Nutrients recovery from anaerobic digestate of agro-waste: techno-economic assessment of full scale applications

N. Frison, F. Fatone, D. Bolzonella

Department of Biotechnology, University of Verona, Strada Le Grazie 15, 37134 Verona, Italy

Keywords: anaerobic digestion, nutrients recovery, drying, stripping, membranes

Corresponding author Email david.bolzonella@univr.it, phone/fax +39 045 8027965

Abstract

The sustainable production of fertilizers, especially those based on phosphorus, will be one of the challenges of this century. Agriculture, urban and industrial organic wastes are rich in nutrients which can be conveniently recovered. In this study five full scale systems for the recovery of nutrients from agricultural anaerobic digestate were studied. Monitored technologies were drying, stripping and membrane separation. Results showed good performances in terms of nutrients recovery while the techno-economic assessment showed how the specificity of the monitored systems played a major role: in particular, membranes were able to produce a stream of pure water (up to 50% of the treated digestate) while drying, because of heat limitation could treat only a limited portion (lower than 50%) of produced digestate and stripping showed some problems because of the presence of suspended solids in the liquid fraction treated. Specific capital and operational costs for the three systems were quite similar ranging between 5.40 and 6.97 € per m^3 of digestate treated.

1. Introduction

Nitrogen (N), phosphorus (P), and potassium (K) are critical to intensive agriculture and there are concerns over long-term availability and costs of production of these nutrients. This is particularly true for P and K which are predominantly sourced from mineral deposits which are concentrated in defined geographical Regions [1]. These problems are of major concern considering a 9 billion population at 2050 and the necessity to sustainably produce more food [2].

Nutrients, however, are present in abundance in waste streams: here, after a proper treatment, they can be collected and concentrated. Among the different agricultural, urban and industrial waste streams, livestock effluents because of their abundance are of primary interest for nutrients recovery. The number of heads in EU28 can be estimated in 100 million dairy cows and cattle, 100 million pigs and 1.5 billion poultries for a global manure production of 30 million tons dry matter per year. Part of this material is used directly on fields but a great portion is stabilized through anaerobic digestion. Noticeably, according to data of the European Biogas Association [3], 14,000 anaerobic digestion plants are currently running in Europe, 80% of which are operating in the agricultural sector and are farm based. During the anaerobic process normally used for the stabilization of livestock effluents part of the organic matter is transformed into biogas, a mix of carbon dioxide and methane, while nutrients, including N, P and K remain in digestate, the residual material: the major part of nitrogen will be then found in the liquid phase (soluble fraction) as ammonium and the remaining in the solid one (particulate fraction), the same is for potassium, while phosphorous will be mainly present in the particulate fraction. Digestate, which is rich in nutrients, can be therefore directly used as a renewable fertilizer because of its contents of stable carbon and nutrients [4,5] or, if the nutrients loads are in excess in a given area, can be further treated for nutrients recovery in concentrated forms to be then transferred at sustainable prices in different agricultural areas [6,7]. The excessive presence of nutrients loads and the necessity to control their in specific areas is a well known problem in some European Countries and Regions, namely: Denmark, Belgium, Netherlands, northern Germany, Brittany (France), Catalonia and Aragon (Spain) and the Po valley in Italy [8].

Among the different commercial option for digestate treatment and nutrients recovery the most relevant are stripping, drying, evaporation and membranes technology which have been applied in recent years with alternate success for the treatment of anaerobic digestate or its solid or liquid fractions [6,7,9].

In this study we have considered the full scale applications of technologies including stripping, drying, and membranes, treating digestates originated from farm scale anaerobic digestion plants treating different livestock effluents and energy crops in the Italian scenario. Beside mass balances also a techno-economic analysis was carried out.

2. Material sand methods

2.1 Experimental set up and studied plants

Five farm anaerobic digestion plants using different techniques for post-treatment of digestate were considered in this study in total: two using a drying belt, one using a stripping column and two adopting membrane technologies. These were monitored for a period of at least six months (on average, a period equivalent to 4 HRTs of the anaerobic digester) and the main relevant parameters were determined for feedstock, biogas, digestate and processed streams. Table 1 reports a resume of the main features of the studied plants: the main biomasses present in the feedstock, the plant size and the digestate treatment technology for each plant are reported. Beside the determination of chemical-physical characteristics also data on investments, labor, energy and chemicals consumption were determined so to define a techno-economical assessment of the studied technologies. Revenues from fertilizers or nutrients selling were not taken into account in the economic balance so to define the worst scenario.

