012-2022; Title, abstract, keywords	115	115	4
23	22/10/2021	Science Direct	ammonia and digestate and mitigation	2012-2022	1,388	200	17
24	22/10/2021	Science Direct	ammonia and digestate and mitigation	2012-2022; Title, abstract, keywords	26	26	4
25	23/10/2021	Science Direct	digestate and "nitrate leaching" NOT sewage	none	140	140	13
26	23/10/2021	Science Direct	improve "nitrogen use efficiency" digestate NOT sewage	2012-2022	107	107	8
27	23/10/2021	Science Direct	depackaging "anaerobic digestion"	none	12	12	0
28	23/10/2021	Science Direct	autoclave plastic "anaerobic digestion"	Title, abstract, keywords	1	1	0
29	23/10/2021	google scholar	autoclave plastic "anaerobic digestion" - sewage	none	1,650	100	3
30	23/10/2021	Wiley	anaerobic+digestion+plastic	keywords	2	2	0
31	23/10/2021	Wiley	biogas+plastic	keywords	3	3	0
32	23/10/2021	Wiley	anaerobic+digestion (anywhere) +plastic (keywords)	see left	82	82	5
33	23/10/2021	ResearchGate	digestate and plastic	none	Many	Many	8
34	24/11/2021	American Chemical Society	digestate and plastic and contamination NOT sewage	none	87	87	1
35	24/11/2021	Royal Society of Chemistry publications	digestate and plastic and contamination	"without" sewage	21	21	0
36	24/11/2021	IEMA	digestate and plastic	none	526	100	0
37	24/11/2021	EthOS	digestate and plastic	none	34	34	2

38	24/11/2021	CORDIS	digestate and plastic	Projects only	44	44	3
39	24/11/2021	Defra Science Search	digestate and plastic	none	0	0	0
40	24/11/2021	CORDIS	digestate and ammonia and mitigation	none	29	29	3
41	24/11/2021	EthOS	digestate and ammonia and mitigation	none	3	3	1
42	24/11/2021	American Chemical Society	digestate and ammonia and mitigation	none	50	50	7
43	24/11/2021	Engineering Village	digestate and ammonia and mitigation NOT sewage	none	106	106	9
44	24/11/2021	American Chemical Society	digestate and nitrate and field and leaching	none	53	53	4
45	24/11/2021	google	depackage food waste plastic removal performance	none	32	32	7
46	06/12/2021	Science Direct	biochar and digestate and ammonia NOT sewage	2011-2022	236	236	15
47	26/01/2022	Google scholar	Citations of https://doi.org/10.2166/wst.2013.005	none	101	101	8
48	26/01/2022	(Muha, Linke and Wittum, 2015) (on google scholar)	Citations of this paper	none	20	20	0
49	26/01/2022	(Scheutz and Fredenslund, 2019) (on google scholar)	Citations of this paper	none	31	31	2
50	26/01/2022	(Baldé *et al.*, 2016a) (on google scholar)	Citations of this paper	none	49	49	6

Table 77 Task 3 search results (valorisation)

Number	Date	Database	Search logic	Limiters	Number of hits	Number reviewed	Number saved for full evaluation
1	21/12/2021	Science Direct	Economic assessment of different biogas digestate processing technologies: A scenario-based analysis	None	1373	250	20
2	21/12/2021	Science Direct	Techno-economic and assessment and digestate	2015-2022	634	300	23
3	21/12/2021	Science Direct	Digestate and valorisation	2015-2022	451	200	19
4	21/12/2021	Science Direct	Vaneeckhaute	Author	27	27	7
5	21/12/2021	Science Direct	Papers citing those examined in search 4	None	176	176	3
6	21/12/2021	Science Direct	Guilayn	Author	4	4	1
7	21/12/2021	Science Direct	Papers citing those examined in search 6	None	43	43	10
8	22/12/2021	Springer Link	Digestate and valorisation	2015-2022	451	200	11
9	22/12/2021	Springer Link	Papers citing those saved in search 8	None	16	16	6
10	22/12/2021	IWA publishing	Digestate valorisation	Journal Articles	35	35	3
11	22/12/2021	EthOS	Digestate and valorisation	Downloadable items only	5	5	2
12	22/12/2021	EthOS	Digestate and management	Downloadable items only	149	149	6
13	22/12/2021	NARCIS	Digestate	Publications	135	135	10
14	22/12/2021	Knovel	Digestate	None	49	49	2
15	22/12/2021	Engineering Village	Digestate and valorisation	None	322	200	7
16	22/12/2021	Wageningen University	Digestate	Publications	61	61	6
17	22/12/2021	CORDIS	Digestate	Project deliverables	119	119	8
18	22/12/2021	keep.eu	Digestate	Projects	15	15	3

19	22/12/2021	Biorefine Cluster Europe	Digestate	None	28	28	6
20	22/12/2021	Life	Digestate	2010-2021; projects	25	25	5
21	23/12/2021	CORDIS	Project reports from search 18	None	74	74	53
22	23/12/2021	keep.eu	Project reports from search 18	None	76	76	10
23	23/12/2021	google	digestate and valorisation and cost	None	65,700	200	27
24	23/12/2021	google	digestate and "economic analysis"	2015-2021	101	101	5
25	23/12/2021	google	digestate and "case study" and costing	2015-2021	107	107	9
26	23/12/2021	Cerda et al., 2019	Citations within this paper	None	n/a	n/a	n/a
27	23/12/2021	Guilayn et al., 2020	Citations within this paper	None	n/a	n/a	n/a
28	23/12/2021	Mejias et al., 2020	Citations within this paper	None	n/a	n/a	n/a

