Digestate Nutrient Reuse and Recovery Technology Summary

Supplementary materials to the Canadian Digestate Management Guide

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Contents

Acknowledgements

ABOUT THIS DOCUMENT

The information provided in this document is based exclusively on a review of the references listed in *Appendix B*. No biogas plant operators or equipment vendors were asked to provide information for inclusion in this document.

The quantitative information provided on the performance or other aspects of NRRT represent a summary of the reviewed information and may not accurately represent the performance of a specific NRRT application. Since many factors unique to a specific application will affect the performance of a NRRT, readers are cautioned against relying on the information provided in this report for important decisions and are recommended to undertake their own investigations supported by individuals with relevant experience and expertise.

1.0 Introduction

The Canadian Biogas Industry

Thanks to a growing global awareness of climate change, an urgency to reduce greenhouse gas (GHG) emissions, and the demand for more sustainable waste management practices and energy systems, biogas production is a growing industry in Canada. In 2021, Canada has nearly 300 biogas & RNG projects already reducing 8 Mt of GHG emissions, processing two million tonnes of manure, crop residues, source separated organics, and organics waste from industrial, commercial, and institutional (IC&I) operations annually, and generating over 20 PJ of energy from agricultural anaerobic digesters (AD), industrial AD, municipal and industrial wastewater treatment facilities, and landfills. The biogas market continues to grow in Canada and the planned renewable natural gas projects indicate there will be a four-fold increase in the next few years compared to 2021 numbers.

Biogas offers important potential environmental benefits, such as:

- Waste management
- Stabilization of phosphorus nutrients
- Reduction of commercial fertilizers
- Protection of water quality
- Odour reduction from manure and landfilling of food waste
- Improved air quality
- Preservation of valuable landfill space

Additionally, economic benefits of biogas projects in Canada include:

- New job creation
- High-quality digestate for improved land management
- Cost savings and/or revenues for municipalities or waste management companies that own biogas facilities
- Bedding savings for farms
- Potential carbon emissions credits

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The Biogas Industry – Important Role in Crop Nutrient Recycling

The food demands of growing populations have driven the need to increase agricultural production. One outcome of this increased production has been specialization of farming operations which often leads to the separation of livestock and crop operations, which has complicated integration of nutrient cycling between livestock and crops within agricultural systems. The flow of agricultural products into linear 'extract – produce – consume – waste' systems has also removed crop nutrients from the agricultural cycle. The result has been an increased reliance on fertilizer derived from extracted, non-renewable resources to supply the crop nutrients necessary to support agricultural production. This is not sustainable and therefore is a risk to food security. The creation of an agro-industrial system to recover and direct nutrients to crop production and to replenish soil organic carbon is understood to be critical for efficient, sustainable and secure agricultural production. This is a role that the biogas industry is ideally suited to fulfill.

The biogas industry is an important part of the agro-industrial cycling system, as a consumer of nutrient-containing organic feedstock materials from agricultural, industrial, commercial, and residential sources, and as a producer of digestate, which is an excellent plant fertiliser, still rich in organic matter and in macro- and micro-nutrients. As the biogas industry expands, opportunities exist to optimize the use of digestate nutrients by employing nutrient recovery and reuse technologies (NRRT). Use of NRRT can increase the value of digestate as an organic fertilizer product, by making the digestate a more concentrated and transportable nutrient source. NRRT can also produce Digestate BioFertilizers (DBF) with high nutrient use efficiency and ability to substitute for commercial mineral fertilizers.

2.0 The Case for Nutrient Recovery and Reuse Technologies

Available today are proven NRRTs able to take advantage of opportunities to increase the value of digestate as a nutrient source for agriculture when used in accordance with Best Management Practices (see: Canadian Digestate Management Guide).

Opportunities

- Improve transportability, making digestate nutrients available to more users
- Concentrating nutrients, making digestate a more practical valuable nutrient source
- Adjusting N:P ratio to better align with crop requirements or regulatory application limits
- Producing DBF with high nutrient use efficiency which can substitute for commercial mineral fertilizers
- Increase environmental benefit by reducing potential for nutrient loss to the atmosphere or ground or surface waters
- Increase GHG reduction benefit by reducing emissions from storage and application
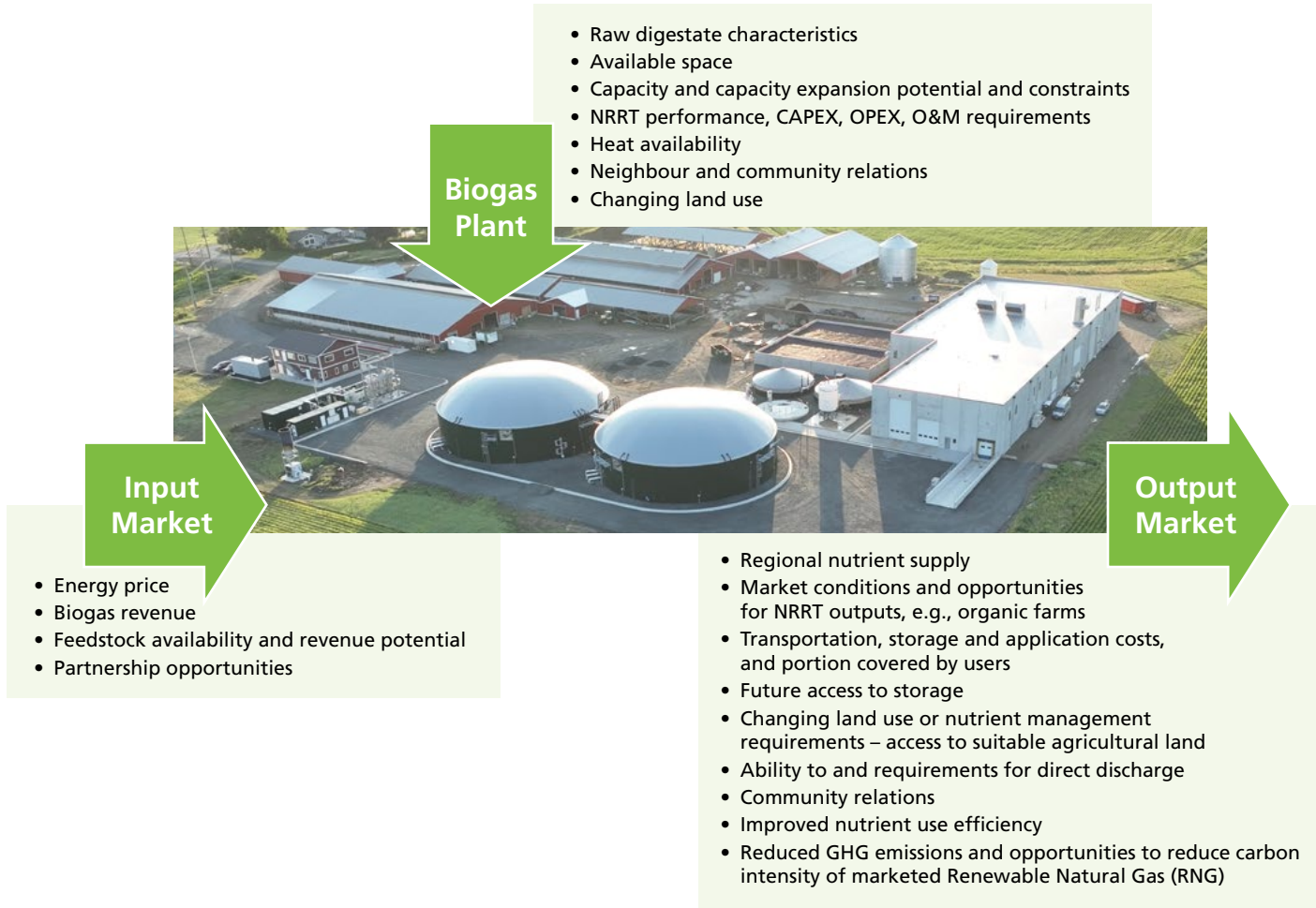- Increase carbon sequestration in soil

NRRT are gaining wider use in jurisdictions with pressing nutrient management challenges and where supportive policies and economic incentives are in place. Use of NRRT in Canada is minimal, largely due to the current reality that most digestate producers have access to agricultural land to apply digestate and the difficulty of justifying the additional capital and operating costs. This represents a lost opportunity for Canadian agriculture and the Canadian biogas industry to maximize the nutrient benefit of digestate.

NRRT can be expensive to acquire and operate and only in rare situations can, under current economic conditions, the cost be significantly offset solely by savings on digestate management or increased product revenues. However, if a NRRT could be shared amongst several biogas plants, such as a mobile system, or obtained when required as a contracted service, costs could be significantly reduced. As well, economic viability could be improved if future government policies enabled the environmental benefits of employing NRRT to be monetized (such as increased nutrient use efficiency or reduced GHGs). Finally, NRRT could become necessary for regulatory compliance if governments adopt more stringent nutrient management, environmental protection, or fertilizer quality requirements.

When considering NRRT, biogas plant operators should weigh investment options in their full business context by comparing future scenarios with NRRT against those without. In addition to costs, revenues and other factors directly attributable to the operation of the biogas plant and management of the digestate, the biogas plant operator should also consider challenges, opportunities and risks on the input and output sides of the biogas plant, as illustrated by Figure 1. NRRT may be impracticable when considered in the limited context of digestate processing and management but may be viable when considered more holistically.

Many reports are available on the performance of specific NRRTs at different stages of development and in different applications. The references listed in **Appendix B** to this document are a good place for an interested reader to start an in-depth investigation of NRRT.

Figure 1: Factors Relevant to NRRT Decisions

Biogas Plant

- Raw digestate characteristics
- Available space
- Capacity and capacity expansion potential and constraints
- NRRT performance, CAPEX, OPEX, O&M requirements
- Heat availability
- Neighbour and community relations
- Changing land use

Input Market

- Energy price
- Biogas revenue
- Feedstock availability and revenue potential
- Partnership opportunities

Output Market

- Regional nutrient supply
- Market conditions and opportunities for NRRT outputs, e.g., organic farms
- Transportation, storage and application costs, and portion covered by users
- Future access to storage
- Changing land use or nutrient management requirements – access to suitable agricultural land
- Ability to and requirements for direct discharge
- Community relations
- Improved nutrient use efficiency
- Reduced GHG emissions and opportunities to reduce carbon intensity of marketed Renewable Natural Gas (RNG)

3.0 Nutrient Recovery and Reuse Technologies

What are Nutrient Recovery and Reuse Technologies?

NRRT can transform digestate into a more valuable organic fertilizer by concentrating nutrients or adjusting nutrient ratios to align with crop requirements. NRRT can also produce DBF which are mineral fertilizer products which are a drop-in substitute for commercial fertilizers derived from extracted and non-renewable resources. Nutrient conservation is also fundamental to the concept of NRRT and technologies that intentionally waste nutrients, such as nitrification-denitrification wastewater treatment systems are excluded.

Digestate transformation and the production of DBF involves a sequence of processing steps, sometimes referred to as a 'technology cascade'. The first step in a technology cascade is to perform a primary separation of the whole digestate into separated liquor (liquid) and separated fibre (solid) fractions. Many biogas plants currently employ screens or screw presses for primary separation and the resulting separated liquor and fibre are used directly as an organic fertilizer or soil amendment. The separated fibre can also be used as livestock bedding.