2.2 Drying system

Anaerobic digestion plants with a combined unit for heat and power (CHP) generation often have the availability of a considerable amount of heat after digester warming [6,7,9,10]. Part of this heat can be used to treat digestate so to obtain a dried solid (powder) material which is strongly reduced in volume and stable. Ammonia nitrogen can be removed with vapor or remain in the digestate if it is acidified. If removed of vapor nitrogen can be recovered as ammonium sulfate by means of scrubbing or reverse osmosis. In general, the heat amount is not sufficient for the complete drying of all produced digestate which is normally characterized by water content of 90% or more. Additional heat can be recovered from the CHP off gas by means of dedicated gas-water heat exchangers.

In this study we considered two farm scale installations where digestate derived from the anaerobic digestion of cow or pigs manure plus energy crops constituted the AD feedstock. In one case also slaughterhouse effluents were treated thus increasing the nitrogen load.

2.3 Stripping system

In this system digestate underwent to a pre-treatment for solid/liquid separation (screw press) and then the liquid stream was further treated for suspended solids removal and sent to the stripping column [6,7,9,11,12]. The studied system considered a double column process: the first column was dedicated to ammonia stripping from the liquid fraction of digestate and the second column recovered nitrogen as ammonium sulfate. In particular, the liquid stream of digestate was basified to pH values over 9 and then injected (up – down) in countercurrent to hot air (down – up) in the first column. Air from environment was put in contact with the cooling system of the CHP unit so air at 60-70°C was produced and used for the stripping process. Also the liquid digestate can be warmed via air-liquid heat exchanger to improve the process efficiency. In the first column because of the combined effect of pH and temperature ammonia leaves the liquid phase to pass in the gas phase. This phase passes in the second column where it reacts with sulfuric acid to form ammonium sulfate. Both columns are filled with filing material with a high specific surface so to facilitate the mass transfer phenomena. The residual liquid phase, with a low nitrogen content, but with the same amount of P and K of digestate was then used on fields while ammonium sulfate was sold.

2.4 Membrane separation systems

The studied systems are characterized by a series of physical treatments which allow for the separation of the particulate and liquid fractions of digestate [6,7,9]: the first solid/liquid separation is achieved by means of a screw press separator followed by an horizontal centrifuge (decanter) for the further removal of particulate solids from the liquid stream effluent the screw press. The separated liquid is then treated in an ultrafiltration membrane system operating at 40 kDa operating a maximum pressure of 3.5 atmosphere. The liquid effluent is then ready for the treatment in a double cartridge reverse osmosis unit operating at 30 atm and able to recovery up to 70-80% pure water from the treated stream (50% of the initial digestate mass). The system operated in batch mode, 14 m^3 each one, and can treat up to 50 or 100 m^3 per day. In this study two digestates of different quality, one deriving from the anaerobic digestion of dairy cows manure and energy crops and the other one coming from the anaerobic digestion of piggery effluents and energy crops, were tested. The system can be further implemented with a stripping tower to recovery ammonium sulfate from the reverse osmosis centrate [13].

2.5 Sampling and chemical analysis

Anaerobic digestate, and the liquid and solid fractions originated from the treatment systems were all sampled at least three times during a period of two months (the typical hydraulic retention time of farm scale anaerobic digesters). The chemical-physical characteristics of collected samples were determined according to the Standard Methods for Water and Wastewater Analysis [14]. In particular, dry and volatile matter, organic matter (as COD), nitrogen and phosphorus in their soluble and particulate phases were the main targets of the monitoring activity.

2.6 Techno-economic analysis

The basics for the techno-economic analysis were the mass and energy balances of the systems and their performances as well as the capital costs (capex) and operational costs (opex). Capex were then amortized over a period of 10 years considering a 3% interest. Opex considered the items: energy, chemicals, labor. These were communicated by the farmers adopting the monitored systems. Both capex and opex were referred to the amount of treated digestate so to obtain a comparison in Euros per cubic meter of digestate treated (€/m^3) and facilitate the comparison among different treatment systems [7].