Appendix 2: Evidence for additional impacts

Table 78 Evidence extraction

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Nicholson *et al.*, 2016)	This report outlines a qualitative priority ranking methodology developed to consider the potential risks from land application of a large number of waste materials, including digestates, in scenarios from cereal crops, livestock grazing and RTE crops. Overviews of hazards of interest are provided for each category of land applied material, together with their scores from the different exposure pathways. RTE crops are the most significant exposure pathway for food and crop derived digestates, but were not considered a viable market for these materials. Evidence gaps relevant to digestates included: antimicrobial resistance, microplastics / nanoparticles, dioxins, furans (chlorinated or brominated) and PCBs / PBBs.	Wide range of biological, chemical and physical hazards	Good	Comprehensive within the bounds of available evidence. Data gaps were identified for some hazards, including organic compound contaminants, microplastics and anti-microbial resistance	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Longhurst *et al.*, 2019)	Summarises a decade of risk assessment research on composts and digestates funded by WRAP. Within the bounds of available evidence, risks from chemical, physical and biological hazards in these materials were deemed acceptably low or negligible (both the human and animal receptors). Hazards such as microplastics are flagged as having been identified after the research had concluded.	Wide range of biological, chemical and physical hazards	Good	Comprehensive within the bounds of available evidence	None
(wca environment ltd, 2014)	A report that assesses the potential human and environmental risks from organic chemicals in materials applied land in Scotland. Quantitative risk assessment for human health based on dietary exposure to dioxins in food produced on waste amended land indicated that there was no risk to health even under worst-case conditions (where mixed-waste derived composts were applied to land) but the authors make a number of recommendations relating to veterinary medicines	Wide range of chemical hazards	Good	Slim evidence base for AD Quality Protocol highlighted	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Tigini *et al.*, 2016)	Digestate from an Italian AD plant processing pig slurry and maize was assessed through a series of ecotoxicity tests - all of which exhibited negative (i.e. detrimental) responses. The authors suggest that this was due to ammonium, salinity, phosphate, COD and colour (the latter contributing to negative response in an algal bioassay). Further tests were recommended to explore other aspects of digestates	Negative responses to digestate in seven common ecotoxicology tests	Good	No risk analysis / contextualisation	None
(Pivato *et al.*, 2016)	Results are reported for a battery of direct and indirect ecotoxicological tests on Italian farm digestate (derived from ~2:1 cattle manure : triticale). Digestate had a DM of ~28% and in accordance with prevailing Italian legislation, had been stored for a minimum of 180 days (under 'naturally aerated conditions') prior to sampling and testing. Benchmark dose-response data for earthworm, plants and other assays are presented - but without subsequent risk analysis	None	Good	No risk analysis performed	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Saveyn and Eder, 2014)	This report sets out the evidence and proposals for EU-wide end of waste criteria for (composts and) digestates. Data on digestate quality (PTEs, physical contaminants, organic compound contaminants) were collated from existing datasets, and a specific sampling / testing campaign was implemented to generate further data on specific material types (results of which are published in TAVAZZI et al. (2013). When moderated via multi-national stakeholder groups and pre-existing quality standards, the final proposals covered digestate quality parameters that are largely already included in the UK end of waste approach. Nonetheless, there are differences: the proposed digestate stability limit is lower; the proposed physical contaminant limit is higher; a weed seed test is included; a PAH limit is included. Weed seeds are considered elsewhere in this table (Johansen *et al.*, 2013)	A range of biological, chemical and physical hazards	Good	Several hazards are not currently limited in UK EoW digestates (eg weed seeds, PAH-16), but this does not indicate an issue.	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Johansen *et al.*, 2013)	Seeds of eight weed species (*Brassica napus*, *Avena fatua, Chenopodium album, Sinapis arvensis, Fallopia convulvulus* and *Amzinckia micrantha*) were placed in lab-scale reactors with cattle slurry and a cattle slurry digestate inoculum. Seeds (100 of each species) were periodically tested for germinability through destructive sampling of four replicates of each treatment. After 11 days under mesophilic conditions (37°C) none of the species germinated. This interval was 2 days under thermophilic conditions (55°C). *Chenopodium album* seeds were most persistent, remaining viable after seven days - but were still non-viable at day eleven	Weed seeds	Good	Seeds killed by day 11 under mesophilic conditions	None
(Dollhofer and Zettl, 2017)	Outlines regulatory framework for compost and digestate use in Germany, with links to specific documents in English. Digestate specification includes weed seed test and area-based limit for 'impurities'	Weed seeds and physical contaminants	Poor	Plastics already in scope; Weed seeds killed during AD	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Tompkins, 2017)	Summarises a series of risk assessments (themselves subject to peer review) relating to agricultural uses of digestate. In some cases relating specifically to crop diseases, the absence of supporting evidence suggested that some crop-derived digestates should not be applied ahead of the same crops - particularly potato crops - unless the AD process included a defined pasteurisation phase	Wide range of hazards considered	Good	Comprehensive within the bounds of available evidence. Potato pathogens may survive processing	Plant pathogens
(Schleusner *et al.*, 2019)	The fate during mesophilic anaerobic digestion of the causative organism of potato wart disease (*Synchytrium endobioticum*) was explored at bench scale, and viable spores found in the digestate after 14 days in the reactor. Spores were still viable in the digestate following six months storage. The authors highlight prior research indicating that heat treatment at 74°C for 4 h, 80°C for 2 h, or 90°C for 1 h (as recommended in EPPO standards) is not effective. Given the serious economic impact and durability of the pathogen, the authors recommend that potato residues should be tested using genetic techniques before they are processed in AD	Plant pathogen	Good	Specific potato pathogen likely to survive processing. No UK risk context	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Spielmeyer, 2018)	The authors review data on excretion of veterinary antibiotics into manures / slurries, and the findings of studies into their impacts on biogas production and fate during AD. While numerous studies report removal during AD or composting, the degree of removal varies according to compound and system under study. The authors highlight the general lack of exploration of mechanisms of removal, suggesting the possible significance of temporary sorption to solids - which may de-sorb following application to land - rather than chemical transformation. Where transformation studies are reported, the metabolites commonly exhibit antimicrobial properties. As with other papers on this topic, the process of AD does not increase loads of antibiotics to the environment	Veterinary medicines	Good	Environmental loads from veterinary compounds in manures / slurries would not be increased by AD processing	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Rodriguez-Navas *et al.*, 2013)	Various hormone compounds were found in digestates from two AD facilities in Denmark. Both AD sites were processing feedstocks comprised largely of pig slurries, with one operating under mesophilic and one under thermophilic conditions. There were differences in hormone profiles between the digestates (in terms of type and concentration), suggesting a lower removal rate under thermophilic conditions. The authors did not test feedstocks prior to digestion, but do present the digestate data against literature values for hormones in pig slurries from a prior study. Modelled hormone loadings from these digestates to soil and water were found to be similar from loadings from undigested manures.	Veterinary medicines	Good	Environmental loads from veterinary compounds in manures / slurries would not be increased by AD processing	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Lu *et al.*, 2021)	Field study investigating impacts of pig slurry digestates on antibiotic residues, ARG (antibiotic resistant genes) and MGE (mobile genetic elements) in five cropped soils over periods of 8 to 18 years. AD processes and digestate application did not mirror UK practice (experiments took place in China), but approaches seem robust. Unfortunately no digestate vs pig slurry vs control (only digestate vs control, mineral fertilisers were added to both at equivalent rates at each of four sites, while at the fifth the experiment was +/- digestate with no fertiliser) so no indication as to whether digestate is exacerbating an issue known to occur in raw pig slurry. Microbial richness, diversity and biomass increased in treated soils over the experimental period (likely as a result of organic matter additions, compared with the controls). Results varied across sites, with ARGs higher in control soils at one site than treated soils at all others. Accumulation of antibiotics was noted, particularly for tetracycline, but this was stated not to have approach problematic concentrations (although its presence was certainly sufficient to drive changes in soil microbial populations)	Veterinary medicines and ARGs	Good	Environmental loads from veterinary compounds in manures / slurries would not be increased by AD processing	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Sanz *et al.*, 2021)	Pig slurries (x10) and digested pig slurries (x2) were collected from 8 different facilities in Spain and tested for a number of antibiotic compounds and the presence of ARGs. ARGs were found in all samples, with AB concentrations and types varying (and tending to correlate with different points in pig production cycles). Clostridia and methanogenic bacterial populations were negatively correlated with the ARGs studied, suggesting a possible reductive effect of anaerobic digestion.	Veterinary medicines and ARGs	Good	Environmental loads from veterinary compounds in manures / slurries would not be increased by AD processing	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Widyasari-Mehta, Hartung and Kreuzig, 2016)	Samples of pig slurry and digested pig slurries were collected from 21 farms in Germany (five of which were operating biogas plants, although four of these were importing other materials for digestion, including poultry manure, cattle manure and silage) and tested for a range of veterinary antibiotics (sulfadiazine, sulfadimidine, sulfadoxine, sulfadimethoxine, trimethoprim, chlortetracycline, doxycycline, oxytetracycline, tetracycline, enrofloxacin, tylosin, tiamulin). Samples of slurry and digestate on sites with AD facilities were taken on the same day (ie there was no attempt to implement a strict 'before and after' study). Concentrations were lower in digestates	Veterinary medicines	Good	Environmental loads from veterinary compounds in manures / slurries would not be increased by AD processing	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Gurmessa *et al.*, 2020)	Review of previously published papers examining the potential for removal of ARGs (antibiotic resistance genes), veterinary antibiotics (VA) and mobile genetic elements in AD. Mechanisms of VA removal are outlined, with adsorption key for numerous compounds. The overall impact of AD on removal was varied, with a range of mitigation strategies suggested (including phase separation and composting of the solid fraction). Overall, there is no clear statement on the magnitude of risk	Veterinary medicines, ARGs and MGEs	Good	Environmental loads from veterinary compounds in manures / slurries would not be increased by AD processing	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Nolan *et al.*, 2020)	This paper describes experiments with replicated field microplots in grass pasture to the surface of which a number of organic materials were applied (cattle slurry, pasteurised and unpasteurised digestate). Simulated rainfall was then applied at a rate of 11mm / hr after 24hr, 48hr, 15 days and 30 days of treatment until sufficient surface runoff could be collected for various analyses - including nutrients (NPKS), potentially toxic elements and faecal indicator bacteria (FIB). FIB numbers, nutrient and PTE concentrations in runoff, soils and grass were always higher for plots treated with cattle slurry. Overall the authors state that reduced microbial runoff from digestate was the most prominent advantage of digestate application.	Faecal indicator bacteria, nutrients and PTEs in surface runoff; soil and grass accumulation of PTEs	Good	Risks from digestate considered lower than from livestock slurries	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Nag *et al.*, 2021)	This paper outlines a quantitative microbial risk assessment (QMRA) for consumer exposure to pathogens in drinking water sourced from locations modelled to have been impacted by runoff from fields where cattle slurry, pasteurised or unpasteurised digestate were applied. The model includes various dilution and water-treatment factors and concludes that after Day 2 (following a rainfall event) risks from all materials were very low. Risks from cattle slurry were moderate (on Day 1) and from unpasteurised digestate low (on Day 1). The authors conclude that their findings reinforce the need to ensure that organic manures are not applied when rain is forecast for the 48 hours following application	Pathogens in drinking water	Good	Context is for Ireland – unclear whether UK context would equate	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Nag, Whyte, *et al.*, 2020)	Desk study from Ireland that outlines a risk ranking methodology for various pathogens based on their inactivation during different AD scenarios (different pasteurisation approaches, MAD vs TAD etc), hazard pathways and human mortality rates. This is not a risk assessment as such - so it is not possible to determine whether any of the top-ranked pathogens are relevant in any practical sense	Pathogens	Good	Not a risk assessment, so impossible to determine relevance of ranked organisms	None
(Murphy *et al.*, 2016)	Pot study in which digestate was used as a fertiliser for lettuce plants, and the fate of various pathogens tested in the growing medium: *E. coli* O157, *Salmonella* Senftenberg and *Listeria monocytogenes*. Tests were also performed to explore internalisation of the organisms within the crop. Trials took place over 50 days - *Listeria* declined to below LOD over two weeks, the other organisms were still detectable until the trial ended. Direct plating from (surface sterilised) leaf material did not identify any pathogens, but both *E coli* and *Salmonella* could be detected following enrichment from some of the root and leaf samples (not in all replicates at all sampling times).	*E. coli* and *Salmonella* in ready to eat crops	Good	Not a risk assessment	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Nag, Bolton, *et al.*, 2020)	A short paper outlining a quantitative microbiological risk assessment (QMRA) model that investigates the potential exposure to *E. coli* O157:H7 from RTE foods (in particular fresh vegetable produce) following the application of anaerobic digestate (with/without pasteurisation) and cattle slurry on agricultural land. Risks from unpasteurised digestate and cattle slurry both considered 'very high', while risks from pasteurised digestate considered 'very low'.	*E. coli* O157:H7 in ready to eat crops	Good	Risks from digestates considered lower than other materials	None
(Nolan *et al.*, 2018)	Reports findings from bench scale AD trials with slurry and FOG (fats, oils and greases) mixes (2:1) on total coliforms, *E. coli*, and enterococci (collectively referred to as FIB or Faecal Indicator Bacteria). Even in the absence of pasteurisation, enterococci numbers were below 1,000 cfu / g, and *E. coli* was no longer detectable after 28 days. In comparison, FIB numbers were still >1,000cfu / g in cattle slurries after 60 days storage under ambient conditions.	*E. coli*, total coliforms and enterococci in stored digestate	Good	Risks from digestate lower than manures	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Le Maréchal *et al.*, 2020)	Reports from an expert workshop on the risks associated with animal botulism, one session of which was devoted to biogas facilities. No BoNT-producing Clostridia were isolated in 154 samples from 8 biogas plants in Bavaria, while D-values of 34.6 ± 11.2 d at 38 °C have been demonstrated experimentally. In contrast, *C. botulinum* had been detected and enumerated from ~80% of digestate samples from French biogas facilities (as well as ~30% of undigested manure samples). Conclusions from a Belgian study that risks to grazing livestock from botulinum were very low.	*Clostridium botulinum*	Average	Workshop concluded that anaerobic digestion does not induce the growth of *C. botulinum*, and that the risk associated with spreading digestate is similar to that of spreading manure	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Derongs *et al.*, 2021)	Bench scale MAD trial with pig manure which investigated the combined effect of operational parameters (OLR / HRT) and pasteurisation on chemical parameters that may affect inactivation of pathogens (volatile fatty acids, ammonia), and the fate of *E. coli*, Enterococci, *Clostridium perfringens* and Clostridioides difficile. Retention times varied from 24 to 48 days, and pasteurisation followed EU norms (70C / one hour). Significant reductions were seen for E. coli (with or without pasteurisation), while Enterococci were eliminated by pasteurisation but present in digestates. Pasteurisation led to a significant increase in C. difficile in feedstocks, but this impact was not consistent across the experimental treatments, and levels in digestates tended to lower than feedstocks across all treatments - although still present	*Clostridium perfringens, Clostridioides difficile*, *E. coli,* Enterococci	Good	*Clostridioides difficile* was found in digestate irrespective of prior pasteurisation or other process changes – but no risk analysis was performed. Compare with Le Maréchal et al. (2020)	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Ehlert *et al.*, 2019b)	Reviews literature values for a number of digestate-derived fertilisers, including the separated liquor fraction of digestates. PTEs and pathogens flagged as of interest, but no suggestion that these need to be considered in more detail	PTEs and pathogens	Average	Not a risk assessment	None
(Ai *et al.*, 2020)	Greenhouse study with aubergines grown in soils amended with a combination of pig slurry digestates and ammonium sulphate (stripped from same digestates). Extremely poorly edited paper with missing units and inadequate description of materials under test.	Elevation in soil Cu, Pb & Zn following digestate use	Poor	Impacts would be similar from undigested pig slurries	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Corden *et al.*, 2019)	Risk assessment for composts and digestates. Draws heavily on Saveyn & Eder, 2014 and has been heavily criticised for collectively examining data for different kinds of materials and suggesting limit values at variance with those adopted in EU FPR (see ECN, 2020 and ESPP, 2020). Ni, Hg and PAH16 flagged for relevant digestates (Table 5.1) - limits for these were agreed for the EU-FPR. Ni and PAH16 flagged as relevant for container growing; Hg flagged for field application	A range of physical, chemical and biological impacts	Average	One of several EU papers suggesting PAH limits in digestates. No such limits in UK at present	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Foster and Prasad, 2021)	Provides the background to development of compost and digestate standards in Ireland. Includes germination test (digestate used in growing media) and adopts As, Cr(VI) and PAH limits from EU FPR [note that PAH limits come from digestate CMC while Cr and other PTE limits come from various PFCs, including soil improver and compost]. Provides information on plastic limits and methods in other countries - including >1mm approach in Germany and area-based approach in Germany and Switzerland. Arsenic on deemed relevant for feedstocks that include tannery wastes	A range of physical, chemical and biological impacts	Good	Adopts EU proposals for PAH limits in digestates. Not a risk assessment	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(TAVAZZI *et al.*, 2013)	Part of the evidence base used to inform proposed EU-wide end of waste criteria for composts and digestates (see Saveyn & Eder (2014) for more detail). 22 minor and trace elements and 92 organic compounds were tested in 139 samples from 15 countries, covering a range of material types (few of which were source-segregated or non-waste digestates). The authors concluded that testing requirements and limit values for should be included for PAHs "as no technology or input material type provides a full safeguard against the presence of organic pollutants".	Suggested testing and limit for PAHs in digestates. Small digestate dataset	Average	One of several EU papers suggesting PAH limits in digestates. No such limits in UK at present. Not a risk assessment	None
(ECN, 2020)	Critiques Corden et al. (2019), highlighting differences between suggested 'safe' limits and those agreed for EU-FPR.	None specific	Poor	No hazards assessed	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Nkoa, 2014)	A review paper exploring digestate-related impacts on air, soil and water. Flags common issues (NH_3 emissions, Cu & Zn in manures etc). Data from 2005 are cited in support of potential accumulation risks from Mn, although subsequent authors have not flagged this as an issue	Cu and Zn from digested pig slurries; Manganese.	Average	Impacts would be similar from undigested pig slurries	None
(Pawlett and Tibbett, 2015)	This brief paper summarises field experiments in which food based digestates were applied to grassland with a view to understanding potential sodium accumulation - and potential long term risk to soil structure through repeated use of these digestates. Na concentrations were significantly higher after digestate use (whether applied at rates equivalent to 100kg N or 200kg N per hectare (~44 or 88kg Na per hectare), and longer-term monitoring recommended.	Sodium accumulation in soil following digestate use, which could impact on soil structure in the long term.	Good	No risk context provided (eg use of agricultural salt in beet crops)	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Ali *et al.*, 2019)	A study reporting concentrations of TCPP, DEET, 25 pharmaceutical and personal care products (PPCPs) and 11 metabolites in digestates from 12 Norwegian AD plants. Eight of these plants process sewage sludge - either as a sole substrate or in combination with food waste; Four plants process food wastes alone (or in one case, with manure). The analysis does not disaggregate results based on AD inputs, focussing instead on chemical partitioning between solid and liquid digestates. The Supplementary information provided does not list all data for all digestate types, meaning that it is not possible to conclude whether specific compounds are of specific relevant to farm or food digestates - although the types of compounds examined would not be expected in such digestates	Organic compound contaminants, including PPCPs	Good	Impossible to disaggregate sewage sludge data from food / farm digestate data (most hazards considered would not be expected in the latter)	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Gómez-Brandón *et al.*, 2016)	Lab incubation study of soils amended with manure-derived digestate (and compared with compost / vermicompost etc) over 60 days. Examined a range of parameters, including impacts on ammonia oxidising bacteria (AOB), faecal indicator pathogens (and *Clostridium perfringens*)	Soil microbial activity and faecal pathogens	Good	Soil type found to have a greater impact than soil amendments	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Risberg *et al.*, 2017)	This study from Sweden compared 20 digestates with 10 pig slurries and 10 cow manures with respect to their chemical characteristics and their effect on soil microbial activities (potential ammonia oxidation rate (PAO) and soil respiration). Digestates were derived from a variety of different inputs, and processed under both mesophilic and thermophilic conditions - with NH_4-N ranging from 1.9 to 5.3kg / t (FW) and dry matter from 1.1 to 7.4%. Pig slurries and cattle manures had higher DM content and lower NH_4-N. Despite the various chemical differences and different soil respiration responses, overall utilisation of organic carbon in the three materials did not differ significantly after 12 days of incubation, leading the authors to infer that digestates were not found to present a higher risk with respect to their impact on soil microbial activity.	Soil microbial activity	Good	No specific impacts determined for digestate	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Natalio *et al.*, 2021)	This study explored mechanisms associated with the effect PAS110 food based digestate on *A. chlorotica* survival following application to soil, and whether there was a different response between the juvenile and adult stages. 10 L microcosms were filled with loamy sand soil and two adult + five juveniles of *A. chlorotica* added and allowed to acclimatise for five days. In addition to digestate, other treatments included Osmotic-Stress; Labile-C; Synthetic-Digestate (i.e. same salt concentration and BOD as digestate); and water as a control. Earthworm biomass declined over all treatments during the 29 days of the trial but overall results were inconclusive (although some mortality amongst adult earthworms was observed under different treatments)	Earthworm mortality	Good	Inconclusive	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Rollett *et al.*, 2021)	This paper analyses results from seven UK field sites where food based digestates and other organic manures (FYM and composts) had been applied over several years. Six months after the final application of materials, earthworm numbers at one grassland site remained significantly lower where digestate had been applied. A subset of sites was resampled after another 18 months numbers remained lower at this site. A combination of high pH, high NH_3 and low applied organic matter were suggested as causative of these differences, together with possible compaction (causes unknown).	Earthworm mortality	Good	Possible link to NH_3 content of digestates – already in scope and could form part of pollution-swapping narrative	Earthworm mortality

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Koblenz *et al.*, 2015)	Reports on field experiments in which cattle slurry /maize digestate is applied ahead of a maize crop and ploughed-in, while on a second site maize / cereal grain / poultry manure digestate was applied ahead of maize and minimally tilled. Sampling and enumeration of earthworms took place four weeks later. Overall there was no significant difference in earthworm numbers between digestate treatments and control, with only biomass being significantly higher at one site - although potentially negative impacts such as salinity and ammonia are mentioned.	Earthworm mortality	Good	No significant digestate impacts	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Moinard *et al.*, 2021)	This study assessed digestate toxicity on earthworms in field trials, compared to cattle effluents and chemical fertilisers, while testing the hypothesis of ammonia-driven toxicity with advanced laboratory-controlled experiments. The tested digestates were sampled from a centralized unit and an agricultural digester treating cover crops. The authors concluded that, in the short term, liquid products can be toxic mainly due to direct contact, which depends largely on ammonia concentration. In field trials, mortality was also observed in the short term, which was associated to earthworms being foraged at the soil surface, where the products were highly concentrated. Over the long term, a positive impact on earthworm population was observed (two years with regular product application).	Earthworm mortality	Good	Short term impact potentially related to ammonia but not only, neutral to positive impact in the long term	Earthworm mortality

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Richards *et al.*, 2021)	This study characterised phosphorus forms and solubility in various soil amendment mixtures before and after a six week pot trial (with planted and unplanted treatments (winter wheat)) using chemical extractions, enzyme availability assays and spectroscopic (^{31}P NMR) techniques. Soil amendments included one food based digestate and one crop based digestate. Total P concentrations in water extracts of the growing media increased over the duration of the trial in planted pots fertilised using both digestates. Since the trial was not designed to explore leaching potential or risk, it did not flag issues for further consideration in this project	Transformation of P forms in soil following digestate application	Good	No leaching / risk assessment undertaken	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Häfner *et al.*, 2021)	Field study in which the fate of 15N-labelled digestates is explored. Seven types of digestate were created (eg maize; beet leaves; whole beet crop). Precautions were taken to reduce N introduction in seed digestate. Digestate was applied to field microplots and N_2O emissions monitored over periods of ~60 days. Emissions factors were in line with IPCC values, with most N_2O released within around two weeks of digestate application. N_2O from digestate accounted for around 30% of these emissions, the remainder originating in the soil N pool	N_2O emissions from digestate-amended soils	Good	Emission factor below IPCC values	None
(Elbl *et al.*, 2020)	Pot study comparing various responses to (manure & silage-derived) digestate, compost and mineral fertiliser in the Czech republic. Nitrate leaching was higher under mineral fertiliser than other materials (although was higher under digestate than composts)	Nitrate leaching	Good	Lower under digestate than mineral fertilisers. Topic already in scope	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Vergote *et al.*, 2020)	Methane and nitrous oxide emissions from digested dairy manure were continuously monitored for three months during autumn in the digestate storage tank of a Belgian dairy farm. A floating closed chamber apparatus was used in the open-topped storage tank to capture gases for quantification. Daily average methane emissions varied between 17 and 37 g / m^2, while daily average nitrous oxide emission varied between 0.01 and 0.40 g / m^2. These numbers were extrapolated to provide volumetric estimates of 4.6 to 14 g / m^3 / day (CH_4) and 0.004 to 0.13 g / m^3 / day (N_2O). These were lower than literature values for manure stores (up to 50 g / m^3 / day for CH_4), but represented between 4 & 8% of the methane produced (and captured in) the digester. N_2O values were also lower than those reported in prior studies, although the authors suggest that this might be an artefact of sampling. Both methane and nitrous oxide emissions were positively correlated with the digestate temperature and the stored digestate volume	CH_4 and N_2O emissions from stored digestate	Good	Storage tank was not covered. Emissions lower than stored manures	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Maldaner *et al.*, 2018)	Study of methane emissions from digestate storage tank on an AD site in Canada. The separated liquor fraction of cattle slurry digestate (derived from ~35% off farm wastes mixed with cattle slurries) was stored in an open, circular concrete tank and methane emissions monitored over a year. The 'slurry year' was drier than average, while the 'digestate year' was wetter than average. Digestate in store was warmer than slurry in store when averaged over the year. Methane spikes were noted following thaw events during winter (which followed periods when the entire store surface was frozen). A 'thin crust' was noted during some summer months, with no floating cover system deployed. Methane emissions were significantly lower from digestate than slurries (1kg methane per m^3 stored digestate vs 6.6kg methane per m^3 stored slurry)	CH_4 from digestate storage	Good	Storage tank was not covered. Digestate emissions lower than stored manures	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Kariyapperuma *et al.*, 2018)	This paper examined methane emissions from a cattle slurry store before implementation of an AD project at the same farm. Maldaner et al. (2018) examine methane emissions from the same store when used for the liquor fraction of cattle slurry digestates	CH_4 from slurry storage	Good	Paper is a pair with the one above	None
(Walling and Vaneeckhaute, 2020)	This paper reviews emission factors for the production, storage, transportation and use of synthetic fertilisers, composts, digestates and manures to identify the main sources of variability between different published emission factors, and how such variability might be reduced. The authors highlight a "lack of real and comprehensive on-site data for emissions associated to digestate production" and list three estimates for emissions that range from 25 to 230 kg CO_2e / tonne of waste. Nonetheless, they also highlight that emissions from digested manures are usually lower than undigested manures	CH_4 during AD and digestate storage; N_2O during digestate storage.	Good	Digestate emissions lower than undigested materials; Fugitive emissions should be monitored in UK plants	CH_4 emissions during AD and digestate storage; N_2O emissions during digestate storage