The subsequent steps in a NRRT cascade involve technologies that can be categorized by their primary function, as follows:

Category	Primary Function
Advanced Solids Separation	Treatment of the separated liquor to remove fine suspended solids as a necessary pre-treatment for subsequent NRRTs.
Digestate BioFertilizer (DBF)	Treatment of the liquid fraction of advanced solids separation to produce mineral fertilizer products.
Digestate Concentrated Organic Fertilizer (DOF)	Removing water from the separated liquor or separated fibre to concentrate nutrients. The product contains organic matter and nutrients are present in a mix of inorganic and organic forms.

Figure 2 illustrates a digestate processing technology cascade expanded to include NRRTs.

Figure 2. Digestate Processing Nutrient Recovery and Reuse Technology Cascade
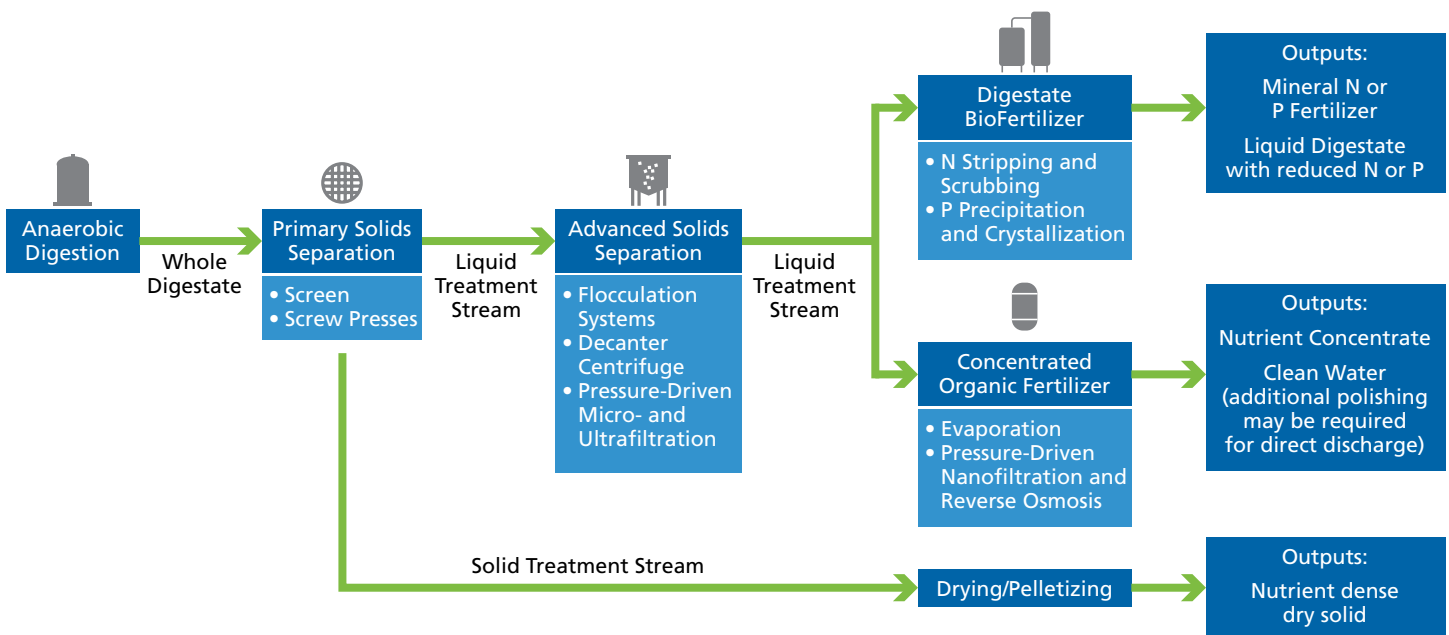
Information on the individual NRRTs identified in Figure 2 is provided in Section 3 and **Appendix A** of this document. Example NRRT technology cascades are presented in Section 4 of this document.

Each biogas plant is unique in the characteristics of the raw digestate produced, so NRRTs are selected and designed on a case-by-case basis. Thoughtful planning for successful implementation of NRRT must be based on a good understanding of the current and future situation of the biogas plant, and comparison of multiple technology cascade options.

Nutrient Recovery and Reuse Technology Summaries

The specific NRRT described in **Appendix A** of this document are all commercially available and in use at operating biogas plants or similar applications and are offered by multiple vendors. At the time of writing these technologies are implemented in Germany, the Netherlands, Denmark, and Belgium, with some deployment in North America.

NRRT summaries are provided for:

Advanced Solids Separation

- Flocculation systems,
- Decanter centrifuge, and
- Pressure-driven micro-filtration (MF) and ultra-filtration. (UF)

Digestate BioFertilizers (DBF)

- NH_3 stripping and scrubbing
- Phosphorus precipitation and crystallization

Digestate Concentrated Organic Fertilizer (DOF)

- Pressure-driven membrane filtration; nanofiltration and reverse osmosis (RO)
- Evaporation
- Drying and pelletization of solid digestate

Many other NRRT technologies are at a pre-commercial stage of development for digestate application and readers are referred to references Kaur (2020), Monfet (2017), Tsapekos (2021), Vaneeckhaute (2017) and Verbeke (2021) for more information.

Key aspects of the NRRT included in **Appendix A** are summarized in Table 1 below.

Table 1. Nutrient Recovery and Reuse Technology Summary Table

NRRT Category, Function	Separation Indices (into primary output) [Units: percent wet weight]			Output P: Primary S: Secondary	Cost (C-capital, O-O&M), Key Cost Drivers	Benefits
Advanced Solids Separation: Separation of fine suspended solids, organically bound P						
Flocculation Systems Belt Press, Flotation	Q	7 - 15		P: digestate solid fraction – concentrated nutrient cake (up to 35% DM) for direct use or additional treatment (drying) S: digestate liquid fraction – N, K fertilizer for direct use or additional treatment	C: $$ O: $$ • Cost of coagulants, flocculants	• Produces a nutrient and organic matter dense solid product that can be efficiently stored and transported • Reduces total digestate transportation and storage requirements • Reduces potential for GHG emissions (CH_4, N_2O) from storage and application • Separated liquid fraction is suitable feed for other NRRT
	DM	65 - 75				
	TN	25 - 35				
	NH_4-N	10 - 20				
	TP	80 - 90				
	TK	5 - 15				
Decanter Centrifuge	Q	10 - 20	15 - 30			
	DM	30 - 50	60 - 80			
	TN	15 - 25	30 - 50			
	NH_4-N	10 - 20	15 - 35			
	TP	60 - 80	75 - 80			
	TK	20 - 30	25 - 40			
	Higher values with flocculant					
Pressure-Driven Micro- (MF) and Ultra-Filtration (UF)	Q	25 - 40		P: MF-UF concentrate – DM and P concentrate (2 - 10% DM) for direct use or additional treatment (drying) S: MF-UF permeate – liquid N, K fertilizer for direct use or additional treatment	C: $$$$ - $$$$$ O: $$$$ • Capital cost • Energy cost • Frequent cleaning and replacement of filter media	
	DM	50 - 70				
	TN	30 - 60				
	NH_4-N	20 - 40				
	TP	80 - 90				
	TK	20 - 40				

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NRRT Category, Function	Separation Indices (into primary output) [Units: percent wet weight]		Output P: Primary S: Secondary	Cost (C-capital, O-O&M), Key Cost Drivers	Benefits
Digestate BioFertilizer: Separation of N, P for production of mineral fertilizer products					
N Stripping and Scrubbing	NH_3	Stripping 80 - 90 Scrubbing 85 - 99	P: DBF as mineral N fertilizer solution depending on scrubbing chemical: • Sulfuric acid = up to 38% ammonium sulfate solution • Nitric acid = up to 25% ammonium nitrate solution • Gypsum = calcium carbonate and ammonium sulfate S: treated liquid digestate with reduced NH_3 for direct use or additional treatment	C: $$$ O: $$$ • Energy (heat) if 'hot stripping' used • Chemical consumption • Frequent cleaning of packed tower media	• Produces DBF product that enables high nutrient use efficiency and commercial fertilizer substitution. • Reduces potential for NH_3 volatilization and NO_2 creation during storage and application of treated liquid fraction. • Treated liquid fraction has reduced NH_3 enabling increased application rates within N application limits.
P Precipitation and Crystallization	N P	10 - 40 of NH_4-N 70 - 90 of soluble (ortho) P	P: Digestate BioFertilizer e.g., Struvite N:P:K:Mg (6-13-0-10Mg) S: treated liquid digestate with reduced NH_3 for direct use or additional treatment	C: $$ O: $$$ - $$$$ • Cost of magnesium and alkali (up to 75% of overall production costs)	• Produces DBF as slow-release mineral N, P fertilizer products • Enables higher nutrient use efficiency and commercial fertilizer substitution • Reduces potential for P runoff and N_2O emissions • Treated liquid fraction can be applied at higher rates without exceeding nutrient application limits

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NRRT Category, Function	Separation Indices (into primary output) [Units: percent wet weight]		Output P: Primary S: Secondary	Cost (C-capital, O-O&M), Key Cost Drivers	Benefits
Concentrated Organic Fertilizer: Separation of water to concentrate nutrients					
Evaporation	Q	Amount of water evaporated depends on heat applied. Generally < 50% evaporation with CHP heat only.	P: clean water for process use or discharge with polishing S: concentrate – for direct use or further processing e.g., combining with digestate solid fraction and drying S: NH_3 recovery stream – suitable for use as DBF supplying mineral N.	C: $$$ O: $$$ • Cost of energy (heat) • Cost of chemicals for pretreatment of the liquid fraction and for odour treatment of non-condensable exhaust gases.	• Reduces quantity of water • Reduces transportation and storage requirements • Concentrates nutrients increasing product value • Option to produce DBF enabling high nutrient use efficiency and commercial fertilizer substitution • Clean water suitable for process and cleaning requirements or discharge with additional polishing
	NH_3	60 - 75 NH_3 evaporated without pre-acidification, with pre-acidification < 10			
Pressure-Driven Nanofiltration and Reverse Osmosis	Q	30 - 45	P: RO concentrate – suitable for use as DBF supplying mineral N, K S: RO permeate is clean water suitable for process use, irrigation, or discharge with additional polishing.	C: $$$$ - $$$$$ O: $$$$ • Capital cost • Energy cost Frequent cleaning and replacement of filter media	• Significantly reduces storage and transportation requirements • Produces DBF enabling high nutrient use efficiency and commercial fertilizer substitution • Clean water suitable for process and cleaning requirements or discharge with additional polishing
	DM	90 - 99			
	TN	90 - 99			
	NH_4-N	80 - 99			
	TP	90 - 99			
	TK	80 - 99			

NRRT Category, Function	Separation Indices (into primary output) [Units: percent wet weight]	Output P: Primary S: Secondary	Cost (C-capital, O-O&M), Key Cost Drivers	Benefits
Fluidized Bed Dryer Belt Dryer Rotating Disc, Rotating Drum Dryer	Water removal from digestate solid fraction > 90% NH_3, Volatile Organic Compounds (odours) volatilized. Quantity of digestate solid fraction reduced by 65% - 75% Dried product suitable for pelletization.	P: dry (80% - 95% DM), stable, odour reduced, nutrient dense product S: from exhaust gas treatment: • NH_3 recovery stream – suitable for use as DBF • wastewater suitable for process use or discharge with additional treatment	C: $$$ - $$$$ O: $$ - $$$ • Capital cost • Cost of heat • Cost of chemicals for N recovery	• Reduces digestate quantity • Improves product characteristics for storage and application • Reduces potential for N loss and GHG emissions during storage • Produces DBF enabling high nutrient use efficiency and commercial fertilizer substitution • Beneficial use for heat from Combined Heat and Power (CHP) systems

Abbreviations used in Table 1

Q   Quantity

P   Phosphorus

DBF   Digestate BioFertilizer

DM   Dry Matter

TP   Total Phosphorus

$ Cost relative to primary solids separation (e.g., screw press)

N   Nitrogen

K   Potassium

TN   Total Nitrogen

TK   Total Potassium

NH_4-N   Total nitrogen in ammonia plus ammonium forms

SI   Separation Index

4.0 Nutrient Recovery and Reuse Technology Cascade Examples

The performance of NRRT is illustrated by the technology cascade examples shown in Figures 3 and 4. The examples employ NRRT in configurations similar to cascades in use at operating biogas plants but are not based on the performance of specific plants. Rather, the performance of each NRRT component is based on Separation Indices (SI) at the middle of the reported range as presented in the technology summaries included in **Appendix A**. Mass balances calculated for individual NRRTs show how each step in the technology cascade contributes to the overall transformation achieved.