Table 1. Main futures of the monitored plants

Plant	Feedstock	Plant Size, kW	Digestate treatment	Products
A1	Pigs effluents, chicken manure, energy crops	999	Dryer	Ammonium sulfate and dried organic digestate
A2	Cow manure, energy crops, slaughter house residues (blood), food waste	999	Dryer	Ammonium sulfate and dried organic digestate
B1	Pigs effluents, energy crops	999	Membrane separation	Reverse osmosis centrate, ammonium sulfate, water
B2	Cow manure, energy crops	600	Membrane separation	Reverse osmosis centrate, ammonium sulfate, water
C1	Cow manure, pigs effluents, energy crops	350	Stripping	Ammonium sulfate

3. Results and discussion

3.1 Drying process

Drying aims at reducing the volume of digestate or its solid fraction in systems like belt dyer, drum dryer, fluidized bed dryer … In all cases the liquid or semi-liquid stream is put in contact with hot air warmed using the heat coming from the CHP unit sometime implemented with the thermal energy recovered by an heat exchanger on the off gas pipe. The heated air allows for the removal of water in the form of vapor (including ammonia if digestate was not pre-acidified) while the solid fraction is dried up to a final dry matter concentrations of 90% or more [6,7,9]. The efficiency of this process is therefore directly connected to the availability of thermal energy (heat). It should be mentioned that the excess heat of the CHP system is not sufficient for the complete drying of digestate. With specific reference to the application of drying process in plants with a size of 1 MW the thermal energy available in a CHP unit is some 22 MWh_{th} per day. Part of this energy is used to keep the digester warm while the rest is used for drying: the quantity of evaporated water would be therefore around 15-18 m^3 per day depending on a number of factors (air temperature and humidity, characteristics of digestate etc…). This figure is only a portion, from 25 up to 50%, of the water content of produced digestate. As a consequence, also ammonia nitrogen recovered is around 50% of the total nitrogen entering the anaerobic digester. The vapor rich in ammonia is treated in a scrubber where sulfuric acid is used to block ammonia into ammonium sulfate or ammonium sulfate can be recovered by means of a reverse osmosis membrane. The N concentration in ammonium sulfate can be modified depending on the operational conditions of the scrubber and is normally greater than 4% but can reach 6%. Organic nitrogen and the totality of phosphorus and potassium originally present in the digestate remain in the dried fraction. This can be eventually pelletised to facilitate transportation and use.

The characteristics of digestates considered in this study are reported in table 2: digestate originated from piggery effluents (A1) presented a lower dry matter and nitrogen and phosphorus content compared to the digestate produced in the digester treating cow manure, energy crops and slaughterhouse residues (A2). Dry matter concentration in the digestate from cow manure was 78 g/kg versus 63 g/kg while nitrogen showed an average concentration of 6.8 gN/L, a value 4 times higher than the one observed in the case of piggery effluents. Also phosphorus was more abundant in the case of cow manure digestate (A2): total phosphorus was 0.8 gP/kg versus 0.3 gP/kg. In these two cases digestate passed through a drum thickener and was slightly dewatered increasing the total solids concentration to levels around 10-12%. This material is squeezed on the drying belt and then dried. Obtained dried solids (table 2) showed a dry matter concentration greater than 90%, 65% volatile matter, while N and P concentrations where 21 and 27 g/kg for N and 4 and 12 g/kg for P. These characteristics are in good agreement with values reported in literature for these systems: average dry matter contents around 90% and N concentrations of 24 gN/kg are reported also in other studies [7,9]. Recovered ammonium sulfate was in both cases diluted: nitrogen reached levels of 2.4 and 3.5% insufficient for the definition of fertilizers (N at 6%) but in any case sufficiently concentrated for a convenient transportation. Nitrogen level can be increased recirculating ammonium sulfate in the scrubber unit: the desired level of concentration is normally reached monitoring the density of the obtained ammonium sulfate.

Table 2 – Characteristics of influent (digestate) and effluents (dried solids and ammonium sulfate) of the drying system

	Dry matter, g/kg	Volatile matter, g/kg	Total nitrogen, gN/kg	Ammonium, gN/kg	Total Phoshorus, gP/kg	Phosphate, gP/kg
Digestate A1	63±5	44±4	3.2±0.3	1.6±0.2	0.3±0.1	0.1±0.1
Dried solids, A1	939±43	709±31	21±21.5	nd	4.0±0.5	nd
Ammonium sulfate, A1	nd	nd	25±2	24±3	nd	nd
Digestate A2	78±7	56±6	9.5±1.8	6.8±0.3	0.8±0.1	0.2±0.2
Dried solids, A2	936±38	625±27	27±2	nd	6±1	nd
Ammonium sulfate, A2	nd	nd	36±7	35±6	nd	nd

nd: not determined;

A typical mass balance for the applied process for the two plants is shown in figure 1. Clearly, because of heat limitation, only part of digestate could be treated: this fraction was between 20% and 30% of total produced digestate. After the treatment in the belt drier half of nitrogen was recovered as ammonium sulfate and half remained in the dried fraction. The total nitrogen present in digestate and then recovered in ammonium sulfate was therefore 38% and 47%, respectively. Dry matter, thus carbon, and phosphorus were completely recovered as a solid.

