Comparative techno-economical study between membrane technology systems for obtaining concentrated fertilizers from biogas plant effluents

Camilleri-Rumbau, M. Salud[1],*; Norddahl, Birgir [1,2]; Nielsen, Anne Kjærhuus[2]; Christensen, Knud V.[1]; Søtoft, Lene Fjerbæk [1]

(1) Department of Chemical Engineering, Biotechnology and Environmental Technology –University of Southern Denmark, Campusvej 55, 5230 Odense M, DK, (2) Renew Energy A/S, Kullinggade 31, 5700 Svendborg, DK

* mscr@kbm.sdu.dk

Abstract

A techno-economic comparison of membrane technologies (microfiltration (MF), nanofiltration (NF) and reverse osmosis (RO)) and physico-chemical operations (struvite precipitation and ammonia stripping) for obtaining nutrient-rich fractions from biogas digestates, has been carried out. Four different treatments for the digestate including solid-liquid separation using a decanter centrifuge or a screw press are compared. A screw press followed by membrane technologies (treatment B) shows the best economical potential with a total potential of 4.9€/t feed.

Keywords: Digested manure, nutrient recovery, membrane technology, techno-economics

Introduction

Biogas plant digestates are a source of nutrients for agriculture. However intensive solid-liquid separation is required to achieve a better nutrient balance for crop and soil requirements and for water reuse [1]. In this aspect a major drawback of digestate is its poor settleability [2]. Thus solid-liquid separation of digestates requires separation technologies [3]. Membrane technology is one promising candidate for producing nutrient-rich fractions from animal slurry. To be viable, a substantially increase of nutrients in mineral concentrates through improved RO and additional technologies are required [4, 5] and a better pretreatment to improve membrane life and performance time is necessary [6]. This paper compares the techno-economical perspective of two main treatments, one based on membrane technologies and the other based on physico-chemical techniques for processing liquid digestates. To make these processes attractive to potential stakeholders, considerable revenue has to be obtained and partial or total substitution of chemical fertilizers by mineral fertilizers from digestates can be considered based on this evaluation.

Material and Methods

For the techno-economical comparison of the digestate treatments, retentions of fertilizer-nutrients such as nitrogen (N), phosphorus (P) and potassium (K) was found using a calculation tool designed and owned by Renew Energy A/S. This tool uses data based on their experience from the bioenergy sector. The tool includes data of different manure and organic waste sources used as feed in biogas digesters as well as nutrient removal efficiencies for different separation operations enabling detailed mass balance calculations. For the purpose of this paper, the design tool was expanded to include further treatment operations and Aspen Plus v7.3 was used for simulating the flash operation.

As feed, a mixture of pig slurry and potato waste was selected for the biogas digester. The resulting digested slurry is separated in a solid and liquid fraction by either a decanter centrifuge (treatments A&C) or a screw press (treatments B&D). The obtained solid fraction is sent to composting. The liquid fraction treatment then can follow one of two main paths. The first (A&B) consists of a MF step, followed by neutralisation, NF and RO. The second (C&D) consists of a MF step followed by struvite precipitation, where the supernatant is sent to a flash, followed by ammonia stripping and RO. In each step, nutrient-rich fractions are obtained. The final permeate from both treatments can be used as process water.

Figure 1 shows the first main treatment path. Treatment A uses a decanter centrifuge to separate the solid-liquid fraction while treatment B uses a screw press. The liquid fraction undergoes rotary MF for removal of solids (80% permeate recovery). The permeate pH is reduced from 8 (pH of digestate) to 6-7 to avoid ammonia vaporization. This effluent is treated by NF (70% permeate recovery). The NF permeate is treated with RO (80% permeate recovery). In each step nutrient-rich fractions: compost, MF, NF and RO concentrates, are obtained.