The mass balances for NRRT cascade examples 1 and 2 are summarized in Tables 2 and 3 respectively.

Both examples convert the whole digestate feed into DBF, in the form of liquid N products, and concentrated organic fertilizers (DOF). These products, while containing all of the nutrients and organic matter present in the feed, represent only 20% - 35% of the quantity of the original feed, achieving a significant reduction in digestate transportation and storage requirements due to decreased volume. For this to be achievable however, a use for the clean water separated from the feed must be secured. Reported uses of the clean water include process water, irrigation or discharge (additional polishing may be required to satisfy local requirements). Alternatively, the clean water can be evaporated, however it is reported that this is usually not achievable without significant supplemental heat (i.e., in excess of that available from biogas CHP).

Providing these examples is intended only to encourage interest in further investigation of NRRT to respond to opportunities and challenges facing individual biogas plants, and not to suggest a best or preferred approach. As well, the performance of NRRT in a specific application may differ significantly from that represented in these examples due to a multitude of site-specific factors. Diligent investigation is recommended before making important decisions regarding the use of NRRT.

Table 2. Mass Balance Summary for NRRT Cascade Example 1

	Whole Digestate Feed	Digestate BioFertilizer Products	Concentrated Organic Fertilizer		Clean Water
		RO Concentrate	Ammonium Sulfate Solution	Pellets	RO Permeate
Component	**Percent (w/w) of mass present in feed**				
Q	100	13.6	-	6.5	64.9
DM	100	8.3	-	89.4	0.4
TN	100	41.2	23.7	27.8	4.6
NH_4-N	100	53.5	32.8	4	5.9
TP	100	2	-	97.9	0.1
TK	100	62.9	-	33.7	3.3

Table 3. Mass Balance Summary for NRRT Cascade Example 2

Component	Whole Digestate Feed	Digestate BioFertilizer RO Concentrate	Concentrated Organic Fertilizer EV Concentrate	Concentrated Organic Fertilizer SP Cake	Clean Water RO Permeate
	Percent (w/w) of mass present in feed				
Q	100	9.3	46.6	10.4	33.8
DM	100	2.8	57	40	0.2
TN	100	44.4	38.3	15	2.3
NH_4-N	100	59.9	27	10	3.2
TP	100	0.6	59.3	40	0
TK	100	0.9	89.1	10	0

Figure 3. Process Block Diagram and Mass Balance for NRRT Cascade Example 1

Whole Digestate

Density 1035 kg m-3   (kg)   (g kg-1)
Q   100 m³   103500   –
DM   6.5 %   6727.5   65
TN   0.45 %   465.8   4.5
NH_4-N 0.325 % 336.4   3.3
TP   0.09 %   93.2   0.9
TK   0.25 %   258.8   2.5

Screw Press

Flocculant

MF-UF Concentrate

Liquid Fraction-1   (kg)
Q   92736
DM   4036.5
TN   395.9
NH_4-N 302.8
TP   55.9
TK   232.9
DM(%)   4.4

Decanter Centrifuge

Liquid Fraction-2   (kg)
Q   90111
DM   1476.8
TN   338.6
NH_4-N 307.9
TP   13.5
TK   245
DM(%)   1.6

MF-UF

MF-UF Permeate   (kg)   (g kg-1)
Q   81250   –
DM   590.7   7.3
TN   213.3   2.6
NH_4-N 200.1   2.5
TP   2   0
TK   171.5   2.1
DM(%)   0.7   –

2-Step RO

RO Permeate   (kg)   (g kg-1)
Q   67220   –
DM   29.5   0.4
TN   21.3   0.32
NH_4-N 20   0.3
TP   0.1   0.001
TK   8.6   0.13

SP Cake SP-SI(%)   (kg)   (g kg-1)
Q   –   10764   –
DM   40   2691   250
TN   15   69.9   6.5
NH_4-N 10   33.6   3.1
TP   40   37.3   3.5
TK   10   25.9   2.4
DM(%)   25   –   –

DC Cake DC-SI(%) DC-Cake (kg)   (g kg-1)
Q   –   11486   –
DM   70   3445.8 300
TN   35   182.4   15.9
NH_4-N 25   102.6   8.9
TP   80   53.9   4.7
TK   20   61.3   5.3
DM(%)   30   –   –

MF-UF Concentrate MF-UF SI(%)   (kg)   (g kg-1)
Q   –   8861   –
DM   60   886.1   100
TN   37   125.3   14.1
NH_4-N 35   107.8   12.2
TP   85   11.5   1.3
TK   30   73.5   8.3
DM (%)   10   –   –

RO Concentrate RO-SI (%)   (kg)   (g kg-1)
Q   –   14030   –
DM   95   561.2   40
TN   90   192   13.7
NH_4-N 90   180.1   12.8
TP   95   1.9   0.1
TK   95   162.9   11.6
DM (%)   4   –   –

Vapour   SI(%)   (kg)
Q   –   15567.6
DM   2   122.6
TN   48.59   122.6
NH_4-N 90   122.6
TP   0   0
TK   0   0

Acid

NH_3

NH_3 Scrubbing   SI (%)   (kg)
NH_4-N   90   110.3

Conversion to Ammonium Sulfate (AS) Solution
kg AS   518.4
kg AS solution at 30%   1728

Dryer Feed   (kg)
Q   22250
DM   6136.8
TN   252.3
NH_4-N 136.2
TP   91.2
TK   87.2
DM(%)   27.6

Dryer

Pelletizer

Pellets   (kg)   (g kg-1)
Q   6682.4   –
DM   6014.2   900
TN   129.7   19.4
NH_4-N 13.6   2
TP   91.2   13.6
TK   87.2   13
DM(%)   90   –

Figure 4. Process Block Diagram and Mass Balance for NRRT Cascade Example 2

Whole Digestate

Density 1035 kg m-3   (kg)   (g kg-1)
Q   100 m³   103500   –
DM   6.5 %   6727.5   65
TN   0.45 %   465.8   4.5
NH_4-N 0.325 % 336.4   3.3
TP   0.09 %   93.2   0.9
TK   0.25 %   258.8   2.5

Screw Press

LF-1   (kg)   (g kg-1)
Q   92736   –
DM   4036.5   43.5
TN   395.9   4.3
NH4-N   302.8   3.3
TP   55.9   0.6
TK   232.9   2.5
DM (%)   4.4   –

Evaporator

Vapour   (kg)
Q   44551.9
DM   201.8
TN   217.7
NH4-N   212
TP   0.6
TK   2.3

2-Step RO

RO Permeate   (kg)   (g kg-1)
Q   34966.5   –
DM   10.1   0.3
TN   10.9   0.3
NH4-N   10.6   0.3
TP   0   0
TK   0.1   0

SP Cake SP-SI(%)   (kg)   (g kg-1)
Q   –   10764   –
DM   40   2691   250
TN   15   69.9   6.5
NH4-N   10   33.6   3.1
TP   40   37.3   3.5
TK   10   25.9   2.4
DM(%)   25   –   –

EV Concentrate EV-SI (%)   (kg)   (g kg-1)
Q   52   48184.5   –
DM   95   3834.7   79.6
TN   45   178.2   3.7
NH4-N   30   90.8   1.9
TP   99   55.3   1.1
TK   99   230.6   4.8
DM(%)   8   –   –

RO Concentrate RO-SI (%)   (kg)   (g kg-1)
Q   –   9585   –
DM   95   191.7   20
TN   95   206.8   21.6
NH4-N   95   201.4   21
TP   95   0.6   0.1
TK   95   2.2   0.2
DM (%)   2   –   –

Note: 50% evaporation of water assumed

Appendix A: Nutrient Recovery and Reuse Technology Summaries

NRRT summaries are provided for:

Advanced Solids Separation

• Including flocculation systems, decanter centrifuge and pressure-driven micro- and ultra-filtration

Digestate BioFertilizers (DBF)

• NH_3 stripping and scrubbing
• Phosphorus precipitation and crystallization

Concentrated Organic Fertilizer (DOF)

• Pressure-driven membrane filtration; nanofiltration and reverse osmosis (RO)
• Evaporation
• Drying and pelletization of solid digestate

NOTES ON THE TECHNOLOGY SUMMARIES

Separation Index

The Separation Index (SI) refers to the fraction of the mass, dry matter, organic matter, nutrients or minerals (N, P, K) present in the feed that is recovered in the primary end product. It describes how efficient a technology can separate, concentrate or recover certain elements from the feed.

Expressed as a formula, the Separation Index (SI) is:

$$Separation\ Index\ (SI,\%) = \frac{mass_{product}(kg) \times concentration_{product}(g/kg)}{mass_{input}(kg) \times concentration_{input}(g/kg)} \times 100\%$$

This fraction is usually expressed as a percentage. e.g., 10% of the mass of the whole digestate that is processed in a decanter centrifuge is found in the solid fraction.

The technology summary for each NRRT includes the range of SIs reported in the references.

Costs and Main Cost Drivers

While some of the references reported information on costs associated with various NRRTs, the information was not reported in a consistent manner. Differences in the origin of the cost information, i.e., whether originating from cost models, vendor estimates or actual projects, and the scope of the reported costs, i.e., whether the costs include transportation and storage and whether the costs are net of revenue, as well as time and currency differences, made it impracticable to present reliable quantitative cost information.

In light of these challenges, the NRRT summaries provide only a qualitative expression of the capital and operating cost of the technology relative to the costs of primary liquid-solid separation by screw press, which are indicated by '$'. The number of '$' noted for the capital or operating cost of a particular NRRT technology are intended to indicate the relative cost of that technology.

This is also necessary as the reality is the cost of any undertaking is largely dependent on factors unique to each biogas plant. A key cost consideration is ongoing energy and chemical consumption, and the unit rates of these inputs vary significantly across jurisdictions and over time. Capital and operating cost estimates specific to the undertaking should be developed in sufficient detail to inform investment decisions.

