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Research article

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

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A B S T R A C T

The sustainable production of fertilizers, especially those based on phosphorus, will be one of the challenges of this century. Organic wastes produced by the agriculture, urban and industrial sectors are rich in nutrients which can be conveniently recovered and used as fertilizers. In this study five full scale systems for the recovery of nutrients from anaerobic digestate produced in farm-scale plants were studied. Monitored technologies were: drying with acidic recovery, stripping with acidic recovery and membrane separation. Results showed good performances in terms of nutrients recovery with average yields always over 50% for both nitrogen and phosphorus. 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 virtually pure water (up to 50% of the treated digestate) reducing the digestate volume, while drying, because of the limitation on recoverable heat, could treat only a limited portion (lower than 50%) of produced digestate while stripping suffered some problems because of the presence of suspended solids in the liquid fraction treated. Specific capital and operational costs for the three systems were comparable ranging between 5.40 and 6.97 € per m^3 of digestate treated and followed the order stripping > drying > membranes. Costs determined in this study were similar to those observed in other European experiences reported in literature.

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 (Mehta et al., 2015). These issues are of major concern especially when considering a possible 9 billion population at 2050 and the necessity to sustainably produce more food through agriculture intensification on a global scale (Buckwell et al., 2015).

Nutrients, however, are present in abundance in waste streams: nitrogen and phosphorus contents are typically 1 kgN/ton and 0.25 kgP/ton in food waste (Micolucci et al., 2016), and 2 kgN/ton and 0.5 kgP in waste activated sludge at 5% dry matter (Leite et al., 2016). On the other hand, typical nitrogen and phosphorus concentrations range between 5 and 15 kgN/ton and 0.1 and 1 kgP/ton respectively in cattle and chicken manure (Giuliano et al., 2013). These nutrients remain in digestate after anaerobic digestion and, after a proper treatment, can be recovered in a concentrated form which can be conveniently transported.

Among the different agricultural, urban and industrial waste streams, livestock effluents because of their abundance, ubiquitous presence and characteristics are of primary interest for nutrients recovery. In fact, the number of heads in EU28 can be estimated in 100 million dairy cows and cattle, 100 million pigs and 1.5 billion poultries (European Commission – DG Environment, 2014; Flotats et al., 2013). The resulting annual production of manure is estimated in some 150 million tons for pigs, 450 million tons for cattle slurry, 300 million tons for cattle dung, and 110 million tons of chicken manure, for a total of 1380 million tons per annum (European Commission – DG Environment, 2014). Part of this material is used directly on fields after open-air stabilization but a considerable portion is stabilized through anaerobic digestion. Anaerobic digestate can be therefore considered as a new mine for fertilisers recovery (Flotats et al., 2013). Noticeably, according to

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data of the European Biogas Association (European Biogas Association EBA: Biogas and Biomethane Report, 2015), over 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 the residual complex organic matter, such as lignin, and the inorganic part, including N, P and K, remain in digestate: during the digestion process the major part of nitrogen bound to organic matter will be released and then found in the soluble fraction as ammonium (NH_4^+) while the remaining part will be in the particulate fraction. The same process is valid for potassium, while phosphorous will be mainly present in the particulate fraction. In fact, also P released in the soluble fraction in the form of phosphate during the anaerobic digestion process will be largely precipitated because of the immediate reaction with soluble cations (i.e., calcium, magnesium, iron ….).

Digestate, which is rich in nutrients, can be therefore directly used as a renewable fertilizer because of its contents of stable organic carbon and nutrients (Möller and Müller, 2012; Vaneeckhaute et al., 2013) or, when the nutrients loads are in excess in a given area, can be further treated for nutrients recovery in concentrated forms to be then translocated at sustainable prices in different agricultural areas (Fuchs and Drosg, 2013; IEA Bioenergy, 1015). The excessive presence of nutrients loads and the necessity to control their presence in specific areas is a well-known problem in some European Countries and Regions, both in north (Denmark, Belgium, Netherlands, northern Germany, Brittany) and southern (Catalonia and Aragon, Spain, and the Po valley, Italy) Europe (Bernet and Béline, 2009).