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Rodhe *et al.*, 2015)	This paper presents pilot-scale CH_4 and N_2O monitoring data captured over one summer and one winter for digestates and livestock slurries stored at four farms in southern Sweden. Stores were either covered (not gas-tight) or uncovered, to compare the impacts of either. Overall, CH_4 emissions were significantly higher from stored digestates compared with other treatments. Emissions from uncovered digestates were significantly higher than covered (which were still significantly higher than cattle slurries). Emissions peaked in the summer, and were not significantly different across any treatment in the winter. In contrast, N_2O emissions were highest from covered digestates, which were significantly higher than for uncovered digestates and uncovered slurries (no significant difference)	CH_4 and N_2O emissions from stored digestate	Good	Covering digestate store decreased CH_4, increased direct N_2O emissions but can reduce indirect emissions by preventing almost all NH_3 emissions. Pilot scale store and not gas-tight	N_2O emissions during digestate storage

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Lovarelli *et al.*, 2019)	LCA of two small agricultural AD plants in Italy - one processing a mix of cattle and pig slurries, one processing a mix of pig slurry and maize silage. Both plants combust biogas in CHP engines. Overall environmental performance was better for the slurry only plant, due to credit for reduced CH_4 emissions from (undigested) slurry storage.	GHG emissions from digestates	Good	Reduced GHG emissions from livestock slurries when digested rather than stored	None
(Baldé *et al.*, 2016b)	Study of methane emissions from digestate storage lagoon in Canada. Digestate derived from cattle slurry and off-farm (food) wastes and was not separated prior to storage. CH_4 emissions were measured over a period of one year using a laser detection method, and peaks were noted during rainfall events and periodic lagoon agitation. A thin moist crust (~5cm) was reported (and noted to be 'patchy' as well as seasonal), but no other cover solution was implemented. Annual average emissions were 19 g CH_4 /m^3 digestate /day equating to 12% of all methane produced by the biogas process (100% = sum of methane produced during both AD and subsequent digestate storage)	CH_4 from digestate storage	Good	Significant methane emissions from uncovered digestate storage lagoon	CH_4 during digestate storage

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Muha, Linke and Wittum, 2015)	Describes the development of a model to predict methane emission from digestate stores under practical conditions. The authors cite prior research in which CH_4 emissions from stored digested cattle slurry were around 25% those of stored undigested slurry, and similar to those from stored liquor fraction of undigested slurry - but highlight that duration of storage varies through the year. Their model draws on one year of data from 21 different AD plants processing energy crops with / without cattle slurries, and with HRTs varying from 40 to 172 days. They suggest that at minimum HRT of 90 days, crop digestate stores need not be covered - but that manure digestates should be stored in covered stores for a minimum of 50 days at 37°C to minimise methane emissions.	CH_4 from digestate storage	Good	Covering digestate store decreased CH_4	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Möller, 2015)	A review paper exploring digestate-related impacts on soil carbon and nitrogen turnover, N emissions, and soil biological activity. Potential for increased nitrate leaching after digestate application is dismissed, with changes in agronomic practices (eg cropping cycles) suggested as having a greater impact. No data on ammonia emissions from liquid digestate stores are provided, but there are comments around potential from separated fibre digestates, linked to the stabilisation of carbon during digestion leading to lack of rapid N lock-up through microbial activity in the fibre. Similar remarks relate to potential for N_2O, with 'stable' carbon in digestate suggested to have a reductive effect on N_2O emissions when compared with undigested inputs due to the lack of microbial priming in soils after application, and consequent lack of anaerobic microsites that could lead to N_2O production. However, uncertainties are expressed due to soil-specific impacts such as wetness which will also impact on the fate of N and C added in digestates (or manures / slurries)	NH_3 loss during digestate storage	Good	Already in scope – to be discussed as part of the modelling baseline	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Seadi and Lukehurst, 2012)	An overview of digestate quality characteristics and controls, drawing on published data. A positive picture is painted overall, without any claims that all aspects have been comprehensively reviewed.	None	Average	Does not highlight any specific digestate issues	None
(Sambusiti *et al.*, 2015)	Paper not relevant upon closer reading - the authors apply a number of treatments to digestates in an attempt to generate biogas, rather than exploring the potential for stored digestate to generate biogas and cause environmental impacts	None	Good	Not relevant	None
(Hermann and Hermann, 2019b)	Provides an overview of legislative frameworks for use of digestates in a number of European countries as well as associated nutrient / fertiliser planning approaches	None	Good	Not relevant	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(Umweltbundesamt and ARCADIS, 2020)	This study explores the application of end of waste approaches to a wide range of materials across Europe, including digestates. It focusses principally on regulatory frameworks, rather than the properties of individual materials and does not therefore contribute to this project. Some of the analysis (specifically in relation to REACH) seems incorrect, undermining confidence in other aspects	None	Average	Not relevant	None
(Reuland *et al.*, 2021)	Not relevant to our project, this paper summarises analyses of extensive datasets for digestates, to understand the potential for whole or separated liquor digestates derived from livestock manures to comply with RENURE criteria. These latter are being established for fertiliser materials recovered from manures, and will allow recovered fertilisers to be used at >170kg N / ha / yr, which currently limits manures and all derivatives in NVZs.	None	Good	Not relevant	None
(ESPP, 2017)	Recommends a number of changes to the wording of the EU-FPR	None	Good	Not relevant	None

Authors	Summary	Relevant impacts considered	Confidence in evidence	Comments	Impacts to discuss in workshop
(ESPP, 2020)	Critiques Corden et al., 2019 digestate and compost risk assessment, highlighting differences between suggested 'safe' limits and those agreed for EU-FPR.	None			None

Appendix 3: Workshop summary

This section provides a record of the workshop and decisions made.

Objectives for the workshop were set out by WRAP:

- Discuss findings from Task 1 (Identifying additional digestate impacts)
- Agree any additional impacts to add to project scope
- Outline approach to system baseline
- Discuss proposed modelling approach

1. It was noted that the decisions made at this workshop will define the impacts to be included in the assessment process and the TEA.
2. Participants were reminded that ammonia emissions, plastics contamination, nitrate leaching potential and the valorisation of digestate to improve its commercial prospects are already in scope and have not been covered by the phase 1 review work.
3. The work remains focussed on AD using farm and food-based feedstocks and does not cover issues that might be associated with sewage sludge digestates, industrial digestates or mixed waste digestates. Nonetheless, where promising mitigation/valorisation techniques are identified that have been demonstrated on these or similar substrates (such as pig slurries), then they may be included in the TEA. This will allow techniques to be categorised into Tier 1 (TRL 7+, demonstrated on farm and/or food digestates) and Tier 2 (TRL 7+, demonstrated on similar materials only).
4. A series of slides were presented that outlined the work completed on a review of potential impacts of digestate that are currently not core to the scope of the work programme.
5. The rapid evidence assessment approach (REA) has filtered >2500 sources of possible information. This exercise has yielded 60 key reference papers that range from peer-reviewed scientific papers to comprehensive EU research reports and risk assessments underpinning recent regulatory framework proposals.
6. The evidence assessment was designed to identify digestate issues that were currently not included in the scope. It was not designed as a risk assessment and did not include any mechanism to assess the potential magnitude of any identified impact or to rank impacts in importance or priority.
7. Most searches were limited to publications from the past decade with an emphasis on search strings that included ‘risk’, ‘impact’ and similar language.
8. The 5 impacts shortlisted for discussion during the workshop were:
    a. CH_4 from stored digestate

b. N_2O from stored digestate

c. CH_4 and N_2O as fugitive emissions from the AD process

d. Earthworm mortality

e. Plant pathogens

9. The evidence assessment also identified several other common themes that may be of interest to regulators and other stakeholders, but for which the evidence did not suggest that there were particular digestate-associated problems. These themes included PAHs, veterinary medicines and salinity. Each of these could be addressed via upstream controls, if necessary, but preliminary work would first be required to understand scale and magnitude of digestate associated risks under these themes – if any.

10. All identified impacts are outlined in the Interim report, whether or not they are taken forward for the TEA. The potential for separate future action on these will be a matter of discussion between government stakeholders.

11. Plant pathogens – concerns were raised for potato pathogens. There is existing guidance for the use of digestates from potato feedstock which should not be applied in front of a new potato crop – and that such digestates should arise from processes including a pasteurisation phase. In one paper a quarantine pathogen was noted to survive pasteurisation. Action: Project team agreed to ask a question of AHDB about the importance of including plant pathogens in the current study.

12. Earthworms – Several papers indicate problems with earthworm mortality following the application of digestate and manure. It was noted that ammonia mitigation is already in scope, and thus earthworms will be included qualitatively in terms of possible result of mitigation action on earthworm exposure to ammonia in digestate.

13. Fugitive emission and emissions from storage – EA noted that permitted stores will all need to be covered with gas extraction mechanisms going forwards. The Department for Energy Security & Net Zero are commissioning a separate project to look at monitoring and measuring fugitive emissions from storage in 2022. The EA have also started a programme of investigating fugitive emissions during AD processes and indicated that this need not form part of the current study.

14. Griff presented a brief presentation on the proposed modelling. It was noted that a decision on whether or not to use benchmarking or baseline had not yet been made. Griff and David have subsequently met with Will Shaw from the Clean Heat Directorate to discuss previous in-house the Department for Energy Security & Net Zero modelling.

15. The need for robust benchmarking and an outline approach for modelling were discussed. The project team agreed to check with the Department for Energy Security & Net Zero that baseline numbers were in line with emissions' directory assumptions. All baseline data will be quality assured during the modelling process, but the project team

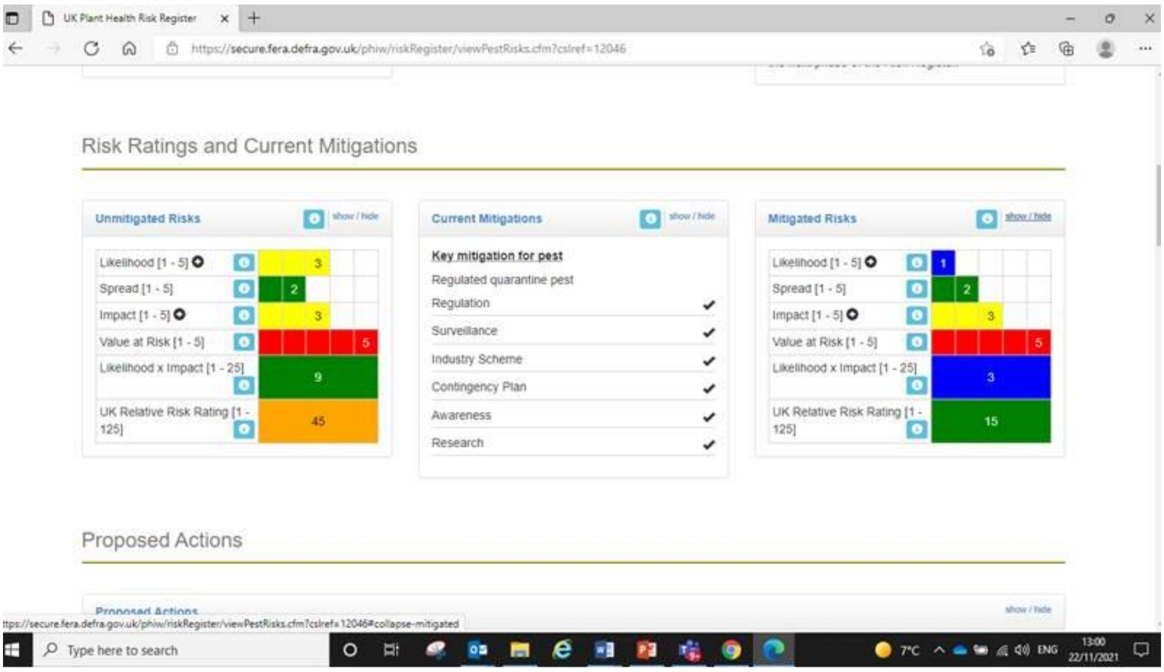
still need to consider and agree a robust approach to QA where benchmarks are not available or vary between farm and food digestates.

16. The next workshop will take place at the beginning of January. The purpose will be to review the initial list of mitigation & valorisation options and to demonstrate initial modelling. There will be 2 separate workshops – one for the advisory group for presentation of results and progress against the project work plan and a second larger event to bring in those individuals and organisations that replied to the the Department for Energy Security & Net Zero call for evidence for the GGSS.

17. Slides will be made available to attendees in pdf format.

As a result of this workshop, AHDB were contacted for comment on plant pathogens – and specifically the quarantine potato pathogen *Synchytrium endobioticum*. The following response was received:

“Nothing specific on this except that if you use the National Tree and Plant disease risk register[27] and put synchytrium into the search, you’ll come to a screen (after a couple of clicks) that details any mitigations in place and a revised figure for likelihood:



From here, you can make a judgement in terms of what else might be required. There are explanatory notes if you dig a bit deeper but, in this case, likelihood is already on the low side.”

[27] https://secure.fera.defra.gov.uk/phiw/riskRegister/index.cfm

Based on this, we inferred those risks from quarantine organisms such as potato wart disease (*Synchytrium endobioticum*) were controlled by regulation – and are low. We did not therefore consider this (potential) impact as suitable for inclusion in the current study.

Clarification was also sought from AHDB on whether there is guidance for the use of digestates ahead of potato crops / field horticulture. It is unknown whether WRAP guidance[28] has achieved significant market uptake – and while this distinguishes between 'pasteurised' and 'unpasteurised' digestates, this is intended for PAS110 certified materials only. No response was received to these further enquiries, and the responsible AHDB staff member has moved on.

The final agreed list of impacts requiring investigation and (potentially) mitigation was:

- Ammonia emissions during digestate storage and use
- Nitrate leaching following digestate use
- Methane emissions during digestate storage and use
- Plastics in digestates

[28] https://wrap.org.uk/resources/tool/renewable-fertiliser-matrix-tool

Appendix 4: Mitigation and valorisation options <TRL 7

Target	Digestate fraction	Option	Description	TRL	References
Valorisation	SLD	Algal biomass	Multiple authors have previously published results of laboratory and pilot studies in which microalgae are cultivated in pre-treated liquor digestates. Pre-treatments are normally required to reduce turbidity (in photoautotrophic configurations) and /or to reduce ammonia to an amenable concentration that does not impair growth. Dilution to address ammonia limitations may then require supplementation with other nutrients. In principle, microalgae can be used as a starting point for various biorefinery cascades - from biofuels to animal feed and beyond.	5	(Xia and Murphy, 2016) (Fernandes *et al.*, 2020)
Valorisation	SLD	Ammonium bicarbonate	Carbon dioxide is bubbled through an ammonium solution (recovered from digestate) to create an ammonium bicarbonate precipitate that can be harvested for use as a fertiliser. Bubbling CO_2 through ammonia solution has previously been a common method of fertiliser manufacture.	2	(Drapanauskaite *et al.*, 2021)

Target	Digestate fraction	Option	Description	TRL	References
Valorisation	SLD	Ammonium nitrate for explosive manufacture	Conventional ammonium nitrate can be used to manufacture explosives. There is no (in principle) reason why digestate could not be used as the ultimate feedstock in such a process, but this has yet to be demonstrated. The Health and Safety Executive provide guidance for safe handling of such substances during manufacture.	2	(Guilayn *et al.*, 2020); (HSE, 2021)
Valorisation	SLD	Ammonium sulphate as flame retardant	Conventional ammonium sulphate can be applied to wood as a fire retardant (TRL 9), and there is no (in principle) reason why digestate-derived ammonium sulphate could not be substituted.	2	(Guilayn *et al.*, 2020); (Borax, 2021)
Valorisation	SFD	Ash as fertiliser	Residues from combustion of digestate pellets can be used as a fertiliser. The use of biomass ashes as fertiliser is well understood and commercialised. There is no evidence that digestate has been used as the combustion feedstock, although there are examples with sewage sludge and poultry litter ashes.	4	(Lemming *et al.*, 2020); (Adriaens *et al.*, 2020).