Table 4. Advanced Solids Separation of fine suspended solids, organically bound phosphorous – Technology Summary

Functional Category	Advanced Solids Separation
Technology	Flocculation Systems, Belt Filter, Decanter Centrifuge, Micro- and Ultra-Filtration
Function and Key Benefits	Separation of fine particulate solids • Separated solid fraction is a nutrient and organic-matter dense product that can be efficiently stored and transported • Separated liquid fraction has reduced potential for GHG emissions (CH_4, N_2O) from storage and application • Separated liquid fraction is suitable feed for other NRRT
Image	**Figure 5. Illustrative Example of Belt Filter Press** [Source: Bamelis 2015] **Figure 6. Illustrative Design of Dissolved Air Flotation System** [Source: https://en.wikipedia.org/wiki/Dissolved_air_flotation]

Figure 7. Illustrative Design of Decanter Centrifuge

[Source: Drosg 2015]

Description	
	Whole digestate processing starts with primary mechanical separation to create separated liquor and separated fibres. Technologies most often used for this initial processing step are screw presses for fibrous digestates, and decanter centrifuges for non-fibrous digestates.

Common purposes for producing a separated fibre are to recover fibre for use as animal bedding, or for reducing digestate transportation costs since the separated fibre from primary separation represents only 10% - 20% of the total quantity of whole digestate but typically contains 40% - 60% of its dry matter and total phosphorus but only 20% - 25% of the total N. Soluble N, P, K, organics and mineral salts are present in the liquid fraction.

Uses of separated fibres

The separated fibre can be applied directly as an organic soil amendment, with the advantage of simpler storage requirements and considerably lower transport costs due to the reduced water content. Separation of solids reduces organic material available to support ongoing anaerobic digestion which very significantly reduces the potential for separated liquor to emit GHGs (primarily CH_4) during storage. As an alternative to direct land application further stabilisation and transformation into a marketable DOF can be achieved, e.g., through drying/pelletizing or composting.

Uses of separated liquor

The liquid fraction can be applied directly as an organic fertilizer but due to its large volume it is expensive to transport and a large structure is required to store the digestate outside of seasonal application periods. Also, since nutrients and organic matter in the liquid fraction are relatively dilute, the per cubic meter fertilizer value of the liquid fraction is low. As well, since the N:P ratio of the liquid fraction often does not align with crop requirements (required N:P typically 3:1 - 5:1), careful agronomic planning is necessary for optimal fertilizer use of the digestate within regulatory N or P application limits.

For more information on Best Management Practices for the use of whole digestate, separated liquor or separated fibre directly as an organic fertilizer or organic soil amendment refer to the Canadian Digestate Management Guide.

NRRT are available to concentrate the separated liquor (remove water), or to produce DBF products. NRRT approaches can reduce total digestate transportation and storage requirements while enabling higher nutrient use efficiency and commercial fertilizer substitution. Further, NRRT processes that effectively separate organic solids, NH_4-N and

soluble P can enable significant reductions in N and P loss and GHG emissions (CH_4, N_2O) from digestate storage and application.

The biogas industry is very familiar with primary mechanical separation and so it is appropriate to omit a detailed description of the technologies from this publication.

Although the degree of separation or concentration of nutrients or organic matter achieved by primary mechanical separation is not high, it is an indispensable first step that makes possible further concentration or separation through the application of advanced NRRT.

Described in this section are advanced solids separation approaches designed to achieve separation of very fine, suspended solids (>90% TSS removal). Importantly, this also removes a significant amount of P, as research has shown a preferential association between these small, suspended solids and P, as well as organic N.

Three of the more common approaches for advanced solids separation are flocculation systems, decanter centrifuges and pressure-driven membrane micro- and ultra-filtration systems.

FLOCCULATION SYSTEMS

Flocculation systems use a variety of technologies such as fine mesh vertical screens, belt presses, and dissolved air flotation (DAF). However, all rely on the addition of coagulants or flocculants to induce the aggregation of small particles of suspended solids into larger particles which can be more effectively separated.

Coagulation and Flocculation

Three steps: (1) Coagulation, (2) Flocculation, (3) Separation

1. Coagulation

   Raw digestate contains high amounts of negatively charged colloid and fine particles which repel each other and don't sink or float. The addition of a coagulant (multivalent cations) neutralizes the charge and makes it possible for small particles to aggregate through a process called flocculation.

   Examples of primary coagulants are metallic salts, such as aluminium sulphate ($Al_2(SO_4)_3$), ferric chloride ($FeCl_3$), ferric sulphate ($Fe_2(SO_4)_3$), and lime ($Ca(OH)_2$). Additions of multivalent cations will enhance the precipitation of P due to formation of phosphate salts such as $FePO_4$ [ferric phosphate], $Fe_5(PO_4)_2(OH)_9$ [beramite], and $Ca_3(PO_4)_2$ [calcium phosphate].

   However, using these coagulants adds iron or aluminium ions to the separated solid phase and sulphates or chlorides to the liquid phase, which must be considered when planning subsequent processing steps or final product use.

2. Flocculation

   Flocculation is the aggregation of coagulated small particles into larger particles (floc) that can be separated by size or density. Flocculants are large polymers with subunits of the molecule having positive (cationic), negative (anionic) or a mix of charges (polyampholyte). It is the nature and density of the charges that induces flocculation. Since all digestates have unique characteristics, field tests are necessary to select the flocculant with the most efficacious charge density and molecular weight and to determine the appropriate dosage.

Flocculants can be of organic or synthetic origin, biodegradable or non-biodegradable and are available as mineral oil emulsions or as powders that need to by diluted in water to form a polymer solution. In practice synthetic polyacrylamides (PAM) (non-biodegradable) are the most commonly used flocculants and are often used without coagulants to reduce cost.

Cautionary Note:

The use of coagulants or flocculants which are not explicitly designated as permitted by applicable policies (see National Standards of Canada – Organic Production Systems) may make the final fertilizer products ineligible for use by certified organic farms.

Certain coagulants and flocculants may also make the separated solid fraction resistant to further treatment or separation, for example for recirculation back into the digestion process.

3. Separation

Effective technologies for separation of flocs include belt filter and flotation systems.

Belt Filter

Two types of belt filter are available: belt filter presses and vacuum belt filters.

A belt press consists of two water-permeable belts guided over several rolls (see Figure 5). The belts are pressed against each other over a certain length. This way shear forces and mechanical pressure are generated between two belts to de-water the digestate. A vacuum belt filter typically uses a single horizontal belt and relies on vacuum pressure rather than mechanical force for dewatering. The final de-watered solid fraction or "cake" is removed from the belts by scraper blades.

The range of reported separation indices for Belt Filter NRRT is summarized in Table 5.

Table 5. Separation Indices for Belt Filter NRRT

Separation Output:	Filter Cake, 20% - 35% DM					
Separation Index (% w/w, into separation output)	Q	DM	TN	NH_4-N	TP	TK
	10 - 20	65 (95% of TSS)	64 (TKN)	-	80 - 90 (20% - 30% of PO_4-P)	15 - 25

Notes:
TSS – Total Suspended Solids
TKN – Total Kjeldahl Nitrogen

Flotation

Flotation is a gravity separation process that attaches small gas bubbles to floc particles which are then carried to the liquid surface where they form a crust, which can be scraped off (see Figure 6). Depending on the way the gas bubbles are generated, flotation is divided into dispersed air, electrolytic air and dissolved air.

The first two processes create gas bubbles by directly injecting air through special nozzles that produce small air bubbles or through electrolysis, respectively. DAF is the most widely used flotation system for digestate treatment. The infeed digestate is saturated with air under pressure and injected into the flotation chamber. The sudden reduction in pressure

leads to the formation of microbubbles which attach to the floc.

The range of reported separation indices for DAF NRRT is summarized in Table 6.

Table 6. Separation Indices for Dissolved Air Flotation NRRT

Input:	Liquid fraction following primary solids separation					
Separation Output:	DAF Cake, 5% - 10% DM					
Separation Index (% w/w, into separation output)	Q	DM	TN	NH_4-N	TP	TK
	7 - 15	65 - 75	25 - 35	10 - 20	80 - 90	5 - 15

DECANTER CENTRIFUGE

Decanter centrifuges use high rotational speed to separate solids (more dense) from water (less dense). The feed product is pumped into the decanter centrifuge through the inlet. Feed goes into a horizontal bowl, which rotates. The bowl is composed of a cylindrical part and a conical part. The separation takes place in the cylindrical part of the bowl. The high rotational speed of the bowl produces a G-force equivalent to between 1000 and 4000 G's which collects the denser solids on the wall of the bowl in a few seconds, producing controllable results. See Figure 7.

A scroll (also screw or screw conveyor) rotates inside the bowl at a slightly different speed. This speed difference is called the differential speed. This way the scroll is transporting the settled particles along the cylindrical part of the bowl and up to the end conical part of the bowl. At the smallest end of the conical part of the bowl, the dewatered solids leave the bowl via discharge opening. The clarified liquid leaves through a paring disc (internal centripetal pump).

Centrifuges can produce a consistent solid digestate product without the use of coagulants or flocculants however without these aids the Separation Indices for nutrients are reported to be typically in the lower end of the range.

The range of reported separation indices for Decanter Centrifuge NRRT is summarized in Table 7.

Table 7. Separation Indices for Decanter Centrifuge NRRT

Input:	Raw digestate or liquid fraction following primary solids separation					
Separation Output:	Decanter Centrifuge Cake, 15% - 35% DM					
Separation Index (% w/w, into separation output)	Q	DM	TN	NH_4-N	TP	TK
Without Flocculation	10 - 20	30 - 50	15 - 25	10 - 20	60 - 80	20 - 30
With Flocculation	15 - 30	60 - 80	30 - 50	15 - 35	75 - 90	25 - 40

PRESSURE-DRIVEN MICRO- AND ULTRA-FILTRATION

Please refer to the technical summary for Pressure-Driven Membrane Filtration (Table 18).

The effect of advanced solids separation NRRT on other important digestate characteristics is presented in Figure 8.

Figure 8. Separation Indices of Solids Separation NRRT

[Source Barampouti 2020]

Input	Raw digestate or liquid fraction following primary solids separation. Digestate containing fibre or other coarse solids or grit should be pretreated by primary solids separation.
Output	Advanced solids separation produces two output streams; digestate solid fraction, often referred to as 'cake', and digestate liquid fraction. The cake output can have a DM content ranging from < 10% up to 35% depending on the technology and use of coagulants and polymers. It typically represents only 10% - 20% of the feed but contains the majority of the DM, organic N and total P.

Soluble N, P, K, organics and mineral salts are present in the liquid fraction.