Digestate can be therefore the mine for fertilizers production in a circular economy vision: this virtuous process is however hindered by legislative constrains for the time being. In fact, the use of bio-based fertilizers is not established yet, and the legislative framework is not encouraging this opportunity: most of these digestate-derived products, despite their characteristics, similar to those of commercial fertilizers, are not classified in any way (Möller and Müller, 2012; Vaneeckhaute et al., 2013).

Among the different commercial options for digestate treatment and nutrients recovery the most relevant are drying, stripping, 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 fraction (Fuchs and Drosg, 2013; IEA Bioenergy, 1015; Bernet and Béline, 2009; Arbor project; Monfet et al., 2017; Sheets et al., 2015).

Here, we have considered the full-scale applications of technologies including stripping, drying, and membranes, the most common technologies for the treating of digestates originated from farm anaerobic digestion plants treating different livestock effluents and energy crops in the Po valley, northern Italy.

Drying consists in removing water in digestate and concentrate the residual fraction by using hot air. In fact, 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 e.g., (Fuchs and Drosg, 2013; IEA Bioenergy, 1015; Arbor project; Sheets et al., 2015; Pöschl et al., 2010). 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 in biological terms. Ammonia nitrogen can be removed with vapor or kept in the digestate if it is acidified through the addition of mineral acids. If removed with vapor, nitrogen can be then recovered by means of acidic scrubbing or reverse osmosis as ammonium sulfate, when H_2SO_4 is used, ammonium nitrate, when HNO_3 is used, or as concentrated ammonium solution (in water). In general, because of the diluted feedstock used in the digester, the heat amount recovered from the CHP unit is not sufficient for the complete drying of all produced digestate which is normally characterized by a water content of around 90% (Monfet et al., 2017; Sheets et al., 2015; Vaneeckhaute et al., 2017). Additional heat can be however recovered from the CHP off gas by means of dedicated gas-water heat exchangers. This will allow for further removing of some water from digestate.

In the stripping systems, digestate undergoes to one or more pre-treatments for solid/liquid separation and the liquid stream is then sent to a packed bed tower where ammonia (NH_3) is stripped and physically transferred from the aqueous to the gas phase. This gas stream passes then in a second system (typically another packed column system) where NH_3 is absorbed in an acidic media, normally sulfuric acid, producing ammonium sulfate at 25–35% (Fuchs and Drosg, 2013; IEA Bioenergy, 1015; Sheets et al., 2015; Bonmati and Flotats, 2003; Adani, 2011). The advantage here is that nitrogen is recovered in a pure form while other nutrients like K, P and stable C, remain in the treated liquid phase which can be used on fields. In case NaOH or other alkali solutions are used to increase pH, relatively high levels of Na^+ can be found in the liquid phase thus altering the salinity of this stream. This aspect should be considered when reusing this stream for agricultural purposes as the high salinity level can then influence the cationic exchange capacity (CEC) of soils (Tao et al., 2016).

In pressure-driven membrane filtration the liquid phase of digestate (after solid/liquid separation and further solids removal by means of centrifuge or cartridge) is treated in ultrafiltration (UF) and reverse osmosis (RO) systems. The produced concentrate from RO is rich in both macro and micro nutrients and has characteristics similar to those of vinasses obtained from distillation, a recognized fertilizer (Fuchs and Drosg, 2013; IEA Bioenergy, 1015; Masse et al., 2007; Ledda et al., 2013).

In this study, we considered the full-scale application of drying, stripping and membranes systems for nutrients recovery and concentration in livestock digestate. Beside the characteristics of obtained outputs (fertilizers), mass balances and efficiencies of the monitored technologies were determined. Finally, a techno-economic analysis was carried out to verify the effective sustainability of the process.

2. Materials and 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: two using a drying belt, one using a stripping column and two adopting membrane technologies. While the drying system can treat the solid fraction or digestate as a whole, stripping and membrane systems operate only on the liquid fraction of digestate after a proper solid/liquid separation step. Both drying belt and the stripping column were coupled with a scrubber to clean up the exhausted air and to recover ammonium sulfate in an acidic solution. These plants were monitored for a period of at least six months (on average, a period equivalent to at least 3 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 feedstock composition, the potential of biogas electrical power and the digestate treatment technology for each plant are reported. Beside the determination of chemical-physical characteristics, also economic data related to capital and operation costs were collected to define the economics of the studied techniques.