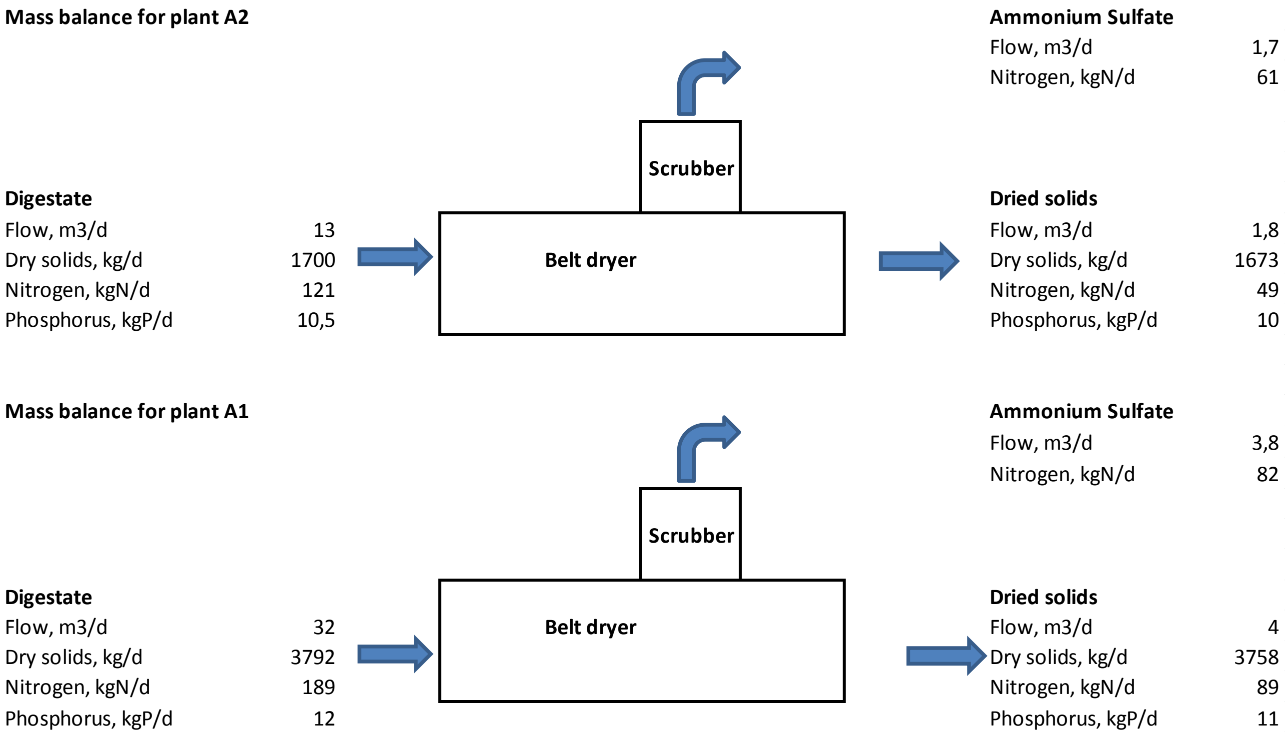

Figure 1 – Mass balance for a typical drying belt system

3.2 Stripping process

In this process digestate undergoes to a preliminary solid-liquid separation system, typically a screw press, and the liquid fraction is then further treated for the removal of residual suspended solids. The remaining liquid is then treated in a stripping column. Here ammonia is transferred from the liquid phase to the gas phase due to the action of hot (60-70°C) air recovered from the CHP unit. Moreover, also the liquid can be warmed to favorite the mass transfer from the liquid to the gas phase. This process can be further improved by adjusting liquid pH to levels above 9.5 adding soda but of this increases opex on one hand and leave Na in the liquid phase increasing the salinity on the other. The gas phase, rich in ammonia, enter then in a second column where sulfuric acid is spread to form ammonium sulfate. Both columns are normally organized with filling media so to increase the specific surface available for the mass transfer.