Example Digestate Solid and Liquid Fraction Characteristics Following Advanced Solids Separation are presented in Table 8. |

Table 8. Example Digestate Solid and Liquid Fraction Characteristics Following Advanced Solids Separation

Digestate Fraction	Parameter	Units	Decanter Centrifuge (with Polymer)	Screw Press	Belt Press
Solid	DM	%	35	26.6	24
	Total N	kg tonne-1	7.5	4.5	9.4
	P_2O_5	kg tonne-1	14.1	5.6	11.6
Liquid	DM	%	3	8	3
	Total N	kg tonne-1	5.0	5.7	3.9
	P_2O_5	kg tonne-1	1.0	3.8	0.5

[Adapted from: Bamelis 2015]

Operational Inputs	Energy: Reported electricity requirements for decanter centrifuge, belt press and DAF technologies range from 0.2 to 0.9 kWh m^{-3} liquid fraction treated. For MF-UF refer to pressure-driven membrane filtration technology summary. No heat is required. Chemicals: Reported dosages have a wide range; 0.4 - 9 L coagulant solution m^{-3} LF treated, 0.06 - 0.3 kg powder polymer flocculant m^{-3} LF treated. Chemical dosages are specific to the digestate characteristics, technology selection and separation goals.	
Cost and Key Cost Factors	CAPEX: $$	OPEX: $$
	Cost of chemicals. See pressure-driven membrane filtration technology summary for MF-UF cost info.	

Table 9. Ammonia Stripping and Scrubbing – Technology Summary

Functional Category	Digestate BioFertilizer
Technology	Ammonia Stripping - Scrubbing
Primary Function and Key Benefits	Produces DBF product that enables high nutrient use efficiency and commercial fertilizer substitution.
	Reduces potential for NH_3 volatilization and NO_2 creation during storage and application of treated liquid fraction.
	Treated liquid fraction has reduced NH_3 enabling increased application rates within N application limits.
Image	**Figure 9. Typical Arrangement of CO_2 Stripping Followed by NH_3 Stripping and Acid Scrubbing**

[Source: Drosg 2015]

Figure 10. Equilibrium of NH_3 and NH_4^+ in Water at Different pH Values and Temperatures

[Source: Drosg 2015]

Description	Ammonia Stripping – Scrubbing technologies employ a carrier gas to extract ammonia (NH_3) from a liquid digestate. Air is the most common carrier gas but steam is also used. The extracted NH_3 is subsequently captured to produce a DBF in the form of a stable ammonium salt solution, suitable for use as a liquid nitrogen fertilizer.
	Stripping of NH_3 involves the physical transfer of aqueous NH_3 from the digestate liquid fraction to a carrier gas phase. The most common mass transfer design is packed towers (aka columns), as they provide increased mass transfer area. (see Figure 9).
	The efficiency of NH_3 stripping is governed by numerous factors like NH_4-N content of substrate, hydraulic loading, packing, retention time, air and liquid flow rates, air to liquid ratio, mass transfer area, etc., but mostly temperature or pH since these parameters can push the NH_4-N to NH_3-N equilibrium towards NH_3-N (see Figure 10).
	Effective NH_3 transfer to gas phase, in the range of 80 - 90%, is reported by 'cold stripping' at 20ºC and pH 12 - 12.5 and 'hot stripping' at 80ºC, at which temperature NH_3 can be fully transferred independent of pH. Between these operating limits, optimum conditions are reported to lie around 70ºC and pH in the range of 10 - 11.5. Non-volatile components, like organic-bound N, phosphorus, potassium, metals, solids etc. remain in the treated liquid digestate.
	The amount of alkali -caustic lime ($Ca(OH)_2$), sodium hydroxide ($NaOH$), magnesium hydroxide ($Ca(OH)_2$) or lime (CaO)- needed to increase the pH towards 10-11 is determined by the buffer capacity of the digestate entering the stripper.
	The buffer capacity of the digestate at pH 8 is mainly due to the carbonate alkalinity (i.e., ions HCO_3^-). Alkali consumption can be decreased or avoided by removing a part of this carbonate buffer by air stripping CO_2 from the liquid digestate feed.
	The carrier gas rich in NH_3 is treated in an air scrubber where it is contacted with a strong acid solution causing mass transfer and absorption of the NH_3 producing a stable ammonium salt solution, which can be evaporated to produce a solid product. Acid scrubbing is reported to capture 85% to 99% of the NH_3 in the carrier gas. Adsorbents commonly used in NH_3 stripping are sulfuric acid (H_2SO_4), nitric acid (HNO_3) or gypsum ($CaSO_4$). The ammonia salt solution contains available N, and S if sulfuric acid is used, and can directly substitute for mineral fertilizer.
	The carrier gas from which the ammonia is removed can be recirculated to the stripping tower. As stripping and scrubbing of ammonia occurs in a closed system, emissions are generally low.
	Stripping technologies using packed towers are prone to fouling and scaling which reduces performance. Pre-treatment by advanced liquid-solids separation to achieve total suspended solid levels (TSS) < 2% in the liquid digestate feed is recommended to minimize cleaning frequency. Stripping technologies that do not use packed towers or require addition of alkali are available. However, they require multiple vessels with diffuser systems in series to achieve maximal ammonia mass transfer.
	Reported separation indices for NH_3 stripping and scrubbing NRRT are shown in Table 10.

Table 10. Separation Indices for NH$_3$ Stripping and Scrubbing NRRT

Input:	Liquid fraction following primary or advanced solids separation					
Separation Output:	**Ammonium Sulfate (NH$_4$)$_2$SO$_4$**					
Separation Index (% w/w, into separation output)	Q	DM	TN	NH$_4$-N	TP	TK
	-	-	-	80 - 95 at 50°C, pH 9.5	-	-
				80 - 90 at 20°C, pH 12 - 12.5		

Input

Liquid digestate pre-treated by advanced liquid-solid separation to reduce TSS

Output

Output The type of DBF as stable ammonium salt solution produced depends on the absorbent used in the scrubbing operation

- Sulfuric acid produces an up to 38% ammonium sulfate solution
  $2\ NH_3 + H_2SO_4 = (NH_4)_2SO_4$
- Nitric acid produces an up to 25% ammonium nitrate solution
  $NH_3 + HNO_3 = NH_4NO_3$
- Gypsum produces calcium carbonate and ammonium sulfate
  $2\ NH_3 + CO_2 + H_2O + CaSO_4 = CaCO_3 + (NH_4)_2SO_4$

It should be noted that the product properties are highly dependent on the technology provider, not only in terms of N and S nutrient content but also in terms of pH (see Table 11). Low pH scrubber solution could cause corrosion to application equipment, leaf burning, and soil acidification after long-term application. Thus, it is advisable to neutralize the acidic pH.

The treated liquid digestate retains the original nutrients, except for extracted NH$_4$-N, and can be applied at higher rates while remaining below N application limits.

Table 11. Typical Characteristics of Ammonium Sulfate Solution Produced by NH$_3$ Scrubbing

Parameter	Ammonium sulphate
Dry matter (%)	14 - 33
pH	2.40 - 6.43
EC* (ms cm^{-1})	157 - 262
N total (g kg^{-1})	30 - 86
NH$_4$-N (g kg^{-1})	30 - 86
N mineral/N total (%)	100
S (g kg^{-1})	30 - 114
	*EC electrical conductivity

[Source: SYSTEMIC PROJECT EU 2021 Ammonium Sulfate Factsheet]

Operational Inputs	Energy: Reported values range from 2 - 12 kWh electricity plus 60 - 95 kWh heat m^{-3} treated.
	Chemicals: Reported alkali dosing ranges from 0 - 6.5 kg NaOH m^{-3} treated.
	Reported acid dosing ranges from 5 - 10 kg H_2SO_4 (50%) or 19 kg gypsum m^{-3} treated.

Cost and Key Cost Factors	CAPEX: $$$	OPEX: $$$
	• Energy (heat) if 'hot stripping' used • Chemical consumption • Frequent cleaning of packed tower media It is reported that N recovery using air stripping-scrubbing only becomes economically feasible when the feed NH_4-N concentration exceeds 400-500 mg N L^{-1}.	

Table 12. Technology	Phosphorus Precipitation and Crystallization – Technology Summary
Functional Category	Digestate BioFertilizer
Technology	Phosphorus Precipitation and Crystallization
Function and Key Benefits	Separation of P and N • Produces DBF as slow-release mineral N, P fertilizer products • Enables higher nutrient use efficiency and commercial fertilizer substitution • Reduces potential for P runoff and N_2O emissions • Treated liquid digestate can be applied at higher rates without exceeding nutrient application limits
Image	**Figure 11. Typical Arrangement of P Precipitation and Crystallization Process** [Source: Fanguerio 2017]
Description	Phosphorus precipitation and crystallization is a method to extract soluble phosphorus (PO_4-P, ortho-P) from the liquid fraction of digestate in the form of solid, crystalline products (phosphate salts) such as magnesium-ammonium-phosphate (MAP), known as struvite, potassium-ammonium-phosphate, known as K-struvite, and various forms of calcium-phosphate (CaP) products. These Digestate BioFertilizer (DBF) products are reported to be effective slow-release fertilizers, suitable for use with little to no additional treatment and for application with existing fertilizer equipment. The treated liquid fraction of digestate retains the nutrients originally present, except for the extracted phosphorus, and can be applied at higher rates without exceeding phosphorus application limits. Inducing phosphorus precipitation requires the addition of magnesium or calcium salts to the liquid fraction of digestate, to achieve the Mg:N:P or Ca:P molar ratios necessary for formation of the desired product, and also the addition of alkali (e.g., NaOH) to increase the pH to 9 - 11.

Phosphorus precipitation technologies are usually based on fluidized bed reactor or continuously stirred tank reactor designs (see Figure 11). The process may take place either in a one-stage reactor, where chemical addition and sedimentation of the struvite crystals occur in the same vessel, or two-stage reactors where the chemicals are added in a first step and separation of the crystals occurs in a second step, usually by centrifugation.

Formation of struvite (MAP) is governed by the reaction:
$$Mg_2^+ + NH_4^+ + PO_4^{3-} + 6\ H_2O \rightarrow MgNH_4PO_4.6\ H_2O$$

Formation of K-struvite is governed by the reaction:
$$Mg_2^+ + K^+ + PO_4^{3-} + 6\ H_2O \rightarrow MgKPO_4.6\ H_2O$$

Struvite formation requires equimolar amounts of Mg_2^+, NH_4^+, and PO_4^{3-} however it is reported that in practice best performance is achieved when magnesium is present in excess and therefore a Mg:N:P ratio of approximately 1.3:1:0.9 is recommended. Since NH_4-N is almost always in excess in digestate, magnesium (magnesium oxide MgO or magnesium hydroxide $Mg(OH)_2$) and phosphoric acid are added to the digestate. The precipitation and formation of struvite crystals are also temperature dependent, and optimal ranges typically vary between 25°C and 35°C.

If both NH_4-N and potassium are present in excess, struvite will precipitate instead of K-struvite. Therefore, K-struvite will be only precipitate if the excess of potassium is much higher than that of NH_4-N. The presence of other ions in solution such as calcium or carbonate can negatively affect struvite precipitation and product quality by competing for magnesium and/or phosphate to form other precipitates species such as calcium phosphates or calcium/magnesium carbonate species. It is reported that the molar ratio of Ca_2^+:PO_4^{3-} should be < 0.5 to obtain efficient struvite precipitation (rather than calcium phosphates formation) and high struvite quality.

Increasing the pH to 9 - 11 is required to initiate the precipitation reaction and can be achieved by blowing air into the reactor to strip CO_2 (CO_2 stripping). However, struvite precipitation generates protons (H^+) and consequently an alkali source must be added to maintain the pH in a suitable range for struvite precipitation. The quantity of alkali required depends on the buffer capacity (mostly carbonate and ammonia/ammonium alkalinity) of the liquid fraction of digestate.