Target	Digestate fraction	Option	Description	TRL	References
Valorisation	SLD	Bacterial floc as fish food	Indigenous heterotrophic bacteria have been cultivated on the separated liquor fraction of poultry manure digestates, by aerating the digestate. This approach has emerged from fish farming as 'biofloc', where the bacterial communities form natural flocs that serve as a feed source for shrimp or tilapia. Exogenous carbon is required to provide optimum CN ratio. Overall N and P removals of ~95 and 65% have been demonstrated, respectively. This approach avoids dilutions necessary to cultivate algae in digestate - but the aeration also strips most of the nitrogen out of the SLD as ammonia.	3	(Sobhi *et al.*, 2020)
Ammonia mitigation	WD and SLD	Biochar as a digestate lagoon cover	Biochar can be used on its own or following acid-treatment, to reduce ammonia losses during digestate storage.	4	(Covali *et al.*, 2021)
Valorisation	SFD	Biochar as a replacement for activated carbon	Biochar (from pyrolysis of biomass) can be used as a replacement for conventional activated carbon. A number of authors have examined the use of pyrolised digestates as adsorbents in various applications but there is no evidence that any have been commercialised. Activation is normally required to improve the surface area exchange properties of biochar but may not be necessary for some chars in some circumstances.	3	(Guilayn *et al.*, 2020); (Hung *et al.*, 2017); (Stefaniuk and Oleszczuk, 2015)

Target	Digestate fraction	Option	Description	TRL	References
Nitrate mitigation	WD and SLD	Biochar to reduce nitrate leaching	Some evidence that biochar reduces nitrification when incubated in soil with digestate.	4	(Plaimart *et al.*, 2021)
Valorisation	SFD	Biogas	Fibre digestates are treated through physical, chemical and/or biological processes before re-introduction to the AD process – with the aim of increasing overall biogas yields. Although techniques such as steam explosion and enzymatic hydrolysis are applied to AD feedstocks with increasing frequency, we have been unable to locate data on their application to fibre digestates beyond experimental scale.	3	(Monlau *et al.*, 2015); (Menardo *et al.*, 2011); (Biswas, Ahring and Uellendahl, 2012)
Valorisation	SLD	Biohydrogen	One possible output from an algal biorefinery process, with microalgae cultivated on digestate liquor.	3	(Uggetti *et al.*, 2014)
Valorisation	WD	Bioplastics derived from digestate extracts	Water-soluble substances are alkali-extracted from digestates, isolated and then blended with other polymers. The extraction techniques have been demonstrated at pilot scale, but blending and use are still at low TRL.	3	(Franzoso *et al.*, 2016)

Target	**Digestate fraction**	**Option**	**Description**	**TRL**	**References**
Valorisation	SFD	Cellulose, lignin and other biomass fractions	There are several processes for treating biomass fibres – including ‘cracking’ with phosphoric acid and dissolution in acetone, followed by recovery of lignin, cellulose and sugars for subsequent valorisation. These tend to be designed for woody and other plant biomass, although some have been applied to fibre digestates at bench scale.	4	(LXP, no date); (Damen *et al.*, 2017); (Stoumpou *et al.*, 2020); (Jesmond Engineering and Anglia Science Writing, 2021); (Teater *et al.*, 2011); (MacLellan *et al.*, 2013).
Valorisation	SFD	Char as a feed supplement	Biochar (from pyrolysis of biomass) can be used as a supplement in animal feed. Commercial for non-waste, biomass-derived char. Use of waste-derived materials for feed is problematic from a regulatory perspective.	2	(Guilayn *et al.*, 2020); (Schmidt *et al.*, 2019).
Ammonia mitigation / valorisation	SLD	Ammonia stripping through the use of hot microbubbles	Hot microbubbles are injected into a thin (3mm) liquid film, with ammonia diffusing into the bubble during the short transition between injection and exit. This approach (in principle) requires neither pH correction nor mass heating of the liquid being stripped and offers mass transfer efficiencies of ammonia from liquid to gas phases several orders of magnitude higher than those delivered in commercial stripping columns. The ammonia-enriched off-gas would be acid-scrubbed in the normal way.	3	(Desai *et al.*, 2021)

Target	Digestate fraction	Option	Description	TRL	References
Ammonia mitigation / valorisation	SLD	Electrochemical removal of ammonia	Numerous electrochemically-assisted methods have been trialled at bench scale for removal and recovery of ammonia from wastewaters. These include floating cathode systems which attract ammonium in solution and create localised alkalinity - which encourages ammonia formation and volatilisation, pending subsequent recovery through scrubbing.	4	(T. L. Chen *et al.*, 2021) (B. Chen *et al.*, 2021) (Muster and Jermakka, 2017) (Lee *et al.*, 2021)
Valorisation	SFD	Enzymes and Biopesticides	Fibre digestate is used as a substrate for solid-state fermentations that give rise to a number of biological derivatives including hydrolytic enzymes, and biopesticides derived from *Bacillus thuringiensis* (Bt).	4	(Rodríguez *et al.*, 2019); (Cerda *et al.*, 2019); (Mejias *et al.*, 2018); (Mejias *et al.*, 2020).
Valorisation	WD	Growing media additive	Trials have examined mixes of digestate with bark and other media to create substrates for container-grown hardy ornamental stock. The authors noted an absence of liverworts, sciarid flies and shore flies – common nuisances in container production.	5	(WRAP, 2015a)

Target	Digestate fraction	Option	Description	TRL	References
Valorisation	WD, SLD	Hydroponic crop production	Digestate liquor is used as a nutrient source in aqueous solutions for the cultivation of protected crops. Crops have been successfully grown in trials, but further research is required to understand potential for blocking of irrigation systems and to improve the business case for a crop where the fertiliser costs are a fraction of the potential crop value on a unit basis. Digestates have to be diluted significantly before use and inorganic nutrients added to match crop requirements.	5	(WRAP, 2015b); (WRAP, 2015c)
Valorisation	SFD	Insect protein	Black soldier fly (BSF) larvae have been reared on fibre digestate derived from vegetable materials as part of previous trials. Yields of BSF on digestate tend to be significantly lower than those grown on other substrates (chicken feed, vegetable waste and restaurant waste), presumably because the AD process converts readily degradable biomass to biogas. Insects for feed (or food) can currently only be reared on vegetable matter and a limited range of pre-consumer food wastes (TRL 9).	3	(Spranghers *et al.*, 2017)
Valorisation	WD	Microbial fuel cell	Microbial Fuel Cells (MFCs) convert chemical energy to electricity via the action of microorganisms. Demonstrated on digestates at lab scale.	4	(Martinez and Di Lorenzo, 2019)

Target	Digestate fraction	Option	Description	TRL	References
Valorisation	SLD	Nutrient concentration via forward osmosis	Water is removed from liquor digestate by forward osmosis, leaving a concentrated nutrient solution.	4	(Camilleri-Rumbau *et al.*, 2019)
Valorisation	SFD	Proteins from vermicomposting	Fibre is used as the sole or one of a number of inputs to a vermicomposting process, with the worms subsequently harvested and used as a dietary supplement for poultry. There is no *in principal* reason why the proposed use of digestate fibre should not work, as both vermicomposting and use of earthworms to feed poultry (KÖSE and ÖZTÜRK, 2017) are well established in some countries. The low TRL reflects the absence of available information on digestates, and as noted in earlier sections, the sensitivity of earthworms to ammonia may prove problematic.	3	(Guilayn *et al.*, 2020); (KÖSE and ÖZTÜRK, 2017)
Ammonia mitigation / valorisation	WD and SLD	Reactive membrane crystallisation	Ammonia is recovered from digestate using gas permeable membrane and strong acid until the draw solution exceeds the saturation point for ammonium sulphate. Crystals then form, which can be recovered through physical processing.	4	(Davey *et al.*, 2020)
Valorisation	SLD	Single cell protein	Single celled proteins are cultivated in digestate liquors for subsequent use in animal feed. This is a different approach to microbial protein (MP) production by methane-oxidizing (methanotrophic) bacteria (MOB).	3	(Khoshnevisan *et al.*, 2019); (Verbeeck *et al.*, 2020)

Target	Digestate fraction	Option	Description	TRL	References
Valorisation	SLD	Struvite as a flame retardant	Struvite has charring properties when impregnated into wood, causing it to act as a flame retardant. In principle struvite recovered from digestates could be used for this purpose.	2	(Guilayn *et al.*, 2020); (Guo *et al.*, 2019)
Valorisation	WD	Syngas (Supercritical water gasification)	Wet biomass is heated to >374°C under pressure of >22MPa, causing its conversion to a combustible syngas. Trialled at bench and pilot scales on digested sewage sludges. As with other hydrothermal processes, the elevated temperature and pressure of SCWG presents significant engineering challenges that have yet to be overcome commercially.	5	(Boukis and Katharina Stoll, 2021)
Valorisation	SLD	Vermicompost	Digestate liquors are used to irrigate vermicomposting substrates (largely) to maintain adequate moisture. As noted in earlier sections, vermicomposting is fully commercial but use of digestates in this system remain experimental. Ammonia content can be challenging.	5	(Crutchik *et al.*, 2020)
Valorisation	SFD	Vitrification	Dried digestate fibre (>85% DM) is incinerated and then the ashes heated to between 1,330 and 1,500 °C, creating a molten glass that is converted to an inert aggregate following quenching. Commercialised as a treatment for hazardous materials but can also applied to biosolids.	2	(MINERGY VITRIFICATION, 2006)

Appendix 5: Data for mitigation techniques

Ammonia and methane

Stripping / Scrubbing

Process cost data: CAPEX

0.56	EUR per kg N removed	(Menkveld and Broeders, 2018)
750000	EUR for 100m3/day plant	(D Bolzonella *et al.*, 2018)
930000	EUR for 977kg/day ammonia removed	(Van Eekert *et al.*, 2012)
300000	EUR for 1t/hr	(Verbeke, Van Dijk and Brienza, 2021)
700000	EUR for 4t/hr	(Verbeke, Van Dijk and Brienza, 2021)
375000	EUR for 4t/hr	(Verbeke, Van Dijk and Brienza, 2021)
750000	EUR for 5t/hr	(Verbeke, Van Dijk and Brienza, 2021)
400000	EUR for 10t/hr	(Verbeke, Van Dijk and Brienza, 2021)
500000	EUR for 15t/hr	(Verbeke, Van Dijk and Brienza, 2021)
668250	EUR for 15t/hr	(Verbeke, Van Dijk and Brienza, 2021)
825000	EUR for 20t/hr	(Verbeke, Van Dijk and Brienza, 2021)
500000	EUR for 800m3/day plant	(Vaneeckhaute, 2015)
1580000	EUR for 800m3/day plant	(Vaneeckhaute, 2015)
150000	EUR for 10000kg N per year removed	(Verbeke, Van Dijk and Brienza, 2021)
400000	EUR for 28361kg N per year removed	(Verbeke, Van Dijk and Brienza, 2021)
800000	EUR for 5260kg N per year removed	(Verbeke, Van Dijk and Brienza, 2021)
1500000	EUR for 534725kg N per year removed	(Verbeke, Van Dijk and Brienza, 2021)
5000000	EUR for 1831200kg N per year removed	(Verbeke, Van Dijk and Brienza, 2021)

Process cost data: OPEX

1.06	EUR per m3 digestate treated	heat	(D Bolzonella *et al.*, 2018)
1.5	EUR per m3 digestate treated	chemicals	(D Bolzonella *et al.*, 2018)
0.3	EUR per m3 digestate treated	labour	(D Bolzonella *et al.*, 2018)
4.22	EUR per m3 digestate treated		(Verbeke, Van Dijk and Brienza, 2021)
4.5	EUR per m3 digestate treated		(Vaneeckhaute, 2015)
8.6	EUR per m3 digestate treated		(Vaneeckhaute, 2015)
1.47	EUR per kg N removed	consumables	(Menkveld and Broeders, 2018)
1.2	EUR per kg N removed	consumables	(Van Eekert *et al.*, 2012)
2.6	EUR per kg N removed	consumables	(Van Eekert *et al.*, 2012)
1.47	EUR per kg N removed	Calculated median	consumables
0.4	EUR per kg N removed	heat	(Menkveld and Broeders, 2018)

Process efficiency data

90	%removal efficiency	when run at pH9.0 and 70°C	(Menkveld and Broeders, 2018)
31	%removal efficiency	when run at pH 9.0	(D Bolzonella *et al.*, 2018)
90	%removal efficiency	when run at pH10.5 and 70°C	(Fangueiro *et al.*, 2017)
90	%removal efficiency	Calculated median	

Confidence in data quality: High (when applied to separated liquor digestate); Medium (when applied to whole digestates); Medium (when used as a side-stream process)

Confidence is high for CAPEX data but medium for OPEX, since the latter can be impacted by factors that include: quantities of caustic soda used for pH correction in digestate prior to stripping, quantities of acid used for scrubbing, costs to maintain the scrubbing bed, costs to heat the digestate. Confidence is also high for performance when applied to liquor digestates, but medium to low when applied to whole digestates, the latter containing suspended solids that buffer pH changes and alter the rheology of the material.

When used for side stripping there are considerable uncertainties around sizing and performance, although the latter is expected to be lower than for whole or liquor digestates since the organic nitrogen within the digester will only be partially mineralised (and therefore potentially available for scrubbing)

Relevant additional information

There is no standard sizing approach for side-stripping, one published example processes ~40% of daily digester flow (Brienza *et al.*, 2020a).

Design and performance characteristics as per whole and liquor processes (below)

Ammonium will precipitate from solution if concentrations are too high (772 g / L of ammonium or 164g / L of N) (Ehlert *et al.*, 2019b)

To minimise precipitation / clogging potential, scrubbing solutions are limited to 58.8g / L of N in Flanders and the Netherlands (Ehlert *et al.*, 2019b)

There are studies comparing nitrate leaching after ammonium sulphate use (compared with use of other conventional fertilisers), and they showed no sig difference between treatments

"ammonium sulphate has become a major source of sulphur (S) for fertiliser use because it is readily available, being a by-product of various industrial processes, and has been relatively cheap compared to most other forms" (Powlson and Dawson, 2021)

The authors collated published lab and field data for ammonia emissions from ammonium sulphate fertilisers and calculated the following emissions factors:

Soil pH ≤7.0	92	g NH3 per kg N applied	alternatively:	7.6	% of N applied lost as NH3
Soil pH >7	170	g NH3 per kg N applied	alternatively:	14	% of N applied lost as NH3

0.074kg NH_3 lost for every kg NH_4 applied as ammonium sulphate in a spray applicator (Roth *et al.*, 2021)

Nitrification / Denitrification

Process cost data: CAPEX and OPEX (nitrification)

Throughput	**CAPEX**	**OPEX**			
23,500	£949,346	not estimated	Project team files		
35,000	£358,213	not estimated	Project team files		
60,000	£1,199,626	not estimated	Project team files		
Throughput	CAPEX	OPEX	Electrical demand		
91,250	£493,301	-			Project team files
91,250	£505,532	-			Project team files
73,000	£393,570	£75,000	750Mwhe/y	10p/kWh	Project team files
			Caustic		
		£86,880	362t/y	240£/t	Project team files
			Membrane maintenance		
		£79,570	1.09 £ per m3		Project team files
Median	Median				
91,250	£493,301	£241,450			
	£5.41	£2.65	per tonne or m3 throughput		
	CAPEX	OPEX			

Process cost data: CAPEX and OPEX (nitrification / denitrification)

Nitrification / Denitrification						
Throughput	CAPEX	OPEX				
10,000	£328,000	£26,300			(WRAP, 2014)	
25,000	£525,000	£65,750			(WRAP, 2014)	(WRAP, 2014
50,000	£820,000	£131,500			(WRAP, 2014)	
15,000	£250,000	-	pig slurry system (2004 price)		(Flotats *et al.*, 2009)	
20,000	£426,500	£65,750	calculated medians			
	£21.33	£3.29	per tonne or m3 throughput			
	CAPEX	OPEX				
		1.57EUR per m3 pig slurry treated			(Riaño and García-González, 2014)	
Throughput	CAPEX	OPEX	NB, converted from EUR per tonne			
		£2.23	per tonne	(maintenance)	(De Vrieze *et al.*, 2018)	
		£1.50	per tonne	(electricity)	(De Vrieze *et al.*, 2018)	
		£223,000	maintenance (per year)			

		£150,000	electricity (per year)	
100,000	**£1,500,000**	**£373,000**	OPEX (per year)	
	£15.00	£3.73		
	CAPEX	OPEX		

Confidence in data quality: Medium

Process cost data are from commercial sources. Performance data are drawn from literature on pig slurry treatment and may not therefore be fully representative of performance with digestates

Process performance data: nitrification

64% reduction in NH_4 (Foged, Flotats, Blasi, *et al.*, 2011)

Process performance data: nitrification / denitrification

95	%reduction in NH_4		(Foged, Flotats, Blasi, *et al.*, 2011)
92	%reduction in NH_4		(Melse and Verdoes, 2005)
87	%reduction in NH_4		(García-González *et al.*, 2016)
47	%reduction in NH_4		(Finzi *et al.*, 2020b)
89.5	%reduction in NH_4	Calculated median	

We were unable to identify evidence of the impact of nitrication or nitrification / denitrification on methane abatement

Additional relevant information

Note that nitrification and nitrification / denitrification processes generate a biological sludge at a rate of 15% of the treated volume (Hoeksma, Mosquera and Melse, 2012)

For the purposes of our valorisation modelling we assume that the nutrient characteristics of these sludges (in terms of Nitrogen, Phosphorus and Potassium: NPK) directly reflect the liquors from which they derive.