The characteristics of digestate treated are reported in table 3: it is a typical digestate originated from the anaerobic digestion of piggery and cow manure with energy crops addition. The dry matter content was around 5% and the nitrogen concentration was 3.6 gN/L, 75% as ammonium. Total phosphorus was 0.5 gP/L. Digestate was then separated in a liquid and solid phase by means of a screw press and the liquid phase is then settled for further solid removal by means of a lamella clarifier. Figure 2 shows the mass balance of the process. Considering the mass balance of the process we see that in such a process around 17% of the nitrogen originally present in digestate is recovered in the form of ammonium sulfate while the remaining part of nutrients remain in the liquid phase and are not concentrated. This liquid part which still contain part of nitrogen and phosphorus is generally use directly on fields.

Table 3 – Digestate, liquid effluent and ammonium sulfate characteristics

	Dry matter, g/kg	Volatile matter, g/kg	Total nitrogen, gN/kg	Ammonium, gN/kg	Total Phoshorus, gP/kg	Phosphate, gP/kg
Digestate	52±4	42±4	3.6±0.5	2.6±0.2	0.5±0.2	0.2±0.2
Liquid effluent	42±9	29±6	2.7±0.7	1.8±0.3	0.2±0.4	0.1±0.2
Ammonium sulfate	nd	nd	26±5	24±4	nd	nd

nd: not determined

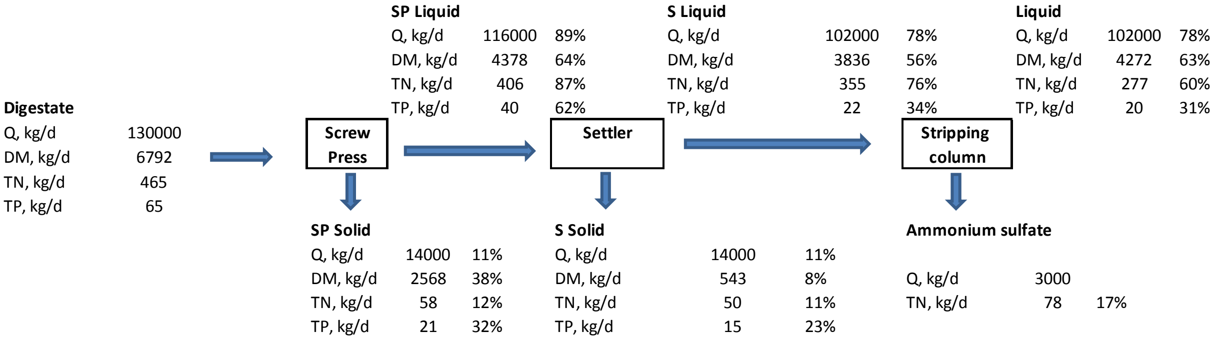

Figure 2 – Mass balance for the stripping process

3.3 Membranes technology

In membrane processes digestate is pre-treated by means of one or more solid/liquid separation systems like screw press and centrifuge so to obtain a stream with a low suspended solids content to be then treated in ultrafiltration and inverse osmosis systems. This will allow for the production of virtually pure water (up to 50% of the treated digestate) and a centrate phase rich in nutrients [6,7,9].

In the studied systems digestate was primarily treated in a screw press separator, the liquid stream generated was added with flocculants and treated in a centrifuge decanter to obtain a liquid characterized by a solid content <2%. This liquid is then refined in an ultrafiltration membrane and then treated in a reverse osmosis unit where nutrients were concentrated. Table 4 and 5 reports the typical concentrations observed in the different steps when dairy cows (table 4) and piggery (table 5) digestates were treated.

Soluble nutrients originally present in the digestate are all retained in the centrate of the reverse osmosis unit. In this process 50% of the digestate mass is recovered as pure water. This reduce the transportation costs of the concentrated nutrients.

The dairy cows digestate showed on average a 7% dry matter content a total nitrogen concentration of 3.35 gN/L, half ammonia, and a total phosphorus concentration of 1.64 g/L, 40% soluble (see table 4). With specific reference to data of table 4, it turned out clear that the soluble forms of N, and P, ammonia and phosphate, passed all the solid/liquid separation steps and were than concentrated in the reverse osmosis centrate, where TN and TP concentration were 4.8 mgN/L and 0.36 mgP/L, respectively. Noticeably, nitrogen was present in the soluble form (ammonia) while most soluble P (phosphate) was only 25% of TP. On the other hand, particulate forms remained in the "solids" fraction: it is of particular interest in this sense to observe that most of N and P particulates forms remained in the solid fraction separated by the decanter. In this case the use of polymers enable to capture most of the suspended solids and colloids, so the major part of nutrients remained in this stream.