It is reported that struvite precipitation can recovery 70% - 90% of the soluble phosphate (orthophosphate) and 10% of the NH_4-N present in the treated digestate liquid fraction (see Table 13).

Phosphorous can also be recovered from digestate as calcium phosphate salts. CO_2-stripping may be performed prior to precipitation preventing competing $CaCO_3$ sedimentation. Adding calcium hydroxide ($Ca(OH)_2$) to the liquid fraction of digestate at 70°C invokes a pH rise to 10, and subsequent fast (5 min) precipitation. Depending on calcium dosage and other factors, different CaP products can result such as, in order of decreasing solubility and fertilizer value, monocalcium phosphate ($Ca(H_2PO_4)$), dicalcium phosphate ($CaHPO_4$), tricalcium phosphate ($Ca_3(PO_4)_2$, and hydroxyapatite ($Ca_5(PO_4)_3OH$).

Table 13. Separation Indices for Phosphorus Precipitation and Crystallization NRRT

Input:	Liquid fraction following treatment by advanced solids separation					
Separation Output:	**Struvite**					
Separation Index (% w/w, into separation output)	Q	DM	TN	NH_4-N	TP	TK
	-	-	-	10 - 40	70 - 90 of PO_4	-

Input	The purity of the precipitated phosphorus salts can be impaired by the presence of suspended solids therefore pretreatment by advanced liquid-solid separation is recommended.
Output	Production of recovered P products is digestate and process specific. The nutrient content of struvite is approximately 6%, 13%, 0% and 10% by weight N:P:K:Mg (6-13-0-10 Mg). The nutrient content of K-struvite is approximately 0%, 12%, 15%, 9% by weight N:P:K:Mg (0-12-15-9 Mg) The treated digestate liquid fraction has lower concentrations of mineral N and P and can be applied at higher rates without exceeding nutrient application limits.
Operational Inputs	Energy: Electricity requirements are reported to range from 0.23 to 0.9 kWh per m^3 treated. Chemicals: Chemical requirements are highly dependent on the characteristics of the digestate, process design and P recovery goal. Mg or Ca requirements depend on the concentrations of NH_4-N and PO_4^{-3} while the quantity of alkali required depends on the pH, process temperature and buffering capacity caused by NH_3/NH_4^+ and $H_2CO_3/HCO_3^-/CO_3^{-2}$ equilibria.
Cost and Key Cost Factors	CAPEX: $$ OPEX: $$$ - $$$$ The costs of struvite precipitation are strongly dependent on the magnesium and alkali sources used. These costs may contribute up to 75% of overall production costs.

Table 14. Evaporation – Technology Summary

Functional Category	Concentrated Organic Fertilizer
Technology	Evaporation
Primary Function and Key Benefits	Concentrates digestate liquid fraction by removing water • Reduces quantity of liquid digestate. • Reduces transportation and storage requirements • Concentrates nutrients increasing product value • Option to produce Digestate BioFertilizer enabling improved nutrient use efficiency and commercial fertilizer substitution • Clean water suitable for process and cleaning requirements or discharge with additional polishing
Image	**Figure 12. Multi-Stage (Multiple Effect) Evaporation System** [Source: Drosg 2015] **Figure 13. Mechanical Vapour Recompression (MVR) Evaporation System** [Source: Ahirrao 2014]

Description	Evaporation is method of reducing the water content and therefore the volume of the liquid fraction of digestate and to beneficially use heat from a combined heat and power (CHP) system. Evaporation technology produces two output streams, 1) vapour comprised of the evaporated water and other volatile compounds, and 2) concentrate which retains almost all of the nutrients present in the untreated liquid digestate with significantly less water.
	It is reported that the volume of concentrate produced by evaporation technologies can be from 20% to 50% of the volume of the untreated liquid fraction (i.e., a 50% to 80% volume reduction) depending on the quantity of heat energy applied, with the lesser volume reduction representing the application of CHP heat only. For further volume reduction of the concentrate stream, drying is recommended.
	In addition to water vapour, other compounds with high vapour pressure will be volatilized, mainly volatile organics (e.g., volatile fatty acids), CO_2 (from carbonates) and ammonia. Ammonia volatilization at evaporator temperatures (100°C) and typical digestate pH (7.5 - 9) is reported to represent 60% - 75% of the total ammoniacal nitrogen present. Ammonia volatilization can be controlled by adjusting the pH of the liquid digestate prior to treatment. Acidic pretreatment (e.g., H_2SO_4) to reduce the pH to < 6.5 will prevent ammonia volatilization.
	The vapour stream is treated to recover NH_3 and to produce a clean water stream for process use, irrigation or discharge. NH_3 recovery can be achieved through several means including distillation, reverse osmosis filtration and acid scrubbing. Distillation and reverse osmosis produce ammonium-water. Ammonium-water is a solution of anhydrous ammonia in which NH_3 and NH_4^+ are present in equilibrium at pH >9. Reducing the pH to neutral is required to prevent NH_3 loss. Acid scrubbing of the vapour stream produces an ammonium salt. Refer to the technical summaries of pressure-driven membrane filtration and N stripping and scrubbing respectively.
	The vapour also contains foul-smelling, non-condensable gases. A method of air purification can therefore be necessary for exhaust gasses.
	Different evaporator technology configurations are available and usually selection is based on the availability of heat and the characteristics of the liquid digestate.
	Evaporator configurations for energy recovery:
	To use the heat of the evaporator as efficiently as possible, multiple configurations are possible. Vacuum evaporation makes use of lowering the pressure and thereby lowering the boiling point of water, and so less heat energy is required for evaporation. Multiple effect evaporation re-uses the heat of the first evaporator in the following evaporating steps which each have lower pressures, and therefore require less energy to heat up (see Figure 12). Mechanical Vapour Recompression (MVR) systems compress the evaporate to increase heat transfer to the liquid digestate feed thereby reducing the heat energy requirement (see Figure 13).
	Evaporator configurations for different digestate characteristics:
	For evaporation of (liquid fraction of) digestate falling film, spray-film or forced circulation evaporators with external heat exchangers are used because they are considered to be more suitable for viscous and heat-sensitive liquids.
	Reported separation indices for evaporation NRRT are summarized in Table 15.

Table 15. Separation Indices for Evaporation NRRT

Input:	Liquid fraction following primary or advanced solids separation					
Separation Output:	**Concentrate**					
Separation Index (% w/w, into separation output)	Q	DM	TN	NH_4-N	TP	TK
	50, with heat from CHP	90 - 99	90 - 99 (organic N)	25 - 40 without pre-acidification, 90 - 99 with pre-acidification	99	99

Input

Input pre-treatment:

- Primary liquid-solid separation to prevent clogging and fouling
- If required, pH reduction to < 6.5 to prevent NH_3 volatilization

Output

Two output streams are produced, concentrate and clean water. A third output stream is produced when the vapour is treated for NH_3 recovery.

Concentrate

The DM and nutrients present in the digestate liquid fraction feed are retained at much higher concentrations as shown in Table 16. With acid pretreatment NH_3 will be retained in the concentrate. Without pretreatment, NH_3 will volatilize with the vapour.

Table 16. Example Digestate Liquid Fraction Feed and Evaporator Concentrate Output

	Digestate Liquid Fraction[1]	Evaporator Concentrate[2]
pH	8.3	6.2
DM (g kg^{-1})	26	115
Organic Matter (g kg^{-1})	14	63
Total N (g kg^{-1})	4.0	7.1
NH_4-N (g kg^{-1})	2.4	3.0
Total P (g kg^{-1})	0.21	2.2
Total K (g kg^{-1})	3.1	5.6

1. Liquid output of decanter centrifuge with flocculant addition
2. Pretreated with sulfuric acid to pH 6.5 - 7 to prevent NH_3 volatilization.

[Adapted from: SYSTEMIC PROJECT EU 2021 Factsheet AM Power]

Clean water

The clean water stream may be suitable for use as process or cleaning water or for irrigation but may require additional polishing to meet local direct discharge requirements.

NH_3 Recovery Streams

Acid scrubbing of the vapour stream can produce an ammonium sulfate or ammonium nitrate solution as described in the technical summary of N stripping and scrubbing.

Distillation and reverse osmosis produce ammonium-water which can have a total ammoniacal N content of up to 20%, as shown in Table 17.

Table 17. Example Ammonium-Water Characteristics

pH	9 - 10.5
DM (%)	0.02 - 0.1
NH_4-N (g N kg^{-1})	28 - 200
NH_4-N/Total N (%)	82 - 90
P_2O_5 (g kg^{-1})	0 - 0.5
K_2O (g kg^{-1})	0 - 0.6

[Source: SYSTEMIC PROJECT EU 2020 Project Factsheet Condensed Ammonium Water]

The NH_3 recovery streams are suitable for use as Digestate BioFertilizer primarily supplying mineral N.

Operational Inputs	Energy: The energy requirement of evaporation technology is dominated by the thermal energy required to evaporate water. Multiple-effect evaporators require between 400 kWh $tonne^{-1}$ (2nd effect) and 200 kWh $tonne^{-1}$ (5th effect) of water evaporated. It is reported that the heat from a CHP unit could be sufficient to evaporate up to 50% of the water using this technology. Vacuum and mechanical vapour recompression (MVR) evaporation technologies require less thermal energy. MVR is reported to require 80% less thermal energy than multiple-effect technology. Chemicals: Acid requirements to reduce pH to < 6.5 depend on the buffering capacity (mostly carbonate alkalinity) of digestate. Reported dosing ranges from 2 - 9 L H_2SO_4 (96%) per m^3.

Cost and Key Cost Drivers	CAPEX: $$$$	OPEX: $$$$
	Cost of thermal energy. Technology is best suited for biogas plants without a beneficial use for CHP heat. Cost of chemicals (acid) for pretreatment of the liquid fraction to prevent NH_3 volatilization (if required) and chemicals for odour treatment of non-condensable exhaust gases.	

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Table 18. Pressure-Driven Nanofiltration and Reverse Osmosis – Technology Summary

Functional Category	Concentrated Organic Fertilizer
Technology	Pressure-Driven Membrane Filtration
Primary Function and Key Benefits	Reduces digestate volume and concentrates nutrients by extracting water. • Complete transformation of liquid fraction into Digestate BioFertilizer Product (DBF) and clean water • Significantly reduces storage and transportation requirements • DBF (mineral N, K RO concentrate) can achieve high nutrient use efficiency and commercial fertilizer substitution • Clean water suitable for process and cleaning requirements or discharge with additional polishing
Image	**Figure 14. Principle of Pressure-Driven Membrane Separation** [Source: Drosg 2015] **Figure 15. Overview of Pressure-Driven Membrane Separation Processes**

Notes:

1. The SI symbol μm is also commonly called as a micron that is an SI derived unit of length equalling 1×10–6 which is the metre that is the SI standard prefix "micro-" = 10–6. Micrometer is the one-millionth of a metre that is or one-thousandth of a millimetre which is 0.001 mm or about 0.000039 inch. [Wikipedia]

2. 'Tenside' refers to detergents or surfactants

[Source: Drosg 2015]

| Description | Pressure-driven membrane filtration technologies can be used to separate the liquid fraction of digestate into a Digestate BioFertilizer and a clean water stream suitable for process and cleaning uses, irrigation or discharge, subject to local requirements. |

Pressure-driven membrane filtration technologies can be used to separate the liquid fraction of digestate into a Digestate BioFertilizer and a clean water stream suitable for process and cleaning uses, irrigation or discharge, subject to local requirements.