Pollution swapping

During nitrification, 0.28kg NH4 produces 0.05kg NO3 and 0.05kg NO2 per tonne	(Willers *et al.*, 1996)
During nitrification / denitrification 0.5% of input total nitrogen is lost as ammonia (range is 0.1 to 0.8%)	(Willers *et al.*, 1996)
Negligible ammonia losses from nitrification / denitrification system	(Finzi *et al.*, 2020b)
During nitrification / denitrification 9% of input total nitrogen is lost as N2O (range is 1 to 20%)	(Willers *et al.*, 1996)
During nitrification / denitrification methane emissions range from 0.09 to 0.87g of carbon per m3 pig slurry treated (highest in spring, lowest in summer)	(Loyon *et al.*, 2007)

Acidification of digestate (in field and in store)

Cost and performance data: in field acidification of whole or liquor digestates

Supplier information:

In-field acidification system is verified for pig and cattle slurry, but not digestates due to variable effect of acid addition on pH change

- 2.5 litres c.H_2SO_4 per m^3 digestate
- 25 % reduction in ammonia emissions in field
- €20 per hectare to apply digestate with in-field acidification system
- €20 per hectare acid costs

There are literature data with higher acid use rates that achieve higher ammonia reductions - we suggest using supplier info as this will hinge on economic optimum

We were unable to identify evidence on the methane mitigation potential of in-field acidification

Confidence in data quality, in-field acidification: High

Data informed by commercial feedback

Process cost data, CAPEX and OPEX: in store acidification of whole or liquor digestates

CAPEX	**14000**	**EUR for acidification unit (in store)**					**(Tamm and Vettik, 2019)**
	10000	EUR for acidification unit (in store)					(Tamm and Vettik, 2019)
	80000	EUR for acid tank (10,000tpa pig slurry system)					(Foged, Flotats, Blasi, *et al.*, 2011)
	45000	EUR for dosing system and pumps (10,000tpa pig slurry system)					(Foged, Flotats, Blasi, *et al.*, 2011)
To use:	£125,000	CAPEX	assume fixed price, irrespective of volume treated				
OPEX	c. H2SO4	750	£per tonne for virgin acid	£	0.94	per litre	Farming Forum, 2019[29]
		110	£per tonne for second user acid	£	0.14	per litre	Farming Forum, 2019[30]
		1.25	t/m3 density of c H2SO4				
To achieve target pH reduction on digestate will take anything from 5 to 16 litres per tonne of digestate (Farming Forum, 2019)[31]							
	2,870	EUR annual maintenance for pig slurry acidification system					(Foged, Flotats, Blasi, *et al.*, 2011)

[29] https://thefarmingforum.co.uk/index.php?threads/covering-slurry-lagoons-good-thing-or-not.298461/page-4
[30] https://thefarmingforum.co.uk/index.php?threads/covering-slurry-lagoons-good-thing-or-not.298461/page-4
[31] https://thefarmingforum.co.uk/index.php?threads/covering-slurry-lagoons-good-thing-or-not.298461/page-4

1litre cH2SO4 per 100l digestate to achieve target pH of 5.5	(Sánchez-Rodríguez *et al.*, 2018b)
Dose cattle slurry in store at 3.6litres cH2SO4 per tonne of slurry	(Tamm and Vettik, 2019)
Dose pig slurry in store at 3.0 litres cH2SO4 per tonne of slurry	(Tamm and Vettik, 2019)

To use:	5	litres cH2SO4 per tonne of digestate
	£0.94	per litre for virgin acid
	£2,870	annual maintenance for system

Performance data (NH_3 mitigation in store) : in store acidification of whole or liquor digestates

75%	**reduction in ammonia emissions during cattle slurry storage, when acidified (Misselbrook *et al.*, 2016)**
62%	reduction in ammonia emissions during cattle slurry storage, when acidified (Sommer *et al.*, 2017)
95%	reduction in ammonia emissions during slurry storage, when acidified (Petersen, Andersen and Eriksen, 2012)
83%	reduction in ammonia emissions during slurry storage, when acidified (Hou *et al.*, 2017)
88%	maximum reduction in ammonia from pig slurry stores when acidified with H2SO4 (Saue and Tamm, 2018)
80%	reduction in ammonia emissions during slurry storage, when acidified (Foged, Flotats, Blasi, *et al.*, 2011)
82%	calculated median

Performance data (NH_3 mitigation in use): in store acidification of whole or liquor digestates

6.10%	**loss of ammonia (as a fraction of applied ammoniacal nitrogen) when applying acidified pig slurry with trailing hose**	**(Nyord *et al.*, 2013)**
8.60%	loss of ammonia (as a fraction of applied ammoniacal nitrogen) when applying acidified pig slurry using injection	(Nyord *et al.*, 2013)
<2%	loss of ammonia from acidified digestate as a fraction of applied nitrogen	(Sánchez-Rodríguez *et al.*, 2018b)
40%	reduction in ammonia from land application of acidified slurry	(Willers *et al.*, 1996)
70%	reduction in ammonia from land application of acidified slurry	(Nyord *et al.*, 2013)
67%	reduction in ammonia loss when using stored acidified pig slurry (compared with unacidified)	(Foged, Flotats, Blasi, *et al.*, 2011)
67%	Calculated median	

Performance data (CH_4 mitigation in store): in store acidification of whole or liquor digestates

87%	**reduction in methane from stored slurry**	**(Willers *et al.*, 1996)**
87%	reduction in methane from stored pig slurry	(Petersen, Andersen and Eriksen, 2012)
68%	reduction in methane from stored cattle slurry	(Sommer *et al.*, 2017)
61%	reduction in methane from stored cattle slurry	(Misselbrook *et al.*, 2016)
86%	reduction in methane from stored cattle slurry	(Emmerling, Krein and Junk, 2020)

Confidence in data quality, in store acidification of whole or liquor digestates:

Medium (ammonia abatement)

Low (methane abatement)

This technique is commonly applied to pig slurries, but rarely applied to digestates. As such, process costs are reasonably well characterised while performance is uncertain and based on livestock slurries (not digestates) as the best available analogue. Readers should note that costs may vary widely from those cited depending on the specific ancilliaries used (such as the type and siez of pumps for digestate) and the quantities of acid required to achieve the target pH.

Relevant additional information

The use of ammonium sulphate will acidify some soils over time, and this has to be mitigated through the application of lime – an additional cost. Since this requirement will be soil-specific, it has not been specifically modelled. Estimates for lime requirement are availalble and can be included here if necessary

Acidification impacts on microbial performance, delaying nitrification following soil application as well as reducing methanogenic potential during storage (Emmerling, Krein and Junk, 2020). The use of acidified digestates may require treated soils to be pH-corrected with lime over time.

Sulphate in sulphuric acid will reduce S fertiliser requirement (Farming Forum)[32]

Less acid is required to mitigate methane emissions from stored digestates. 1.2grammes cH_2SO_4 per litre of cattle slurry reduce methane by 89% (Sokolov *et al.*, 2021)

Alum-treatment (3.5% alum by weight) of whole pig slurry digestates has also been demonstrated, potentially offering a cheaper alternative to H2SO4 dosing. The treated digestates were subsequently dewatered and NH_3 loss monitored during storage (Regueiro *et al.*, 2016). Data are reproduced in the next row

WD	**38**	**%reduction in NH3 over 70 day storage period in alum-treated pig slurry digestates**	**(Regueiro *et al.*, 2016)**
SLD	96	%reduction in NH3 over 70 day storage period in dewatered alum-treated pig slurry digestates	(Regueiro *et al.*, 2016)
SFD	97	%reduction in NH3 over 70 day storage period in dewatered alum-treated pig slurry digestates	(Regueiro *et al.*, 2016)
WD	92	%reduction in CH4 over 70 day storage period in alum-treated pig slurry digestates	(Regueiro *et al.*, 2016)
SLD	95	%reduction in CH4 over 70 day storage period in dewatered alum-treated pig slurry digestates	(Regueiro *et al.*, 2016)
SFD	0	%reduction in CH4 over 70 day storage period in dewatered alum-treated pig slurry digestates	(Regueiro *et al.*, 2016)
WD	93	%reduction in N2O over 70 day storage period in alum-treated pig slurry digestates	(Regueiro *et al.*, 2016)
SLD	20 %	%reduction in N2O over 70 day storage period in dewatered alum-treated pig slurry digestates	(Regueiro *et al.*, 2016)

[32] https://thefarmingforum.co.uk/index.php?threads/decentralised-digestate-storage.247982/

SFD	98	%reduction in N2O over 70 day storage period in dewatered alum-treated pig slurry digestates	(Regueiro *et al.*, 2016)

OPEX: in store alum-acidification of fibre digestates

Price of alum powder	**£300**	**per tonne**	**Kavanagh et al., 2019**
	£0.30	per kg	
Mixing costs	£1.50	per tonne fibre	Internal team data, based on liming of biosolids
Dose	200	kg per tonne SFD	

Note that we have assumed no capital costs for this option, although adequate storage and mixing facilities will be required for alum treatment. We assume that the operational cost (of alum) will be more significant at the scales modelled

Performance data (NH_3 mitigation in store) : in store alum- acidification of fibre digestates

97	**%reduction in NH3 over 70 day storage period in dewatered alum-treated pig slurry digestates**	**(Regueiro *et al.*, 2016)**
70	% reduction in NH3 from poultry litter during 42 day storage as a result of alum treatment	(Buckley *et al.*, 2020)
99	% reduction in NH3 from poultry litter during 42 day storage as a result of alum treatment @20% by weight	(Moore *et al.*, 1996)
95	% reduction in NH3 from poultry litter during 42 day storage as a result of alum treatment @13% by weight	(Moore *et al.*, 1996)
36	% reduction in ammonia loss from poultry manure when alum treated @ 10% by weight	(Eugene *et al.*, 2015)
99	% reduction in ammonia loss from poultry manure when alum treated @ 20% by weight	(Eugene *et al.*, 2015)
98	% reduction at 20% addition, median calculated from above	

Performance data (CH_4 mitigation in store) : in store alum- acidification of fibre digestates

Acidification of poultry manure with alum had no significant impact on methane emissions	**(Eugene *et al.*, 2015)**
No impact from alum acidification of pig slurry SFD	(Regueiro *et al.*, 2016)

Confidence in data quality, in store acidification of fibre digestates: Low

This technique is not commercially applied to fibre digestates, and data on both costs and performance are based on poultry litter, as the best available analogue

Pollution swapping

98% reduction in N_2O during 70-day storage of alum-treated SFD of pig slurry digestate	(Regueiro *et al.*, 2016)
Potential for acidification in soil over time (similar reasons as for ammonium sulphate solution)	(Buckley *et al.*, 2020)
21% reduction in N_2O during storage of acidified livestock slurries	(Emmerling, Krein and Junk, 2020)

Covered stores

Pollution swapping
From a one year trial comparing digested and non-digested cattle slurries: a combination of summer storage and autumn spreading of digested cattle slurry had the largest impact on global warming potential (GWP100) in terms of CO2e (28.7 kg CO2e m^{-3} slurry), with the impact from storage dominating. Adding a roof reduced CH_4 emissions, but also stimulated formation of N_2O during summer and therefore had no net effect on GWP100. With winter storage and spring spreading, cattle slurry (not digested) gave the lowest impact (2.51 kg CO2e m_3 slurry) in the scenarios examined (Rodhe *et al.*, 2015).
The covering of solid manure heaps has been shown to reduce nitrous oxide emissions during storage. Covering prevents rainfall leaching nutrients from the heap and results in more nitrogen and potassium (in particular) being retained in the heap, with potential agronomic benefits following land application. However, the greater readily available nitrogen content at spreading means that, if manure is not rapidly incorporated into the soil, increased ammonia losses following spreading can offset reductions achieved during storage (Misselbrook *et al.*, 2008)

Plastics

Depackaging, pulp separation, screening and skimming

Depackaging: performance evidence from published sources	
Between 63% and 96% removal of plastics >2mm, depending on configuration of depackaging system	(Alessi *et al.*, 2020)
Between 2% and 18% of biogas potential lost in reject stream, depending on configuration of depackaging system (highest loss where output was cleanest)	(Alessi *et al.*, 2020)
88% removal of plastics through pre-treatment press process	(Jank *et al.*, 2015)
10% loss of organics with plastics in pre-treatment process	(Jank *et al.*, 2015)
11% biogas potential lost due to pre-treatment	(Jank *et al.*, 2015)
3 or 4% non-target material in AD feedstock (at two Swedish AD plants)	(Bernstad *et al.*, 2013)
Screening removed around 30% of all incoming material (by mass), resulting in a corresponding loss in biogas potential	(Bernstad *et al.*, 2013)
Loss of biogas potential following depackaging of household, supermarket and restaurant wastes was ~32%, 23% and 33%, respectively	(Moretti *et al.*, 2021)
Removal efficiency of plastics <12mm ranged from 32.5 to 98.7%, depending on depackaging process	(Do Carmo Precci Lopes *et al.*, 2019)
95% of non-target material rejected by pre-treatment process	(Naroznova *et al.*, 2016)

(plastics comprised between 0.4 and 1.9% of feedstock, on a fresh weight basis)	(Naroznova *et al.*, 2016)

Depackaging system cost and performance data from confidential industry report

System A	
CAPEX	EUR450,000 for complete system and instal
OPEX	6000EUR plus labour
Capacity	10tph
Uptime	6000h per year
Quality of output	0.5% impurities in pulp
Rejected organics	Up to 10% by mass
System B	
CAPEX	110 to 520,000EUR
OPEX	3% of CAPEX
Capacity	1 to 20tph depending on model
Uptime	8500h per year
Quality of output	Up to 1% impurities in pulp
Rejected organics	Up to 10% by mass
Process efficiency	95%
System C	
CAPEX	From 500,000EUR
OPEX	unknown
Capacity	5 to 20tph depending on model
Uptime	24h/d if required
Quality of output	Less than 0.02% impurities in pulp
Rejected organics	Up to 10% by mass
Process efficiency	90% removal of impurities
System D	
CAPEX	not stated
OPEX	unknown
Capacity	up to 40tph
Uptime	24h/d if required
Quality of output	Less than 0.5% impurities in pulp
System E	
CAPEX	280,000EUR
OPEX	3EUR per tonne treated
Capacity	6 to 11t/h model
Uptime	3200h per year
Quality of output	0.025% impurities in pulp
Rejected organics	10.5% by mass
Process efficiency	98.9% removal
System F	
CAPEX	250,000EUR
OPEX	Up to 45kW demand
Capacity	15 to 30m3 per hour
Uptime	3500h per year
Quality of output	Less than 0.5% impurities, guaranteed (0.02% plastic was actually found during performance tests)
Rejected organics	Less than 5% by mass
	0.02% plastic in performance tests
System G	
CAPEX	27,000EUR
OPEX	3,000EUR per year
Capacity	Up to 20tph
Uptime	3500h per year
Quality of output	Less than 1% by mass