Table 4 – Characteristics of dairy cows digestate, filtrated and centrate streams in a membrane process

	Dry matter, g/kg	Volatile matter, g/kg	Total nitrogen, gN/kg	Ammonia, gN/kg	Total Phosphorus, gP/kg	Phosphate, gP/kg
Digestate	70±3	49±2	3.35±0.3	1.73±0.1	1.64±0.3	0.069±0.03
Screw press solid fraction	220±27	198±15	3.25±0.3	nd	4.00±0.9	nd
Screw press liquid fraction	55±2	37±2	3.23±0.2	1.61±0.2	1.29±0.1	0.067±0.03
Centrifuge solid fraction	201±13	140±12	7.25±1.0	nd	5.25±1.2	nd
Centrifuge liquid fraction	18±1	10±1	1.7±0.1	1.5±0.1	0.13±0.05	0.060±0.01
Ultrafiltration centrate	38±2	27±1	2.9±0.2	1.25±0.2	0.25±0.03	0.066±0.01
Ultrafiltration filtrate	8±1	3.5±1	1.3±0.1	1.3±0.1	0.092±0.01	0.060±0.01
Reverse osmosis centrate	36±2	15±2	4.8±0.3	4.8±0.2	0.36±0.03	0.086±0.02
Reverse osmosis permeate	< 1	< 1	< 0.1	< 0.1	< 0.01	< 0.01

nd: not determined;

In a second plant monitored in this study piggery digestate was treated. Here the level of total solids is clearly lower than the one observed in the case of dairy cows digestate: 32 vs 70 g/kg. Also the nutrients concentrations were lower: these were 2.25 gN/L for TN and 0.36 gP/L for TP. Also in these case we observed that the particulate fractions were mainly blocked at the level of the centrifuge while soluble forms remained in the reverse osmosis centrate were final concentrations for N and P reached average levels of 5.27 gN/L and 0.26 gP/L, respectively.

Table 5 – Characteristics of piggery digestate, filtrated and centrate streams in a membrane process

	Dry matter, g/kg	Volatile matter, g/kg	Total nitrogen, gN/kg	Ammonia, gN/kg	Total Phosphorus, gP/kg	Phosphate, gP/kg
Digestate	32±3	21±2	2.25±0.4	1.61±0.3	0.36±0.01	0.079±0.01
Screw press solid fraction	231±12	198±10	4.62±0.8	nd	1.92±0.01	nd
Screw press liquid fraction	21±5	11±3	2.20±0.3	1.60±0.3	0.25±0.02	0.077±0.01
Centrifuge solid fraction	187±12	130±11	3.74±0.3	nd	1.54±0.02	nd
Centrifuge liquid fraction	9.4±1.2	3.6±0.6	1.66±0.2	1.46±0.2	0.15±0.01	0.076±0.02
Ultrafiltration centrate	21±2.2	9.5±1.1	1.52±0.5	1.31±0.1	0.19±0.02	0.078±0.01
Ultrafiltration filtrate	7.1±0.5	3.5±0.3	1.56±0.3	1.42±0.1	0.08±0.02	0.078±0.03
Reverse osmosis centrate	25±2	12±0.9	5.27±0.8	4.37±0.6	0.26±0.01	0.1±0.03
Reverse osmosis permeate	< 0.1	< 0.1	0.08±0.05	0.07±0.06	< 0.01	< 0.01

nd: not determined;

The mass balances of the process for the two treatment systems are reported in figure 3 and 4. These put under light that some 50% of water originally present in digestate can be recovered (43% for cows effluent and 46% for piggery effluent) while considering the final fate of nutrients 41% of nitrogen is recovered in the reverse osmosis centrate when treating piggery effluents but only 17% when treating dairy cows digestate. On the other hand, phosphorus is recovered in the solid streams originated from screw press and centrifuge: more than 80% of P is present in those streams for both the monitored case study.