The basic operation of this technology involves forcing the liquid digestate feed stream through the pores of a membrane by applying pressure (see Figure 14). The pore size of the membrane determines which molecules pass through to the permeate and which are retained in the concentrate.

In general, there exist two types of membrane; porous and solution-diffusion. Porous membranes are applied where the particles are retained by size-exclusion, because they are not able to enter the pores of the membrane. Solution-diffusion membranes rely on the different abilities of compounds to dissolve in the membrane material and consequently be separated by differences in their diffusion velocity. Either polymer membranes or ceramic membranes are used. The latter are only applied in micro- and ultrafiltration and have the advantage that they are more robust and can withstand harsh chemical cleaning.

In a typical application of this technology, a series of membranes arranged in order of decreasing separation size; microfiltration (MF) then ultrafiltration (UF) then nanofiltration (NF) and finally reversed osmosis (RO). The permeate of the MF, UF and NF steps becomes the feed for the subsequent filtration step and in this way separation of ever smaller items is achieved as illustrated by Figure 15.

The separation efficiency may be improved by the addition of surfactants, and water-soluble polymers (for example, chitosan, polyethylenimine, or polyacrylamide) which are able to complex with metals and improve their removal. Operating temperatures range from 10-40°C. Increasing temperatures (20°C and 40°C) can lead to reduced viscosities of anaerobic sludges which can reduce pressure requirements and have a positive effect on the performance of UF. Ensuring the predominance of NH_4^+ through acidification (H_2SO_4) to pH 6.6 - 6.8 will improve N separation efficiency of RO since NH_3 can permeate through RO membranes whereas NH_4^+ cannot.

Reported ranges for the separation indices of MF-UF and NF-RO systems are presented in Table 19 and Table 20 respectively. It is reported that up to three passes through the RO step are necessary for the RO permeate to satisfy water quality requirements for discharge, see Table 22.

The concentrate streams from the MF and UF steps can be returned to the digester, combined with the solid product and dried, or combined with the RO concentrate and managed as a concentrated fertilizer product. Since almost all nutrients are retained in the concentrate streams, the nutrient density of a combined concentrate is increased by 2X or 3X compared to that of the untreated digestate liquid fraction.

The operational challenge of membrane filtration is reported to be fouling and scaling of the membrane which increases the hydraulic resistance and therefore the energy consumption and maintenance costs.

Fouling can be caused by suspended solids (i.e., colloids of 1µm-1nm), organic substances like humic acids, oil, hydrocarbons and (bio)polymers, extracellular substances, or components in additives used in previous process steps (for example, silicones in the anti-foam, polymer solution) that adhere to the membranes. Fouling can be minimized by effective pre-treatment for suspended solids removal. Vibrating (60 - 90 Hz) shear enhanced processing (VSEP) filtration is a potential option for reducing cleaning requirements. Cleaning options to remove fouling include ultrasonication, frequent backwashing or chemical methods such as use of acidic or alkaline media, surfactants, chelants or oxidants.

Scaling is the process where inorganic substances reach the saturation level in the solution and precipitate as salts that separate from the liquid and stick to the membrane causing gradual blocking of the membranes. Scaling can be relieved by inducing extreme pH (usually caustic) and using anti-scalants, i.e., chelating agents.

NF-RO can also be used to treat the condensate of evaporation NRRT producing ammonium-water and clean water outputs.

Table 19. Separation Indices for Pressure-Driven Microfiltration - Ultrafiltration NRRT

Input:	Liquid fraction following primary or advanced solids separation					
Separation Output:	Membrane Concentrate					
Separation Index (% w/w, into separation output)	Q	DM	TN	NH_4-N	TP	TK
	25 - 40	50 - 70	30 - 60	20 - 40	80 - 90	20 - 40

Table 20. Separation Indices for Pressure-Driven Nanofiltration + Reverse Osmosis NRRT

Input:	Liquid fraction following advanced solids separation					
Separation Output:	RO Concentrate					
Separation Index (% w/w, into separation output)	Q	DM	TN	NH_4-N	TP	TK
	30 - 45	90 - 99	90 - 99	80 - 99	90 - 99	80 - 99

Input	Liquid fraction pre-treated by decanter centrifuge or flotation technologies aided by the addition of flocculants to remove coarse and fine suspended solids.
Output	The MF-UF step produces a concentrate and a permeate. The concentrate can have a DM content ranging from 2% - 10% and contains the majority of the DM, organic N and TP present in the feed (see Table 21). The MF-UF concentrate can be used directly, returned to the digestion process, or combined with the digestate solid fraction for drying / pelletizing. The permeate contains soluble organic matter and most of the NH_4-N and K and is typically treated by NF-RO processes.
	The final NF-RO step also produces concentrate, which is the DBF product, and permeate output streams.

Concentrate

The volume of the concentrate stream can be 20% - 40% of that of the digestate liquid fraction following advanced solids separation. Example RO concentrate / DBF product characteristics are presented in Table 21.

Table 21. Examples of Concentrate Characteristics

	UF1	2-Step RO[1]	2-Step RO[2]
pH	8.1	7.9	7.9
DM (g kg^{-1})	29	29	33.4
Organic Matter (g kg^{-1})	21	7	13.3
TN (g kg^{-1})	4.5	6.9	7.1
NH_4-N (g kg^{-1})	2.2	5.4	6.4
NH_4-N / TN	0.49	0.78	0.9
TP (g kg^{-1})	0.5	0.1	0.2
TK (g kg^{-1})	4.1	10	7.2

Notes:

1. Adapted from: Chiumenti 2013
2. Adapted from SYSTEMIC PROJECT EU 2020 Mineral Concentrate Factsheet

Permeate

The volume of the permeate stream can be 20% - 50% of that of the digestate liquid fraction following advanced solids separation. The permeate stream generated from RO contains low concentrations of nutrients (see Table 22) and can be re-used as process water, or for irrigation, or discharged to sewer or surface water, after a polishing step, subject to local requirements.

Table 22. Examples of Permeate Characteristics

Parameter	UF1	2-Step RO[1]	2-Step RO[2]	3-Step RO[2]
pH	7.8	8.1	-	-
DM (g L^{-1})	7.7	1.3	0	0
COD (g L^{-1})	4.7	< 0.01	0.05 - 0.06	< 5
TN (g L^{-1})	1.93	0.085	0.32 - 0.34	3.5
NH_4-N (g L^{-1})	1.59	0.025	0.3 - 0.32	-
TP (g L^{-1})	0.05	-	0.053	< 0.5
TK (g L^{-1})	2.74	0.05	-	-

Notes:

1. Source: Chiumenti 2013. Pretreatment by decanter centrifuge with flocculant addition.
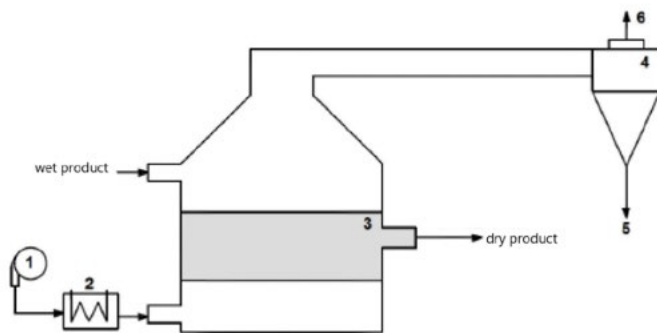2. Adapted from Drosg 2015. Solids separation pretreatment not specified.

Operational Inputs	Energy: Reported energy requirements range from 0.1 - 0.5 kWh electricity m^{-3} treated for MF/UF and from 4 - 6 kWh electricity m^{-3} treated for RO and 13 kWh electricity m^{-3} treated for UF + RO. Chemicals: Coagulant and flocculant dosages pre-MF-UF are reported to be similar to requirement for other advanced solids separation technologies. Acid (H_2SO_4) may be added pre-RO to prevent NH_3 from permeating the membrane. Other chemicals depending on membrane cleaning requirements.	
Cost and Key Cost Factors	CAPEX: $$$$ - $$$$$	OPEX: $$$$
	Capital cost	
	Energy cost	
	Frequent cleaning and replacement of membrane media	

Table 23. Fluidised Bed, Belt, Rotating Disc, Rotating Drum – Technology Summary

Functional Category	Concentrated Organic Fertilizer
Technology	Thermal Drying
Primary Function and Key Benefits	Removes water from separated solid fraction. • Reduces digestate quantity • Improves product characteristics for storage and application • Reduces potential for N loss and GHG emissions during storage • Produces DBF enabling high nutrient use efficiency and commercial fertilizer substitution • Beneficial use for heat from CHP
Image	**Figure 16. Typical Arrangement of Fluidized Bed Dryer** [Source: Drosg 2015] **Figure 17. Typical Arrangement of Belt Filter Dryer** [Source: Barnelis 2015]
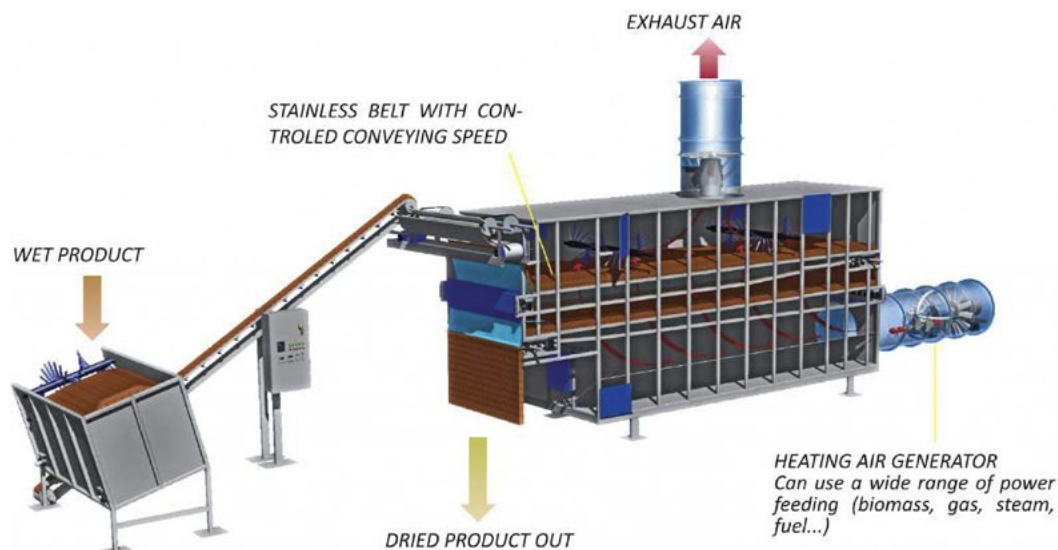
Figure 18. Typical Arrangement of Rotating Disk Dryer
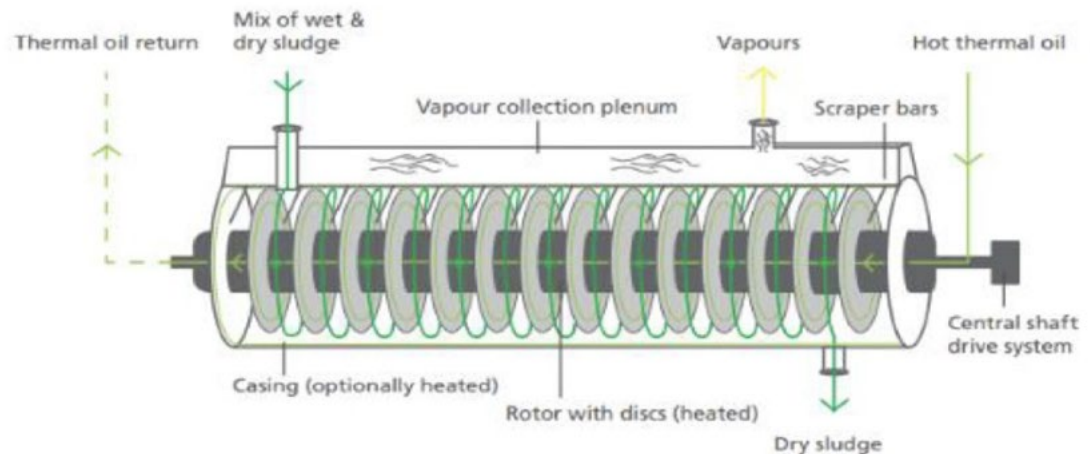
[Source: Drosg 2015]

Description

Thermal drying is a method of removing water in order to reduce the quantity of digestate solid fraction to be managed, to improve its characteristics for storage and handling, and to beneficially use heat from a combined heat and power (CHP) system.