Rejected organics	Less than 5% by mass
Process efficiency	Between 95 and 99% removal of impurities

Depackaging system cost and performance data from suppliers

Supplier 4

Capacity	6	t/h	CAPEX	£164,990	OPEX	£4.00	per tonne	Residual plastic	0.1	%DS
Capacity	5	t/h	CAPEX	£95,000	OPEX	£1.00	per tonne	Residual plastic	0.3	%DS
Capacity	10	t/h	CAPEX	£102,000	OPEX	£1.00	per tonne	Residual plastic	0.3	%DS
Capacity	35	t/h	CAPEX	£251,900	OPEX	£1.10	per tonne	Residual plastic	0.3	%DS
Capacity	45	t/h	CAPEX	£302,300	OPEX	£1.25	per tonne	Residual plastic	0.3	%DS
Capacity	21000	t/yr	CAPEX	£164,990	OPEX	£4.00	per tonne	Residual plastic	0.1	%DS
Capacity	17500	t/yr	CAPEX	£95,000	OPEX	£1.00	per tonne	Residual plastic	0.3	%DS
Capacity	35000	t/yr	CAPEX	£102,000	OPEX	£1.00	per tonne	Residual plastic	0.3	%DS
Capacity	122500	t/yr	CAPEX	£251,900	OPEX	£1.10	per tonne	Residual plastic	0.3	%DS
Capacity	157500	t/yr	CAPEX	£302,300	OPEX	£1.25	per tonne	Residual plastic	0.3	%DS

Supplier 2			
Capacity	12t/h	70080	tpa (assuming 5840 hours uptime)
CAPEX	£2,300,000	for full design and instal	
OPEX	£7.40 per tonne	£ 518,592	
Process efficiency	99.90%	removal of plastic	
Supplier 3			
Capacity	5t/h		
CAPEX	£185,000		
OPEX	£0.60 per tonne		
Capacity	20t/h	116800	tpa (assuming 5840 hours uptime)
CAPEX	£287,000		
OPEX	£0.36 per tonne	£ 42,048	
Quality of output	0.05%	residues of plastic >5mm	
Quality of output	0.07%	Residues of plastic < 5mm	

Confidence in data, depackaging removal of plastics: High

Cost and performance data are from commercial suppliers and a range of published sources

Dewatering (screw press) cost and performance data from suppliers:

Supplier 1	
CAPEX	Minimum of £70,000 plus installation costs
OPEX	£8000 per year
Capacity	75m3 per hour
Uptime	5840 hours per year
Quality of output	Less than 3% impurities in pulp (trial data from actual sites below)

Data from supplier trials with screw press

kg of plastic per tonne	1	2	3	4	5		**Removal rates**
Input	0.04	0.27	0.62	1.28	0.28	**59%**	**Min**
Output	0	0.11	0.17	0.36	0.11	**100%**	**Max**
Removal	100%	59%	73%	72%	61%	**72%**	**Median**

Supplier 2		Annual
Hourly throughput	CAPEX	OPEX

	70	t	£50,357	£3,871
	75	t	£71,733	£8,247
	150	t	£99,616	£13,593
Uptime		2190 hours per year		

No data on removal efficiency, but Supplier 2 process outputs meet PAS110 specification - and available site data also indicate compliance with lower limits in Scotland (all <0.01kg/t physical contaminants)

Confidence in data, screw press separation of plastics: High

Cost and performance data are from commercial suppliers, although performance data are (relatively) scant

Appendix 6: Stakeholder Workshop

Table 79 Topics covered in the stakeholder workshop and associated resolutions

	Comment	Response
1	Risks of nitrite leaching?	We have found no evidence of issues associated with either nitrate or nitrite leaching from digestates applied in Spring
2	Are ammonia emissions from the AD process in scope?	No
3	Are odour impacts from any processing option in scope?	No – but very interesting point to flag to regulators
4	Screw press is the preferred dewatering technique for both farm and commercial digestates	Noted.
5	Gas to grid plants will have a small CHP or boiler on site to meet heat demands. They won't have any spare	Data on boiler costs and performance have been collated and built into relevant mitigation models
6	Acidification of solids (with liquid acid is not possible / advisable)	Available evidence suggests that acidification with powdered alum is effective in similar substrates, and this has been modelled
7	One AD operator happy to discuss performance of vibrating screen for plastics separation	This operator processes a food waste soup, and the vibrating screen is intended as a final polishing step. No specific (before / after) plastic removal data for this site
8	Pulpers and gravity separators commonly used in feedstock preparation in Italy	Discussions are ongoing
9	Chilling digestate can reduce ammonia emissions (some operators are sending it out warm)	Noted
10	Can the Department for Energy Security & Net Zero consider targets rather than technologies?	Noted
11	Are there opportunities for closed-loop acidification? For example, with biogas condensates?	An interesting option – out of scope for our modelling but noted

12	ADBA and REA happy to follow-up with specific operator requests	Key system cost and performance data were circulated for consultation, see Appendix 8:
13	We will meet separately with the combined set of regulators (England Wales and Scotland) to try to resolve the outstanding regulatory issues and questions regarding the approach to the baseline.	We agreed to use the 'least best' store cover technique for whole and liquid digestates (floating cover) and to leave fibre digestate stores uncovered. The 'least best' spreading technique was also used (trailing hose)
14	We asked whether stakeholders had experience with gas-permeable membranes for ammonia recovery	No experiences were shared, but suppliers have subsequently been identified and discussions are ongoing to obtain cost and performance data
15	Since evaporation technologies can be deployed in different ways (and in some cases fractionate different outputs) it was suggested that we remove them as an ammonia mitigation technique and instead consider them in valorisation scenarios	Agreed
16	An AD operator was suggested to have 'skimming' technology for removing plastics from stored digestates	The subsequent discussion revealed that the operator was using a variant of a conventional screw press to perform this task
17	Due to the complexities associated with implementation of valorisation options, it was suggested that the project team instead focus on a series of valorisation 'archetypes' to illustrate relevant costs / benefits / issues	Agreed
18	Request the Department for Energy Security & Net Zero Defra slides for sharing with workshop participants in WS3	WRAP to ask the Department for Energy Security & Net Zero Not sure whether this happened
19	Mitigation and valorisation option list to be re-circulated to all participants	Done
20	The application of acidified digestate could acidify soils which then need lime addition	Noted, and comments have been made in the relevant mitigation scenarios
21	One operator noted that their acidification work was driven by the need to reduce inorganic fertiliser costs	Noted. This aspect is captured in a valorisation scenario

22	Comment on nitrification inhibitors – the process is merely slowed down and not stopped entirely through the use of inhibitors	Noted
23	Stakeholders were unaware of any data on nitrate leaching from separated fibre digestates	-
24	Post digestate screening is present on most commercial plants	Noted
25	It was suggested that there is experience in Italy with the use of skimmers for the removal of plastic	Contact was made, and discussions are ongoing
26	Valorisation options should consider the exploitation of non-agricultural markets	Noted: a number of amenity / landscaping scenarios have been considered
27	Comment from a regulator that once digestates are treated the outputs are considered waste. This needs to be considered as part of the QP review.	Noted and reflected in discussion around mitigation and valorisation options and their fit within current regulatory frameworks
28	Food waste is diluted for treatment so there needs to be a consideration of digestate volumes.	We have assumed that process dilution is (in effect) a closed loop, and have estimated digestate volumes as a percentage of feedstocks on a simple mass balance basis (the percentage not converted to biogas remains as digestate)
29	Key questions document to be circulated to the advisory board again with a request for them to fill in answer	NS/RP Was this done? Comment from WRAP needed
30	Issue of microplastics raised as currently technologies only target plastics over a certain size	Noted, although current mitigation technologies are not designed specifically to address this issue
31	On the point of denitrified digestates it was raised that as long as it is demonstrating agricultural benefit it can be used on land even if it is less effective than commercial alternatives	Noted – we will cost the use of these materials as though they are wastes

Appendix 7: Building the valorisation models

The valorisation models are built as a series of simple process cascades in which the mass of material as well as the main nutrients (nitrogen, phosphorus and potassium) can be mapped through to their end points. The data behind these models are set out in the following sections.

Fertiliser values

		"Element" per tonne of fertiliser (kg)	Fertiliser (per tonne)	"Element" (£ per tonne)		"Element" (pence per kg)
UK produced ammonium nitrate	34.5% N	345	£616	1786	N	178.6
Muriate of potash	60%K2O	600	£532	887	K2O	88.7
Triple super phosphate	46%P2O5	460	£524	1139	P2O5	113.9
Source of fertiliser price data: https://ahdb.org.uk/fertiliser-information						

Digestate characteristics from RB209[33]					
Food	**Dry matter (%)**	**N-total (kg/t fresh weight)**	**NH4-N (kg/t fresh weight)**	**Total P2O5**	**Total K2O**
Whole digestate	4.1	4.8	3.84	1.1	2.4
Separated liquor	3.8	4.5	3.6	1	2.8
Separated fibre	27	8.9	7.12	10.2	3
Farm	**Dry matter (%)**	**N-total (kg/t fresh weight)**	**NH4-N (kg/t fresh weight)**	**Total P2O5**	**Total K2O**
Whole digestate	5.5	3.6	2.88	1.7	4.4
Separated liquor	3	1.9	1.52	0.6	2.5
Separated fibre	24	5.6	4.48	4.7	6
	Food	**Readily available NPK***	**NH4-N**	**P2O5**	**K2O**
	Whole digestate		3.84	0.55	2.16
	Separated liquor		3.6	0.5	2.52
	Separated fibre		7.12	5.1	2.7
	Farm	**Readily available NPK***	**NH4-N**	**P2O5**	**K2O**
	Whole digestate		2.88	0.85	3.96
	Separated liquor		1.52	0.3	2.25
	Separated fibre		4.48	2.35	5.4
		*[assumes 100% of NH4-N; 50% of P2O5; 90% of K2O]			

[33] https://ahdb.org.uk/knowledge-library/rb209-section-2-organic-materials

	Food	Readily available NPK	NH4-N	P2O5	K2O
	Whole digestate		£6.86	£ 0.49	£2.46
	Separated liquor		£6.43	£ 0.44	£2.87
	Separated fibre		£12.71	£ 4.52	£3.08
	Farm	**Readily available NPK**	**NH4-N**	**P2O5**	**K2O**
	Whole digestate		£5.14	£ 0.75	£4.51
	Separated liquor		£2.71	£ 0.27	£2.56
	Separated fibre		£8.00	£ 2.08	£6.15

Ammonium sulphate is the same price as ammonium nitrate[34]	
£616	per tonne
58.8	kgN per tonne in recovered ammonium sulphate
277.5	kg ammonium sulphate per tonne in recovered solution
0.2775	t ammonium sulphate per tonne in recovered solution
£170.96	per t of recovered ammonium sulphate solution

Spreading and selling

	Spreading costs					
	Ammonium sulphate	14.16	£ per ha		For non-wastes only	Beattie, 2021
	Digestates as wastes	15	£ per m3 or t		For digestates and most derivatives (assumed from waste industry knowledge)	
	Digestates as non-wastes					
		WD	SLD	SFD		
	Kemble Farms		£ 1.69	£2.50	Marinari, 2019	
	Keen's Farm		£ 3.00	£5.00	Marinari, 2019	
	Y-farms	£2.50			Marinari, 2019	
	Wyke Farm	£3.00			Marinari, 2019	
	Bromham Farm	£3.50			Marinari, 2019	
	Medians	£3.00	£2.35	£3.75	per tonne or m^3	
	Calculated from the above					
Sewer disposal	£ 11.65	per m3			WRAP, 2014	
Landfill	£ 116	per tonne			WRAP Gate Fees report [35]	

[34] https://theandersonscentre.co.uk/fertiliser-prices-selected-products/

[35] https://wrap.org.uk/sites/default/files/2021-01/Gate-Fees-Report-2019-20.pdf

Selling fibre	£ 50	per 730L bag			Apsley Farms[36]	
	£ 130	per 900L bag			PlantGrow[37]	
	£ 0.14	per kg			Assume 1L weighs 0.5kg	
	£ 0.29	per kg			Assume 1L weighs 0.5kg	
Average	£ 0.21	per kg	for bulk sale			
	£ 16	per 40L bag			PlantGrow[38]	
	£ 5.99	per 50L bag			Bloomin Amazing[39]	
	£ 0.80	per kg			Assume 1L weighs 0.5kg	
	£ 0.24	per kg			Assume 1L weighs 0.5kg	
Average	£ 0.52	per kg	for retail sale			
Hopper to fill bulk bags	£600				Hopper[40]	(assumes site has an appropriate loader)
Bagging line for retail bags	£25,000				Bagging system[41]	(assumes site has an appropriate loader)
Selling concentrate	£30	per 10L container			Apsley Farms[42]	
	£29.99	per 10L container			PlantGrow[43]	
Average	£ 30.00	per 10L container				
Bottling line to fill containers	£30,000				Bottling line[44]	huge uncertainty over this number

Screw press

CAPEX is £100,476

OPEX is £13,838

These costs are based on those provided by a supplier.

Separation rates

	partitions to fibre	partitions to liquor
Mass	30%	70%
N-total	35%	65%
P-total	45%	55%

[36] https://mulch.apsleyfarms.com/product/mulch-soil-improver/
[37] https://www.plantgrow.co.uk/shop/PlantGrow-Organic-Fertiliser-&-Mulch-900-Litre-p174437277
[38] https://www.plantgrow.co.uk/shop/PlantGrow-Natural-Soil-Conditioner-Mulch-&-Fertiliser-40-Litre-p377049136
[39] https://www.bloominamazing.com/orders/bloomin-amazing
[40] https://metalcagesandpallets.co.uk/products/free-standing-bulk-bag-tonne-bag-filling-hopper?variant=32823191273569
[41] http://www.organics-recycling.org.uk/uploads/article1762/Screening%20and%20Bagging%20guide.pdf
[42] https://mulch.apsleyfarms.com/product/liquid-plant-feed/
[43] https://www.plantgrow.co.uk/shop/PlantGrow-Natural-Fertiliser-Liquid-1-Litre-or-10-Litre-p153173166
[44] https://www.ebay.co.uk/itm/193319825266?hash=item2d02c26f72:g:4dkAAOSwpnlfu83m

K-total	27%	73%

Adapted from (Guilayn *et al.*, 2019)

Centrifuge

CAPEX is £160,110

These costs are based on data from (Verbeke, Van Dijk and Brienza, 2021)

OPEX is £27,677

Separation rates:

	partitions to fibre	partitions to liquor
Mass	28%	72%
N-total	41%	59%
P-total	79%	21%
K-total	26%	74%

Adapted from (Guilayn *et al.*, 2019)

DAF

CAPEX is estimated at £0.32 per m^3 treated

OPEX is estimated at £1.39 per m^3 treated

These costs are based on data from (Verbeke, Van Dijk and Brienza, 2021)

Separation rates

	partitions to fibre	partitions to liquor
Mass	31%	69%
N-total	34%	66%
P-total	92%	8%
K-total	24%	76%

Performance data are based on (Verbeke, Van Dijk and Brienza, 2021)

Microfiltration

CAPEX is estimated at £11.87 per m^3 treated

OPEX is estimated at £0.52 per m^3 treated

These costs are based on data from (Verbeke, Van Dijk and Brienza, 2021)

Separation rates

	partitions to retentate	partitions to permeate
Mass	45%	55%
N-total	57%	43%
NH4-total	41%	59%
P-total	82%	18%
K-total	45%	55%

Performance data are based on (Brienza *et al.*, 2020a) with the exception of the ammonium data, which are based on (Verbeke, Van Dijk and Brienza, 2021)

Ultrafiltration

CAPEX is estimated at £11.87 per m^3 treated

OPEX is estimated at £0.78 per m^3 treated

These costs are based on data from (Verbeke, Van Dijk and Brienza, 2021)