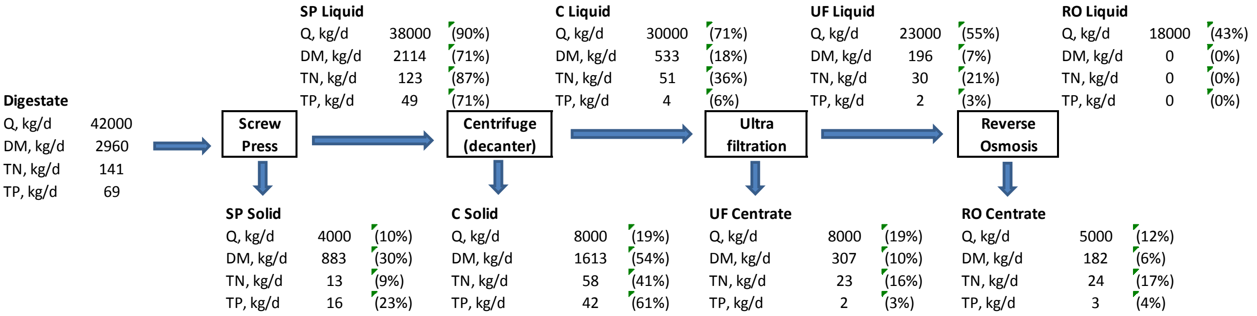

Figure 3 – Mass balance for the system treating digestate of dairy cows effluents

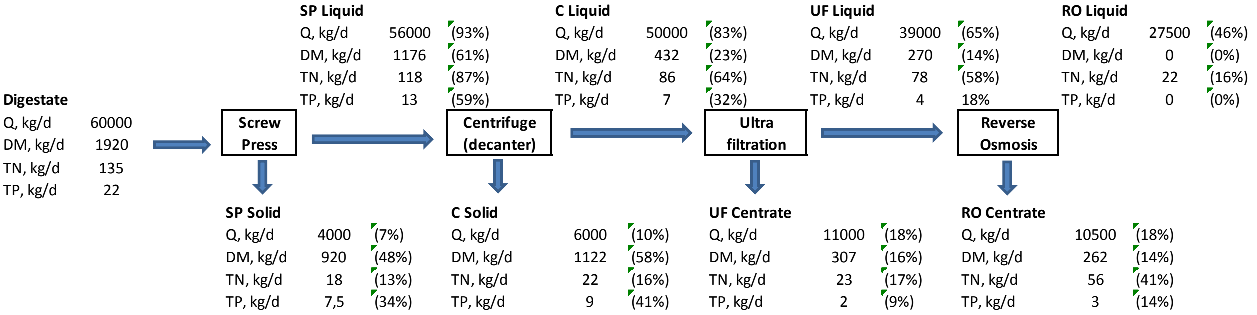

Figure 8 – Mass balance for the system treating digestate of piggery effluents

If nitrogen is the major target this can be further separated by means of a (cold) stripping process adding alkali and varying the pH in the range > 10 as it was the case in these plants [13].

3.4 Techno-economic assessment

The techno-economic assessment considered both capital (capex) and operational (opex) costs. The capital costs for the dryer, stripping and membrane systems were amortized over a period of 10 years considering an interest of 3%. The flowrate treated in the same period was considered so to determine a specific value referred to a single cubic meter of digestate treated in the system. In the same manner, operational costs for energy, chemicals, labor/service were considered and referred to the treated digestate so to obtain a specific value to be added to the capex. Table 6 reports a summary of the calculated costs. Clearly, costs estimation is a difficult exercise since there are great uncertainties on industrial investments and running costs. However, a first estimate, at least for the considered case studies, can be defined and compared with other similar researches.

The capital cost of a dryer treating 30 m^3 per day was estimated in 300,000 € with an amortization span of 10 years the corresponding capex was calculated in 2.74 €/m^3. The specific costs for energy were calculated in some 1.00 € per m^3. Requested chemical is sulfuric acid, for a corresponding cost of 1.00 €/m^3. The costs for personnel/service were estimated in 1.30 €/m^3. The corresponding total specific cost was some 6.04 €/m^3.

The investment cost for a stripping system treating up to 100 m^3/d was estimated in 750,000 €. The corresponding specific amortization is 1.58 €/m^3. The installed power in our study was around 40 kW working 24 hours per day. The specific cost is therefore 1.06 €/m^3. Chemicals used in the stripping system are soda or $Ca(OH)_2$ for pH correction above 9, and sulfuric acid for ammonium sulfate recovery. Costs for chemicals were estimated in 1.5 € per m^3. As for labor and service we considered 1 person per year fully dedicated to the system and some additional costs for a total of 1.3 €/m^3. The total specific costs was calculated in some 5.44 € per m^3 of digestate treated.