Primary or advanced solids separation and evaporation processes can maximally achieve an end product with dry matter content of 30-40%. When a drying step is added, the dry matter content can be increased to 95-95%.

Thermal drying relies on evaporating water by heating up the product by means of heat transfer from another medium (e.g., air, steam, heated oil). Drying temperatures reported for digestate range from 80°C to up to 200°C depending on the type of dryer and heat source. Thermal drying technologies are categorized by the method of heat transfer, direct or indirect.

DIRECT DRYERS

Direct dryers (a.k.a. convection dryers) directly use the evaporation energy of the heat medium which is typically heated air, flue gas or inert gas. Direct dryer technology types used in biogas plants include fluidized bed, belt and rotating drum dryers.

Fluidized bed dryer

'Wet' digestate is blended with dried product to achieve the 60% - 70% dry matter required to prevent clumping which impedes the drying process. The blend is fed to the drying chamber which is typically a cylindrical vessel with a perforated bottom plate. The heat medium is forced upwards through the bottom plate at a velocity which is sufficient to cause the mass of digestate to behave as a fluid (see Figure 16). The intense contact between the heat medium digestate particles facilitates rapid and efficient moisture evaporation. The water, 80% - 90% of the NH_3, other volatile compounds and digestate dust particles, are carried away by the heat medium. Vibration is often used to move material through the process.

In open systems, which use heated air as the heat medium, this air is treated to remove dust (which is blended with 'wet' feed material), odours and to recover NH_3 (by acid scrubbing) prior to discharge. Because digestate dust is potentially explosive, precautions are required to ensure that the dust concentration in the heat medium remains below the lower explosion limit.

Closed systems use an inert gas, typically nitrogen, to eliminate explosion risk. The inert gas is treated to remove dust and to condense water, NH_3 and other condensable compounds, and recycled through the fluidized bed. The condensate solution can be treated, such as by reverse osmosis, to produce a mineral N fertilizer solution and clean water suitable for process uses or discharge.

Belt dryer

'Wet' digestate is blended with dry product in a mixer which conditions and granulates the material, creating small, uniform particles with a larger surface area for efficient drying. The conditioned feed is placed at a consistent depth on a continuously moving conveyor belt made of perforated stainless-steel plates or woven synthetic fibres which may be coated with silicon or Teflon for added durability. The belt transports the digestate through different drying zones within the dryer (see Figure 17).

Heated air or flue gas from biogas or natural gas combustion is typically used as the heat medium and is blown through the digestate layer from below or both sides. The perforated belt allows for efficient airflow through the material, facilitating moisture evaporation. The drying temperature and airflow are carefully controlled to optimize the process and prevent product degradation.

As the belt moves forward, the dried digestate reaches the end of the dryer and is discharged through a collection system. A portion of the heat medium is recycled to reduce energy requirements and maintain a low oxygen environment. Excess heat medium is cooled which produces an exhaust gas, that can be treated by biofiltration or wet scrubbing (acid scrubbing to recover NH_3) and wastewater which can be used as process water or treated, such as by reverse osmosis, and discharged.

Rotating Drum Dryer

Similar in operation to belt dryers however the drying vessel design is a rotating horizontal drum or series of concentric drums. The rotation of the drums and internal features like paddles, exposes the digestate to the heat medium and moves it through the drying vessel, making several 'passes' if the design includes concentric drums. Solid, liquid and gas outputs are managed similarly to belt dryers.

INDIRECT DRYERS

Indirect dryer (a.k.a. conduction dryers) dry the product by transfer of heat through a surface (i.e., a heat exchanger), meaning that the heat medium does not come into direct contact with the product. The heat medium can be a hot liquid (e.g., thermal oil, hot water) or gas (e.g., steam). Each type of medium has its own advantages and disadvantages:

- Hot water is often immediately available from cooling or production processes but due to the lower temperature a high flow rate and larger contact surface is required

- Steam provides high temperature thereby limiting the flow and contact surface area required but has additional operational requirements due to the higher pressures involved.

- Thermal oil combines a high temperature and heat exchange at relatively low pressure. Like steam, a smaller contact is surface required, yet it requires a higher mass flow compared to steam.

Since indirect drying systems use airtight drying vessels and there is no direct contact between the heat medium and the digestate the risk of creating an explosive dust environment is minimized.

Indirect dryer technology types used in biogas plants include rotating disk dryers and rotating drum dryers.

Rotating Disk Dryer

'Wet' digestate is blended with dry product in a mixer which conditions the material for efficient drying. The conditioned material is fed to an airtight horizontal cylinder that contains a rotating horizontal shaft on which are mounted a series of discs. The heated exchange surfaces are the shaft, discs, and in some designs also the wall of the enclosing cylinder. Stationary scraper blades positioned near the discs continuously remove the dried material from the discs' surfaces. Rotation of the discs exposes digestate to the exchange surfaces and moves the digestate through the mixer. Dried digestate is removed from the end of the dryer and is discharged through a collection system (see Figure 18).

The water vapour generated within the drying vessel also contains NH_3, VOCs and other volatile compounds, and requires cooling and treatment. Cooling produces an exhaust gas, which can be treated by biofiltration or wet scrubbing (acid scrubbing to recover NH_3) and water which can be used as process water or treated, such as by reverse osmosis, and discharged.

Rotating Drum Dryer

Similar in operation to rotating disc dryers however the drying vessel design is a rotating horizontal drum or series of concentric drums. The walls of the drums are the heat exchange surfaces. The rotation of the drums and internal features like paddles, exposes the digestate to the exchange surfaces and moves it through the drying vessel, making several 'passes' if the design includes concentric drums. Solid and vapour outputs are managed as with a rotating disc dryer.

A further note regarding the heat requirements for thermal drying:

It is reported that in general the excess heat of the CHP system is not sufficient for the complete drying of digestate, especially when liquid feedstocks are used (e.g., liquid manure). Since approximately 1.1 MWh of thermal energy is required per ton of water evaporated the general approach is that available heat from a CHP is sufficient to evaporate

a portion of water ranging between 25% and 50% of the total water in the digestate. Because of this limitation on recoverable heat, the digestate effectively treated is less than 50% of the total amount produced.

Pelletization

Dried digestate can be pelletized to further improve its characteristics for transportation, storage and application, and to adjust its nutrient content to meet the requirements of specific markets.

A typical pelletization process involves grinding the dried digestate followed by blending with additives to achieve the desired physical and nutrient properties in the final product. Additives can include:

- Binding agents: materials like starch, lignin, or cellulose help bind the digestate particles together and maintain the pellet structure.
- Nutrients: additional nutrients like nitrogen, phosphorus, or potassium can be added to enhance the fertilizer value of the pellets.
- Bulking agents: materials like wood shavings or straw can be included to improve pellet handling and storage properties.

The prepared digestate mixture is fed into a pelleting mill where it is forced through a pelleting die with small circular holes. As the mixture is pressed through the die, the friction and pressure cause the particles to agglomerate and form hard, dense cylindrical pellets. The die holes determine the pellet diameter which can range from 6 mm to 12 mm, with smaller sizes being preferred for most agricultural applications. The bulk density of digestate pellets is reported fall within the range of 500-650 kg m^{-3}.

Input	Separated solids from primary or advanced solids separation. Feed dosing with mineral acid (e.g., H_2SO_4) if retention of NH_4-N in solid product is desired.
Output	The primary output of thermal drying is a dry (80% - 90% dry matter) biologically stable solid fertilizer product free of odour with reduced or eliminated pathogens and pathogen indicators. The organic nitrogen and the totality of phosphorus and potassium originally present in the digestate remained in the dry product together with stabilized organic matter and other inorganic nutrients. NH_4-N can be retained in the dry product if the feed is acidified through the addition of mineral acids (H_2SO_4) before drying however this does not appear to be common practice and typically NH_3 is allowed to volatilize with the evaporated water and is subsequently recovered by acid stripping of the dryer exhaust gas (see Table 24).

Table 24. Example Dry Matter, Total N and NH$_4$-N in Solid Fraction and Dried Digestate

Variant	DMin %	Total N in mg g^{-1} TM	NH$_4$-N in mg g^{-1} DM
Dewatered digestate	24.4	26.2 ± 0.53 [a]	14.0 ± 0.18 [a]
Dried 45°C	90.0	13.9 ± 0.92 [b]	2.7 ± 0.04 [b]
Dried 70°C	91.3	13.9 ± 0.62 [b]	2.4 ± 0.01 [c]
Dried 80°C	93.4	13.5 ± 0.14 [b]	1.8 ± 0.02 [d]
Different superscript letters in a column represent significant differences (α = 0.05).			

[Source: Awiszus 2018]

Thermal drying produces secondary streams requiring management including exhaust gas, wastewater and recovered NH$_3$ in solution as ammonium sulfate or ammonium nitrate (when H$_2$SO$_4$ or HNO$_3$ are used for acid scrubbing, respectively), or as ammonium-water if the condensed vapour is treated by reverse osmosis. The NH$_3$ recovery outputs are suitable for use as Digestate BioFertilizers.

Operational Inputs	Energy: Thermal Drying, 1.2 - 2 kWh heat plus 0.03 - 0.05 kWh electricity per tonne of water evaporated. Pelletization, 0.5 to 2 kWh electricity per kilogram of dry pellets. Additional electrical energy required treatment of secondary streams. Chemicals: Mineral acids (H$_2$SO$_4$, HNO$_3$) for N recovery from exhaust gas by scrubbing.
Cost and Key Cost Factors	CAPEX: \$\$\$ - \$\$\$\$ OPEX: \$\$ - \$\$\$ Capital cost Cost of heat Cost of chemicals for N recovery

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