Separation rates

	partitions to retentate	partitions to permeate
Mass	27%	73%
N-total	29%	71%
NH4-total	22%	78%
P-total	79%	21%
K-total	22%	78%

Performance data are based on (Brienza *et al.*, 2020a) with the exception of the ammonium data, which are based on (Verbeke, Van Dijk and Brienza, 2021)

Reverse osmosis

CAPEX is estimated at £13.70 per m^3 treated

OPEX is estimated at £1.03 per m^3 treated

These costs are based on data from (Verbeke, Van Dijk and Brienza, 2021)

Separation rates

	partitions to retentate	partitions to permeate
Mass	47%	53%
N-total	91%	9%
P-total	98%	2%
K-total	95%	5%

Performance data are based on (Brienza *et al.*, 2020a) with the exception of the ammonium data, which are based on (Verbeke, Van Dijk and Brienza, 2021)

Evaporation

CAPEX is calculated as follows: (17.924 * annual throughput in m^3) + 64816

OPEX is estimated at £3.40 per m^3 treated

These costs are based on data from (Verbeke, Van Dijk and Brienza, 2021)

Separation rates

	partitions to condensate	partitions to retentate
Mass	63%	37%
N-total	3%	97%
P-total	0%	100%
K-total	0%	100%

The retentate is the residual, concentrated digestate

Performance data are based on (Brienza *et al.*, 2020a)

In-field acidification

A per hectare charge of £20 is made for use of the relevant acidification equipment

2.5 litres of c. H_2SO_4 are required for each m^3 of digestate applied

These estimates have been provided by a supplier

H_2SO_4 costs vary between £110 and £750 a tonne, depending on their origins (Farming Forum, 2019)[45]

In-store acidification

CAPEX is estimated at £125,000 for an acid-dosing unit and associated ancillaries (Foged, Flotats, Blasi, *et al.*, 2011)

Annual maintenance costs are estimated at £2,870 (Foged, Flotats, Blasi, *et al.*, 2011)

Concentrated H_2SO_4 is dosed at a rate of 5 litres per m^3 of digestate (Farming Forum, 2019)[46]

H_2SO_4 costs vary between £110 and £750 a tonne, depending on their origins (Farming Forum, 2019)[47]

Nitrification / Denitrification

CAPEX is estimated at £15.00 per m^3 of liquor treated

OPEX is estimated at £3.73 per m^3 of liquor treated

[45] https://thefarmingforum.co.uk/index.php?threads/covering-slurry-lagoons-good-thing-or-not.298461/page-4
[46] https://thefarmingforum.co.uk/index.php?threads/covering-slurry-lagoons-good-thing-or-not.298461/page-4
[47] https://thefarmingforum.co.uk/index.php?threads/covering-slurry-lagoons-good-thing-or-not.298461/page-4

These costs are based on those provided by a supplier

It is estimated that this process generates a biological sludge equivalent to 15% of the volume of liquor treated (Hoeksma, Mosquera and Melse, 2012). We assume that the nutrient characteristics of this sludge are the same as the liquor being treated

Stripping / Scrubbing

CAPEX is calculated as follows: (2.5273 * annual quantity of Nitrogen scrubbed (in kg)) + 328151

OPEX is estimated at £1.87 per kg of Nitrogen scrubbed

CAPEX data are based on (Verbeke, Van Dijk and Brienza, 2021); OPEX data are based on (Menkveld and Broeders, 2018)

Each litre of recovered ammonium sulphate solution is containing 58.8g of nitrogen (Ehlert *et al.*, 2019a)

Appendix 8: Process cost and performance survey

Volumes of material in scope

Please note that we are not seeking feedback on numbers in this section – they are provided for information only. The two types of AD system we are examining are: Food (inputs are 100% food waste); and Farm (inputs are a mix of crops and manures)

Plant capacities

	Food	Farm	
Small	50,000	150,000	tonnes per year (fresh weight)
Medium	100,000	250,000	tonnes per year (fresh weight)
Large	200,000	575,000	tonnes per year (fresh weight)

Whole digestate production

	Food	Farm	
Small	43,000	115,000	m^3 per year
Medium	74,000	200,000	m^3 per year
Large	171,000	461,000	m^3 per year

Storage costs

The modelling baselines assume that storage will already be provided for digestates (whether whole, separated liquor or separated fibre). In some scenarios additional storage will be required for materials such as ammonium sulphate solution. We have assumed that these will be stored in above-ground steel tanks. Costs for these are estimated as follows:

Capacity (m^3)	CAPEX (installed)
2,000	£90,000
5,000	£225,000
10,000	£450,000
15,000	£675,000
20,000	£900,000
25,000	£1,125,000

Spreading costs

We have assumed that all 'non-digestate derivatives' will be classified as wastes which may need to be applied to agricultural land under bespoke Mobile Plant permits / deployments at the following unit cost:

£15 per m^3 or t of material spread, including local haulage

Removal of plastics

Depackaging (pre-AD)

Annual throughput (tonnes FW)	CAPEX	OPEX (annual)
50,000	£200,000	£21,000
100,000	£350,000	£36,000
200,000	£800,000	£84,000

Plant efficiency: 95% of plastics removed

Screw press dewatering (post-AD)

Annual throughput (tonnes FW)	CAPEX	OPEX (annual)
43,000	£50,000	£4,000
74,000	£72,000	£8,000
171,000	£100,000	£14,000

Plant efficiency: 70% of plastics removed

Solid-liquid separation in screw press

Annual throughput (tonnes FW)	CAPEX	OPEX (annual)
131,000	£100,000	£14,000
228,000	unknown	unknown
526,000	unknown	unknown

Fibre to liquor mass ratio in output: 1:9

Ammonia stripping and scrubbing

Stripping and scrubbing system: end of pipe

kgN recovered per year	CAPEX	OPEX (annual)*
205,000	£790,000	£271,000
355,300	£1,960,000	£470,000
819,900	£2,190,000	£1,080,000

*OPEX excludes costs for heat

Recovery of ammonia: 90%

Scrubbing temperature: 70°C

Ammonium concentration in recovered ammonium sulphate: 100g/litre

This option is considered applicable to both whole and separated liquor digestates. We will assume the same costs for treating both

Stripping and scrubbing system: side-stream

Cost and performance will be modelled as for end of pipe process (above), although stripping in this way is likely to be less efficient than stripping at the ‘end of pipe’

We assume that a side-stream unit is sized to process 40% of daily digestate flow

Process heating

It is assumed that process heat demands (for stripping) are provided by a dedicated boiler

Boiler sized @ 750kW$_{th}$ at a capital cost of £45,000

Boiler powered with natural gas at wholesale price

Digestate acidification

In-field acidification

Contractor charge of £20 per ha to spread digestate using acidification equipment, with the cost of acid (c.H_2SO_4) in addition

conc. H_2SO_4 @ £1.00 per litre

Acidification of whole or liquor digestate in store*

*Digestate acidification is not commercially practiced, so we will draw on slurry acidification experience for modelling

Acid dosing unit @ £10,000

Assumes that store / lagoon has a mixing system pre-installed

Assumes 16 litres c.H_2SO_4 per m3 digestate treated

Acidification of fibre digestate in store*

*Alum stabilization of fibre digestate is not practiced, so we will draw on poultry manure treatment experience for modelling

Alum is mixed with fibre digestate – we have no data on costs for mixing

Alum @ £300 per tonne

Alum dosed at 200kg per tonne of digestate

Nitrification / denitrification

Nitrification

	Annual throughput (tonnes FW)	Annual throughput (kg NH_4-N)	CAPEX	OPEX*
Food AD (small)	29,900	107,600	£ 161,608	£ 79,100
Food AD (medium)	51,800	186,500	£ 280,120	£ 137,100
Food AD (large)	119,600	430,500	£ 646,430	£ 316,400
Farm AD (small)	80,600	122,600	£ 435,977	£ 213,400
Farm AD (medium)	139,800	212,500	£ 755,693	£ 369,900
Farm AD (large)	322,600	490,300	£ 1,743,907	£ 853,600

*Includes electricity, consumables and maintenance at £3.31 per m^3

Cost of NaOH (caustic soda) solution @ 25% (w/v): £240 / m^3

Nitrification & denitrification

	Annual throughput (tonnes FW)	Annual throughput (kg NH_4-N)	CAPEX	OPEX*
Food AD (small)	29,900	107,600	£ 448,409	£ 111,500
Food AD (medium)	51,800	186,500	£ 777,242	£ 193,300
Food AD (large)	119,600	430,500	£ 1,793,634	£ 446,000

Farm AD (small)	80,600	122,600	£ 1,209,694	£ 300,800
Farm AD (medium)	139,800	212,500	£ 2,096,802	£ 521,400
Farm AD (large)	322,600	490,300	£ 4,838,775	£ 1,203,200

*Includes electricity, consumables and maintenance at £3.73 per m^3

Appendix 9:Process baseline data

Plant sizing

THE DEPARTMENT FOR ENERGY SECURITY & NET ZERO impact assessment reference plants are set at:

	Small	7.5	MW
	Medium	13	MW
	Large	30	MW
Which converts energy production to:			
	Small	60444	MWh
	Medium	104770	MWh
	Large	241776	MWh
	or		
	Small	60444000	kWh
	Medium	104769600	kWh
	Large	241776000	kWh
For farm plants, 50% energy from crops and 50% from manures, meaning each has to contribute:			
	Small	30222000	kWh
	Medium	52384800	kWh
	Large	120888000	kWh

THE DEPARTMENT FOR ENERGY SECURITY & NET ZERO assume a five-year average of 92% generation

This equates to 8059.2 generating hours per year

THE DEPARTMENT FOR ENERGY SECURITY & NET ZERO assume the following energy yields from feedstocks	kWh/tonne (fresh)	Nm3CH4/tonne	tonne biogas/tonne	tonne digestate/tonne input*
Food waste	1100	110	0.22	0.78
Energy crop	642	64.2	0.13	0.87
Manure mix	376	31.3	0.06	0.94
Wet manure	124	12.4	0.03	0.97

*Water loss for hydrolysis not considered

By considering an energy content of

10	kWh/Nm3 of CH4
36	MJ/Nm3
and	
60%	CH4 in biogas
we have	
1	Nm3 of CH4
0.666666667	Nm3 of CO2
thus	
0.716071429	kg CH4/Nm3
1.30952381	kg CO2/Nm3
2.025595238	kg biogas/Nm3 methane

100% food AD plants	tonnes input per year	tonnes digestate per year
Small	54,949	42,706
Medium	95,245	74,023
Large	219,796	170,822

For farm plants we can assume 50% of energy from crops and 50% from manure mix

	Crop	Manure	Total tonnes input per year	Tonnes digestate per year
Small	47,075	80,378	127,452	115,209
Medium	81,596	139,321	220,918	199,695
Large	188,299	321,511	509,810	460,836

100% food AD plants	Nm3 of CH4 per year
Small	6,044,400
Medium	10,476,960

Large	24,177,600

For farm plants we can assume 50% of energy from crops and 50% from manure mix

	Crop	Manure	Nm3 of CH4 per year
Small	3,022,200	3,022,200	6,044,400
Medium	5,238,480	5,238,480	10,476,960
Large	12,088,800	12,088,800	24,177,600

Digestate characteristics

Digestate characteristics from RB209: RB209[48]

Food	Dry matter (%)	N-total (kg/t fresh weight)	NH4-N (kg/t fresh weight)*
Whole digestate	4.1	4.8	3.84
Separated liquor	3.8	4.5	3.6
Separated fibre	27	8.9	7.12

Farm	Dry matter (%)	N-total (kg/t fresh weight)	NH4-N (kg/t fresh weight)*
Whole digestate	5.5	3.6	2.88
Separated liquor	3	1.9	1.52
Separated fibre	24	5.6	4.48

*Note that ammoniacal N is assumed to be 80% of total N for all digestate types

This aligns with approach taken in National Atmospheric Emissions Inventory — Emissions inventory[49]

[48] https://ahdb.org.uk/knowledge-library/rb209-section-2-organic-materials
[49] https://uk-air.defra.gov.uk/reports/cat07/2103191000_UK_Agriculture_Ammonia_Emission_Report_1990-2019.pdf

Ammonia emissions

During storage

WD & SLD	Tank store (no cover)	[based on pig slurry]	of total ammoniacal nitrogen (TAN)	13%	(Misselbrook and Gilhespy, 2021)
WD & SLD	Lagoon store (no cover)	[based on pig slurry]	of total ammoniacal nitrogen (TAN)	52%	(Misselbrook and Gilhespy, 2021)
SFD	Field heap	[based on pig FYM]	of total ammoniacal nitrogen (TAN)	32%	(Misselbrook and Gilhespy, 2021)

Whole digestate	mgNH3 lost per kg WD	255	(Holly *et al.*, 2017)
Liquor digestate	mgNH3 lost per kg SLD	190	(Holly *et al.*, 2017)
Whole digestate	gNH3 lost per m2 of storage	2.06 to 4.44	(Tiwary *et al.*, 2015)
Liquor digestate	gNH3 lost per m2 of storage	7.89 and 14.6	(Tiwary *et al.*, 2015)

Baseline	Storage of WD and SLD	Floating cover	[based on pig slurry]	60%	abatement	(Misselbrook and Gilhespy, 2021)
	Storage of SFD	No cover		0%	abatement	

During application

WD & SLD	Food digestates	[without mitigation]	of total ammoniacal nitrogen (TAN)	43%	(Misselbrook and Gilhespy, 2021)
WD & SLD	Farm digestates	[without mitigation]	of total ammoniacal nitrogen (TAN)	43%	(Misselbrook and Gilhespy, 2021)
SFD	Broadcast	[based on pig FYM]	of total ammoniacal nitrogen (TAN)	68%	(Misselbrook and Gilhespy, 2021)

NB. The NAEI uses undigested manure emissions as proxies for digested manure. For convenience we have assumed the same emission from commercial and farm digestates (as a % of total ammoniacal N present)

Baseline	Application of WD and SLD	Trailing hose	[based on pig slurry]	30%	abatement	(Misselbrook and Gilhespy, 2021)
	Application of SFD	Surface applied and disced-in within 24 hours	[based on pig FYM]	23%	abatement	(Misselbrook and Gilhespy, 2021)

Methane emissions

Methane losses

Whole digestate	0.14	mgCH4 lost per kg WD	(Holly *et al.*, 2017)
Dairy slurry digestate (whole)	4.6 to 14	g CH4 per m3 per day during storage of dairy slurry digestate	(Vergote *et al.*, 2020)

Farm/food digestate (whole)		19	g CH_4 per m3 per day during storage of mixed food / farm digestate	(Baldé *et al.*, 2016a)
Digested cattle slurry	Winter	0.01	g CH_4 per m3 digestate per day	(Rodhe *et al.*, 2015)
	Summer	10.39	g CH_4 per m3 digestate per day	(Rodhe *et al.*, 2015)
Digested cattle slurry	Autumn	3.15	g CH_4 per m3 digestate per day	(Maldaner *et al.*, 2018)
	Spring	1.73	g CH_4 per m3 digestate per day	(Maldaner *et al.*, 2018)
	Summer	5.8	g CH_4 per m3 digestate per day	(Maldaner *et al.*, 2018)
	One year	10.8	Mg CH_4 per year from 10000t digestate	(Maldaner *et al.*, 2018)
Digested cattle slurry	Summer	7.79	g CH_4 per m3 digestate per day from open store	(Rodhe *et al.*, 2015)
	Summer	6.78	g CH_4 per m3 digestate per day from store with roof [significantly lower than open store]	(Rodhe *et al.*, 2015)
Digested cattle slurry	Winter	1.14	g CH_4 per m3 digestate per day	(Clemens *et al.*, 2006)
	Summer	8.2	g CH_4 per m3 digestate per day	(Clemens *et al.*, 2006)
Open storage of manure/food co-digestate in Canada	Winter	0.19	g CH_4 per m3 digestate per hour	(Baldé *et al.*, 2016a)
	Spring	0.53	g CH_4 per m3 digestate per hour	(Baldé *et al.*, 2016a)
	Summer	2.15	g CH_4 per m3 digestate per hour	(Baldé *et al.*, 2016a)
	Autumn	1.36	g CH_4 per m3 digestate per hour	(Baldé *et al.*, 2016a)
	Average	7	kg CH_4 per m3 digestate over one year	(Baldé *et al.*, 2016a)
			(92% of methane emissions were between May & October)	(Baldé *et al.*, 2016a)
Methane emitted from digestate storage was about 12% of the annual quantity of CH_4 produced in the digester.				(Baldé *et al.*, 2016a)
		12	%annual loss of methane as percentage of that produced	
Liquor digestate		0.06	kgCH_4 lost per tonne SLD of dairy cattle digestate over six months storage	(Holly *et al.*, 2017)