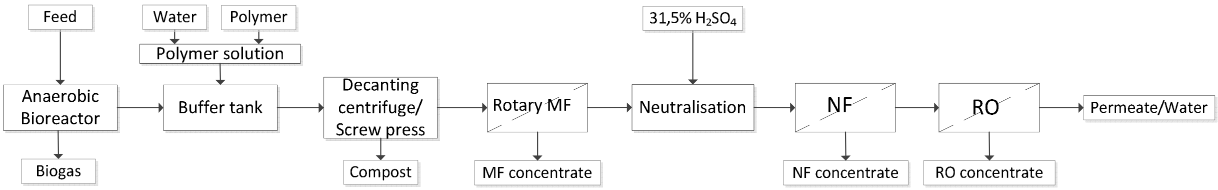

Figure 1. Treatments A&B using of decanter centrifuge/screw press, MF, neutralisation, NF and RO

Figure 2 shows the second main treatment path. Treatment C uses a decanter centrifuge and treatment D a screw press for the solid-liquid separation of the digestate. The resulting liquid fraction is send to a rotary MF (80% permeate recovery) for particle removal .The permeate is mixed with MgO to produce struvite. Theoretically, the molar ratio of struvite is 1:1:1 ($Mg:NH_4^+:PO_4^{3-}$) but co-precipitation of metal ions with struvite occurs (i.e. Na^+, K^+, Zn^+, Cu^{2+} and Ca^{2+}) although at an inclusion far below the allowed limit. A total of 65% total P is recovered as struvite [7]. After struvite precipitation, the solution is decanted and the supernatant, which contains 29ppm of Mg^{2+} [7], is flashed for CO_2 removal at 90^{o}C to increase the pH. The gas released is mostly CO_2, water vapour and a marginal amount of ammonia. The pH of the flashed liquid changes from 7 to 8. This pH is increased to 10 by adding a 50% NaOH solution. The NaOH solution dosage is calculated taking into account the buffer capacity of NH_3/NH_4^+ and HCO_3^- CO_3^{2-}. This caustic effluent undergoes ammonia stripping, the ammonia being absorbed into a 31.5% H_2SO_4 solution. A 38% ammonium sulphate solution is obtained. The stripped effluent is treated with RO (75% permeate recovery).

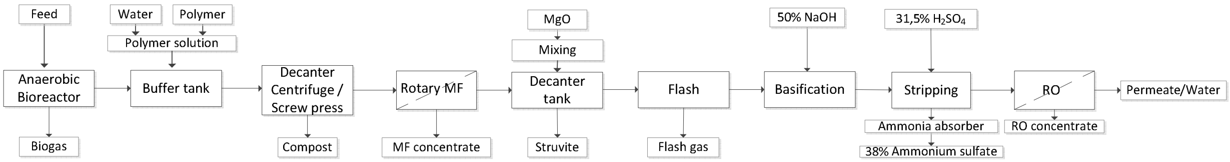

Figure 2. Treatments C&D using decanter centrifuge/screw press, MF, flash, struvite precipitation, ammonia stripping and RO

Results and discussion

Table 1 presents the mass balances for each treatment. 1t of feed to the pretreatment is used as a basis. Nutrient concentrations are expressed as kg/t fraction obtained in each unit operation. Data for centrifuge pretreatment, membrane rejections, basification and ammonia stripping was provided by Renew Energy. Data for struvite precipitation and screw press solid removal was taken from [7, 8], mass balances and energy consumption for the flash unit calculated in Aspen Plus v7.3.

Decanter centrifuge pretreatment (A&C) achieved a higher compost mass flow than the treatments using a screw press (B&D). Higher dry matter content was obtained as well. The compost composition in terms of N-P was higher when a decanter centrifuge was used achieving concentrations of 4.3kgTKN/t and 1.8kgP/t while 3.1kgTKN/t and 0.5kgP/t were obtained with a screw press. However, the content of K was higher when using a screw press. Compost was the fraction most influenced by the pretreatment in terms of nutrient distribution, with a 75%P inclusion when using a decanter centrifuge as compared to 15%P when using a screw press. The solid removal achieved during pretreatment affects the downstream unit operations. Using a screw press, a MF (80% permeate recovery) concentrate with 10% total solids (TS) was achieved while 4.6%TS was achieved when using a decanter centrifuge. A high solid removal is desired at this point, to minimize later clogging and damage of membranes and ensure that struvite precipitation is not affected by a high solid presence in the liquid (limit 1g suspended solids (SS)/L) [7]. The nutrient composition in MF concentrates is relatively similar in all treatments except for P, due to different removal efficiencies in the pretreatments.