When considering the membrane system the investment cost is particularly high but so is the treated digestate so the specific cost is only 2.74 €/m^3 as for drying. The installed power for the two membrane systems considered in this study were around 50 kW. The corresponding specific cost was 1.85 €/m^3. Costs for used chemicals were associated with flocculant for the decanter and the solutions for membranes cleaning. Specific costs were estimated in 0.33 €/m^3 while costs for personnel / service were high because of the need for a skilled person. These were some 2.05 €/m^3 for a total specific cost of 6.97 €/m^3 treated.

Beside the costs, the specific peculiarities of the systems should be mentioned: a membrane system can recovery half of the water content of digestate in a virtually pure for. So, half of the volume is reduced while water of very good quality is recovered. On the other hand the dryer system can treat only part of the digestate (unless external heat is added) and the stripping system maintain unaltered the volumes treated.

Despite all these uncertainties and boundaries conditions it is important to emphasize how determined costs are more or less in line with those reported for German case studies by the IEA [7].

Table 6 – Costs analysis for the three technologies considered. All costs are in € per m^3 of digestate treated.

Cost item	Dryer	Stripping	Membrane
Capital cost (amortization)	2.51	1.58	2.74
Energy (power)	1.00	1.06	1.85
Chemicals	1.00	1.50	0.33
Labor / service	1.3	0.3	1.05
Total estimated costs	5.81	5.44	6.97

4. Conclusions

Five full scale treatment systems for anaerobic digestate treatment and nutrients recovery were monitored. The studied systems were drying, membranes and stripping. The systems worked properly and gave good results which are however quite different: membranes systems can recovery pure water while reducing the digestate volume, while drying system because of heat limitation can treat only part of the digestate although very effectively. The stripping system allowed for the recovery of less than 40% of the influent nitrogen and do not change the volume of the residual part. Costs for operations, including amortization of capital costs are in the range 5.40 – 6.97 € per treated m^3 of digestate and in the order stripping < drying < membranes. These results are in line with similar studies carried out around Europe.

Acknowledgments

This study was funded through the Riducareflui project. The Veneto Region and Veneto Agricoltura Spa are gratefully acknowledged for the financial support of this initiative.

References

1. Mehta CM, Khunjar WO, Nguyen V., Tait S., Batstone DJ: Technologies to Recover Nutrients from Waste Streams: A Critical Review. Critical Reviews in Environmental Science and Technology, 45(4), 385-427 (2015)
2. Buckwell A, Nordang Uhre A, Williams A, Poláková J, Blum WEH, Schiefer J, Lair GJ, Heissenhuber A, Schiessl P, Krämer C, Haber W: The Sustainable Intensification of European Agriculture. A review sponsored by the RISE Foundation (2015)
3. European Biogas Association EBA: Biogas and Biomethane Report 15. Annual statistical report of the European Biogas Association on the European Anaerobic Digestion Industry and Markets (2015)
4. Möller K, Müller T: Effects of anaerobic digestion on digestate nutrient availability and crop growth: A review. Eng. Life Sci., 12, 242–257 (2012)
5. Vaneeckhaute C, E Meers, E Michels, J Buysse, FMG Tack: Ecological and economic benefits of the application of bio-based mineral fertilizers in modern agriculture. Biomass and Bioenergy 49, 239-248 (2013)
6. Fuchs W., Drosg B. (2013) Assessment of the state of the art of technologies for the processing of digestate residue from anaerobic digesters. Water Sci Technol. 67(9), 1984-1993

7. IEA Bioenergy: Nutrient Recovery by Biogas Digestate Processing. ISBN 978-1-910154-15-1
8. Bernet, N., Béline, F.: Challenges and innovations on biological treatment of livestock effluents. Bioresour. Technol. 100, 5431–5436 (2009)
9. Arbor project. Biomass for Energy. Inventory. Techniques for nutrients recovery from digestate.
10. Pöschl M, Warda S, Owende P: Evaluation of energy efficiency of various biogas production and utilization pathways. Applied Energy 87, 3305–3321 (2010)
11. Bonmatı´ A, Flotats X: Air stripping of ammonia from pig slurry: characterisation and feasibility as a pre- or post-treatment to mesophilic anaerobic digestion. Waste Management 23, 261–272 (2003)
12. Adani F.: Sustainable management of nitrogen and nutrients. BioCycle, 54-57 (2011)
13. Ledda C., Schievano A., Salati S., Adani F.: Nitrogen and water recovery form animal slurried by a new integrated ultrafiltration reverse osmosi and cold stripping process: a case study. Water Research, 47, 6157-6166 (2013)
14. APHA 1998. Standard Methods for the Examination of Water and Wastewater, 20th ed., American Public Health Association, Washington DC