Cattle slurry digestate (liquor)	1	kg CH4 per m3 of stored liquor digestate over one year (from cattle slurry)	(Maldaner *et al.*, 2018)
		(Compares with 6.6kg per m3 for undigested cattle slurry)	(Maldaner *et al.*, 2018)
We have been unable to identify data for SFD	0.68	CH4 lost during storage of separated pig slurry solids as a percentage of initial volatile solids, over 30 days at 5C	(Dinuccio, Berg and Balsari, 2008)
These are examples of manure solids	0.6	CH4 lost during storage of separated pig slurry solids as a percentage of initial volatile solids, over 30 days at 25C	(Dinuccio, Berg and Balsari, 2008)
	19.1%	% volatile solids in separated pig slurry solids	(Dinuccio, Berg and Balsari, 2008)
	50.4	CH4 lost in g carbon per day per tonne of separated pig slurry solids	(Loyon *et al.*, 2007)

Storage and spreading

Costs of stores (WD and SLD)					
Tank	4360	m3 capacity	£120,000		Farming Forum
Tank	1364	m3 capacity	£50,000		Farming Forum
Tank	2500	m3 capacity	£250,000	with roof	Farming Forum
Tank	£28	per m3	Calculated from above		
Tank	£37	per m3	Calculated from above		
Tank	£100	per m3	Calculated from above		
Above ground circular store (steel and concrete)					
>2500m3	45	£ per m3	Assume that these exclude gas capture & abatement cost		(Beattie, 2021)
Median tank cost (not covered)	£41	£ per m3			

Covered stores cost 50% more than uncovered stores				(Giner Santonja *et al.*, 2017)
Covered tank	£61.24	£ per m3	Calculated based on above	
Slurry bag	2000	m3 capacity	£70,000	Farming Forum
Slurry bag	1200	m3 capacity	£30,000	Farming Forum
Average slurry bag cost ('covered')	£31	per m3	Calculated from above	
Lagoon (not including earth lined) total installed cost including fencing and gating				
From	£12	£ per m3	Assume that these exclude cost of any kind of cover	(Beattie, 2021)
To	£20	£ per m3	Assume that these exclude cost of any kind of cover	(Beattie, 2021)
Lagoon	7000	m3 capacity	£50,000	Farming Forum
	£7.14	per m3	Calculated from above	
Median lagoon cost (not covered)	£12	per m3		

Largest tanks	85	m	diameter	Permastore[50]
	15	m	height	
	5726	m2	area	
	24200	m3	volume	

We assume zero cost for baseline storage of separated fibre digestates, which we agreed would be uncovered (as a baseline)

Spreading costs				
Ammonium sulphate	14.16	£ per ha	For non-wastes only	(Beattie, 2021)
Digestates	15	£ per m3 or t	For digestates and most derivatives (assumed from waste industry knowledge)	

Ammonia abatement options during spreading: based on livestock slurries and manures

[50] https://www.permastore.com/wp-content/uploads/2021/02/P123-Rev-3-Series-1400-Slurry-Tank-Capacity-Chart-Nominal-Volume-m3.pdf

For WD and SLD		Trailing shoe	60%	abatement	(Misselbrook and Gilhespy, 2021)
		Injection	70%	abatement	(Misselbrook and Gilhespy, 2021)
For SFD		Plough immediately	90%	abatement	(Misselbrook *et al.*, 2008)
		Plough within 4h	70%	abatement	(Misselbrook *et al.*, 2008)
		Plough within 24h	35%	abatement	(Misselbrook *et al.*, 2008)

Abatement costs for spreading: based on livestock slurries and manures

For WD and SLD	1.4	£ per m3 premium to apply with trailing hose	NB. This is the baseline	(Misselbrook *et al.*, 2008)
	1.6	£ per m3 premium to apply with trailing shoe		(Misselbrook *et al.*, 2008)
	2.8	£ per m3 premium to apply using injection		(Misselbrook *et al.*, 2008)
				(Misselbrook *et al.*, 2008)
For SFD	1.1	£ per tonne additional cost of ploughing		(Misselbrook *et al.*, 2008)

Note that there are no consistent data for CH4 abatement using different spreading techniques for WD, SLD or SFD

Cover systems

Costs of cover systems (WD and SLD)

Baseline:	Floating cover	60%	abatement using floating cover system	(Misselbrook and Gilhespy, 2021)

Possible mitigation upgrades

LECA balls	5.4	EUR per m2		(Tamm and Vettik, 2019)	80% NH3 reduction
LECA balls	7	EUR per m2	[2011 price]	(Giner Santonja *et al.*, 2017)	

LECA balls	33	£ per m2		(Environment Agency, 2012)	
Median LECA balls	7	£ per m2			
Hexacover plates	33	EUR per m2		(Tamm and Vettik, 2019)	90% NH3 reduction
Hexacover plates	25	£ per m2		(Environment Agency, 2012)	
Hexacover plates	39.5	EUR per m2	[2011 price]	(Giner Santonja *et al.*, 2017)	
Median hexacover plates	33	£ per m2			
Tent cover	40	EUR per m2		(Tamm and Vettik, 2019)	95% NH3 reduction
Tent cover	68.2	EUR per m2		(Giner Santonja *et al.*, 2017)	
Median tent cover	54.1	£ per m2	[2012 price]		
[assume 1EUR = 1GBP for conversions]					
Gas-tight cover	81.15	£ per m2			100% NH3 reduction
Estimated based on 50% additional cost cf tent cover					

Flexible lagoon cover	0.5	£ per m3 slurry	(Misselbrook *et al.*, 2008)	40% NH3 reduction
Rigid cover	1.1	£ per m3 slurry	(Misselbrook *et al.*, 2008)	80% NH3 reduction
Flexible tank cover	0.35	£ per m3 slurry	(Misselbrook *et al.*, 2008)	40% NH3 reduction
Floating cover (tank or lagoon)	33	£ per m2	(Environment Agency, 2012)	
Floating cover (tank or lagoon)	28.4	EUR per m2	(Giner Santonja *et al.*, 2017)	[2012 price]

Estimated surface areas of storage

Lagoon

Depth of lagoon	5	metres	AHDB slurry wizard[51]

Tank

[51] https://ahdb.org.uk/knowledge-library/slurry-wizard

		Depth of tank			15	metres	Permastore[52]	
				(15 is absolute max)				

This information is from a review of slurry (not digestate) cover options

	Slurry type	Cover type	n	Median	Average	Max.		
NH3	Cattle	LECA	4	73.4	58.6	86.0	% abatement	(Kupper *et al.*, 2020)
NH3	Pig	LECA	12	76.9	74.2	95.0	% abatement	(Kupper *et al.*, 2020)
NH3		LECA		75.2	% abatement		calculated	
CH4	Cattle	LECA	2	10.9	10.9	16.1	% abatement	(Kupper *et al.*, 2020)
CH4	Pig	LECA	6	3.2	8.2	38.0	% abatement	(Kupper *et al.*, 2020)
CH4		LECA		7.0	% abatement		calculated	
N2O	Pig	LECA	1	-8.3	-8.3	-8.3	% abatement	(Kupper *et al.*, 2020)
NH3	Pig	Hexacover	2	87.9	87.9	96.0	% abatement	(Kupper *et al.*, 2020)
CH4	Pig	Hexacover	1	24.8	24.8	24.8	% abatement	(Kupper *et al.*, 2020)
CH4		Hexacover		56.4	% abatement		calculated	
N2O	Pig	Hexacover	1	-6.7	-6.7	-6.7		
NH3	Cattle	Tent covering	2	77.4	77.4	84.0	% abatement	(Kupper *et al.*, 2020)
NH3	Pig	Tent covering	2	89.0	89.0	94.0	% abatement	(Kupper *et al.*, 2020)

No CH4 or N2O data for tent covers

No impact on CH4 emissions from stored pig slurries (Misselbrook *et al.*, 2016)

[52] https://www.permastore.com/wp-content/uploads/2021/02/P123-Rev-3-Series-1400-Slurry-Tank-Capacity-Chart-Nominal-Volume-m3.pdf

No CH4 impact in UK NAEI is assumed when slurries are covered (by whatever means) (Defra, 2020)

Costs of cover systems (SFD)

Baseline: No cover

Possible mitigation upgrade

Plastic sheeting	0.6	£ per t	(Misselbrook *et al.*, 2008)	
	0.57	EUR per t	(Giner Santonja *et al.*, 2017)	[2011 price]
[assume 1EUR = 1GBP for conversions]				
Median plastic sheeting	0.59	£ per t		

Ammonia abatement from plastic sheeting

	60%	abatement		(Misselbrook and Gilhespy, 2021)
	12%	abatement		(Giner Santonja *et al.*, 2017)
	65%	abatement		(Misselbrook *et al.*, 2008)
Median abatement	60%	abatement	calculated	

Methane abatement from plastic sheeting

88	%abatement	(Giner Santonja *et al.*, 2017)

Energy prices

Energy prices

Wholesale gas	100	pence per therm	Ofgem[53]
Wholesale electricity	100	£ per MWh	Ofgem[54]
Wholesale gas	3.41	pence per kWh	Assumes 1 therm = 29.3001kWh

[53] https://www.ofgem.gov.uk/energy-data-and-research/data-portal/wholesale-market-indicators
[54] https://www.ofgem.gov.uk/energy-data-and-research/data-portal/wholesale-market-indicators

Wholesale electricity	10.0	pence per kWh

Heat provision and pricing

Heat availability

Although food waste AD sites include pasteurisation, the heat is usually recycled to warm the incoming feed

We therefore need to size a boiler to deliver sufficient heat to take digestate from 37 to 70C for stripping purposes

Boilers			
Supplier A 750kW, 8 bar, natural gas	£41,320	incl burner	Prices from project team
Supplier B 599kW and expansion vessel	£59,623	excl burner	
Supplier C steam boiler 600kW, 10 bar	£30,080	excl burner	
Boiler cost			
Supplier A	£41,320	incl burner price	
750kW, 8 bar, natural gas	£55.09	per kW	(for scaling purposes)

Operational hours

15	h/d
6	d/w
304	d/y

Required temperature increase in digestate		
from	C	35
To	C	70
Cp Sludge/Water	kJ/kg.K	4

Boiler reference price

n		0.6
CAPEX		£41,320
Capacity	kW	750
Coeff		1

Appendix 10: SYSTEMIC project case studies

Overview of AD facilities that are linked to the SYSTEMIC project, including nutrient recovery and reuse outputs and process steps (Verbeke, Hermann, et al., 2021). Data on AD feedstocks and processes is from other sources, as cited in the table. NR = Not Reported

Biogas Plant	Country	Process steps	Digestate derivatives	AD feedstocks and process
Groot Zevert Vergisting	The Netherlands	Centrifuge DAF Micro filtration Reverse osmosis Re-P-eat	NK-concentrate P-fertiliser (P-salts) Low-P soil conditioner Dischargeable water	Manure (90kt) Biowaste (30kt) Mesophilic AD (Hermann, Hermann and Schoumans, 2020)
AMPower	Belgium	Centrifuge Evaporator Reverse osmosis Dryer Acid air scrubber	NPK concentrate Dried fibre digestate Dischargeable water	Biowaste (150kt) Manure (21kt) Thermophilic AD (Hermann, Hermann and Schoumans, 2020)
Aqua e Sole	Italy	Ammonia stripper/scrubber	Ammonium sulphate Low-N digestate	Sewage sludge (62kt) Food waste (10kt) Thermophilic AD (Hermann, Hermann and Schoumans, 2020)
Benas	Germany	FiberPlus® system	Ammonium sulphate Calcium carbonate Low-N fibre Liquor digestate Fibre digestate	Energy crops (82kt) Poultry litter (20kt) Thermophilic AD (Hermann, Hermann and Schoumans, 2020) (Magaverde, no date)
Waterleau New Energy	Belgium	Centrifuge Dryer Nitrification-denitrification Evaporator Reverse osmosis	Dried fibre digestate Dischargeable water NPK concentrate Ammonia water	Biowaste (41kt) Manure (25kt) Mesophilic AD (Hermann, Hermann and Schoumans, 2020)
SCRL Kessler	Belgium	Screw press Dryer	Fibre digestate Liquor digestate Dried digestate	Livestock manure (Verbeke, Hermann, *et al.*, 2021)
GMB	The Netherlands	Centrifuge Nitrification-denitrification Composting Acid air scrubbing	Dischargeable effluent Composted fibre digestate Ammonium sulphate	Food waste Sewage sludge (Verbeke, Hermann, *et al.*, 2021)

Biogas Plant	Country	Process steps	Digestate derivatives	AD feedstocks and process
Emeraude Bioénergie	France	Centrifuge Ammonia stripper-scrubber Nitrification-denitrification Dryer	Ammonium sulphate Dischargeable water Dried fibre digestate	Pig slurry and slaughterhouse waste (Verbeke, Hermann, *et al.*, 2021)
Waternet	The Netherlands	Struvite precipitation Centrifuge Nitrification-denitrification	Struvite Incinerated fibre digestate Dischargeable water	Sewage sludge (Verbeke, Hermann, *et al.*, 2021)
Biogas Bree	Belgium	Centrifuge Drying Air stripping-acid scrubbing	Liquor digestate Fibre digestate Dried digestate Ammonium sulphate	Livestock manures (Verbeke, Hermann, *et al.*, 2021)
Greenlogix Bioenergy	Belgium	Centrifuge Lime softener Ammonia stripper-scrubber Nitrification-denitrification Centrifuge	Fibre digestate Ammonium sulphate Dischargeable water Sludge from N/DN reactor	NR
NDM	Germany	Screw press Acid air washer Centrifuge Dryer Incineration CO_2 stripper Ammonia stripper-scrubber	Fibre digestate Ammonium sulphate NPK concentrate P-rich ash Ammonium sulphate	Livestock manures (Verbeke, Hermann, *et al.*, 2021)
Agro Energy Hohenlohe	Germany	Screw press acidification Drying greenhouse Pelletizer	Pelletized dried fibre digestate	NR
Suiker unie Dinteloord	The Netherlands	Centrifuge Nitrification-denitrification	Fibre digestate Dischargeable water	NR
AFBI	Northern Ireland	Screw press and centrifuge	Fibre digestate Liquor digestate	NR
Bioenergy Neukirchen	Germany	Screw press	Solid fraction Liquid fraction	NR
Lüleburgaz, Agman Inc.	Turkey	Sedimentation pond	Fibre digestate Liquor digestate	NR
IVVO	Belgium	Screw press Composting Nitrification-denitrification Evaporation	Composted fibre digestate Ammonia solution NPK concentrate	NR
Grupo Biogas Fuel-cell	Spain	Separation	Fibre digestate Liquor digestate	NR

Biogas Plant	Country	Process steps	Digestate derivatives	AD feedstocks and process
Camposampiero	Italy	Centrifuge Nitrification-denitrification	Fibre digestate Low-N liquor	NR
Arbio	Belgium	Belt press Nitrification-denitrification Decantation tank Filters Reverse osmosis Dryer Mixing with NK concentrate Pelletizer	NPK pellets Low-N liquor	Pig manure (55kt) Food industry waste (35kt) (SYSTEMIC, 2020a)
Group Op de Beeck	Belgium	Centrifuge Composting Evaporator Nitrification-denitrification	Composted fibre digestate Ammonia solution Dischargeable water	NR
Stormossen	Finland	Centrifuge Nitrification-denitrification Composting	Composted fibre digestate Dischargeable water	NR
BioStorg	Belgium	DAF Belt press Composting Evaporator	Composted fibre digestate Ammonia solution KP concentrate	NR

WRAP's vision is a world in which resources are used sustainably.

Our mission is to accelerate the move to a sustainable resource-efficient economy through re-inventing how we design, produce and sell products; re-thinking how we use and consume products; and re-defining what is possible through re-use and recycling.

Find out more at **www.wrap.org.uk**

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