In treatments A&B, the concentrate compositions of NF are relatively similar except for P content, again caused by the pretreatment. In treatments C&D the pretreatment had no effect on the ammonium sulphate yield as the TKN content is not affected by the pretreatment. For treatments C&D the struvite recovery is influenced by the P removal by the pretreatment as more valuable struvite can be formed when using a screw press due to a higher P content in the pretreated liquid. The presence of solids in the RO concentrate varied between pretreatments, i.e. 3.6-9.3% (80% permeate recovery in treatments A&B; 75% in C&D). However, similar compositions for N-K were achieved in the RO concentrates of A&B and C&D, respectively, while the P content decreased with 70% when a decanter centrifuge was used.

The income calculated per treatment is based on the nutrient content on the fractions' composition. The fertiliser prices are set at 0.67€/kg TKN, 1.18€/kg P and 0.79€/kg K (Danish Agriculture Advisory Board, August 2010). The price of tap water is 5.4€/m^3 (Denmark, February 2012). Although the fractions obtained in the different treatments vary in terms of composition, the final income is similar in all four treatments as the starting feed is the same for all four treatments. The main difference comes from the nutrient distribution in the obtained fractions. The small income differences between the processes are due to higher RO permeate flows obtained in treatments C&D.

Table 1. Nutrient mass balance distribution in valuable fractions and related income estimation

	Mass ratio (% pretreatment feed)	TS (%)	TKN (kg/ton fraction)	TP (kg/ton fraction)	TK (kg/ton fraction)	Income per fraction (€/ton pretreatment feed)
Treatment A:						
Decanter centrifuge feed	100	6.3	2.7	0.4	1.9	
Compost	15	28	4.3	1.8	1.5	0.94
MF concentrate	17	4.8	3.4	0.1	2.1	0.68
NF concentrate	20	5.2	4.9	0.3	2.6	1.18
RO concentrate	10	3.6	5.1	0.03	8.3	0.95
RO permeate (m^3/d)	38	-	-	-	-	2.1
Total income	**3,8 (rich fraction) + 2,1 (RO permeate)= 5,8 €/ton pretreatment feed**					
Treatment B: *Screw press feed*	100	6.3	2.7	0.4	1.9	
Compost	11	22	3.1	0.5	1.9	0.45
MF concentrate	18	10	3.9	0.4	2	0.82
NF concentrate	21	8.3	5.4	1.1	2.6	1.48
RO concentrate	10	4.4	5.4	0.1	8	1
RO permeate (m^3/d)	40	-	-	-	-	2.2
Total income	**3,8 (rich fraction) + 2,2 (RO permeate) = 5,9 €/ton pretreatment feed**					
Treatment C:						
Decanter centrifuge feed	100	6.3	2.7	0.4	1.9	
Compost	15	28	4.3	1.8	1.5	0.94
MF concentrate	17	4.8	3.4	0.1	2.1	0.68
Struvite	0.1	100	9	20	843.6	0.53
Ammonium sulphate	1.2	38	80.6	-	-	0.66
RO concentrate	17	4.9	1	0.3	3.9	0.68
RO permeate	50	-	-	-	-	2.7
Total income	**3,5 (rich fraction) +2,7 (RO permeate)=6,2 €/ton pretreatment feed**					
Treatment D: *Screw press feed*	100	6.3	2,7	0.4	1.9	
Compost	11	22	3.1	0.5	1.9	0.45
MF concentrate	18	10	3.9	0.4	2	0.82
Struvite	0.1	100	25	55	696	0.59
Ammonium sulphate	1.4	38	80.6	-	-	0.73
RO concentrate	17	9.3	1.3	1	3.7	0.86
RO permeate	52	-	-	-	-	2,8
Total income	**3,5 (rich fraction) +2,8 (RO permeate) =6,3 €/ton pretreatment feed**					

The chemical costs estimation was carried out for each treatment. The prices for chemicals were obtained from reports and companies: 76€/t H_2SO_4 (96%) solution, 132€/t NaOH (30%) solution and 274€/t MgO. The chemical consumption depends on the volume of effluent to treat. The chemical usage is higher for treatments C&D which produce struvite and use NaOH for ammonia stripping and H_2SO_4 as absorber. The chemical consumption in processes C&D is about 10 times more expensive than processes based on membrane technologies (an average of 0.135€/t for A&B against 1.2€/t for C&D). The energy costs estimation for each treatment was also evaluated. The energy price is set to 0.302€/KWh (Denmark, the EU Energy Portal, 31st January 2013). The decanter centrifuge pretreatment is the most energy consuming unit with 0.7€/t compared to 0.3€/t for the screw press. This situation makes processes using decanter centrifuges more expensive in terms of energy consumption. Energy costs for A&B running with membrane units (MF, NF, RO) are comparable to C&D running with flash and ammonia stripping units coupled with membrane units (MF, RO).
Table 2 shows the economic potential for each of the four treatments. Treatment B appears to be the most feasible mainly due to energy and chemical savings, followed by treatment A which also uses membrane technologies. Treatment C&D are the less economically feasible processes, treatment C being the most expensive one, mainly due to the decanter centrifuge pretreatment energy costs.

Table 2.Economic potential of each treatment

ECONOMIC POTENTIAL	Income (€/t)	Expenses (€/t)	Balance (€/t)
Treatment A - *Decanter centrifuge pretreatment*	5.8	1.5	4.3
Treatment B – *Screw press pretreatment*	5.9	1.0	4.9
Treatment C – *Decanter centrifuge pretreatment*	6.2	2.5	3.7
Treatment D – *Screw press pretreatment*	6.3	2.3	4.0

Conclusions

Pretreatment plays an important role in solid and P removal in digestates, resulting liquid fractions being higher in TS when a screw press is used instead of a decanter centrifuge. The income related to the nutrient-rich fractions is similar for all treatments. However, pretreatments using decanter centrifuges are more energy consuming while processes with struvite and ammonium sulphate formation increase chemical expenses up to ten times compared to treatments using membrane technologies. It is concluded that treatment B, using screw press and membrane technologies (MF, NF and RO), is the most economically feasible treatment.

Acknowledgments

This research was performed with the support of Renew Energy A/S. This research was financed by the ReuseWaste Project under Marie Curie Initial Training Network from the European Commission.

References

[1] Waeger F., *et al*, 2010. The use of ceramic microfiltration and ultrafiltration membranes for particle removal from anaerobic digester effluents. *Sep.Purif. Tech*, 73(2), 271-278.
[2] Choo K.-H. *et al*, 1992. Characteristics of membrane filtration as a post treatment to anaerobic digestion. *J. Korean Ind. Eng. Chem.*, 3, 730–738.
[3] Schoumans O.F. *et al*, 2010. Phosphorus recovery from animal manure. Alterra Report 2158. WUR
[4] Hoeksma, P. *et al*, 2012. Full-scale production of mineral concentrates from pig slurry using reverse osmosis. WRU-Conference Paper
[5] Velthof G.L. 2011. Synthesis of the research within the framework of the Mineral Concentrates Pilot. Alterra Report 2224. WUR
[6] Masse L. *et al*, 2007. The use of membranes for the treatment of manure: a critical literature review. Bio. Eng. 98, 371-380
[7] Liu, Y. *et al*, 2011. Recovery of nitrogen and phosphorus by struvite crystallization from swine wastewater. *Desalination*, 277(1-3), 364-369.
[8] Møller, H. B. et al, 2002. Separation efficiency and particle size distribution in relation to manure type and storage conditions. Bio. Tech. 85 (2002) 189-196