Drying and combustion of an anaerobic digestate: Results and economical evaluation of a demonstrative-scale plant

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***Abstract*—** *A demonstrative-scale drying-and-combustion plant, treating a third of the digestate produced in a large cattle slaughterhouse in Italy, was designed, built, operated, and monitored for two years in order to define its energetic, environmental, and economical performance. Raw and dried digestate, ash, as well as flue gases compositions, were monitored during the research period and mass balances were defined. Energy and chemicals consumption were accounted in order to obtain representative scenarios and to discuss the practicability of this in-situ approach. It resulted that the drying-combustion solution is interesting if: (a) the lower heating value (LHV) of the digestate is higher than 17,000-18,000 kJ per kg of dry matter, (b) the anaerobic plant is large, with a relevant production of digestate (more than 10 t d^{-1}), (c) the cost of conventional disposal of the digestate is higher than 50 € t^{-1}. The chosen technologies appeared adequate to respect the regulatory limits regarding emissions.*

Keywords*— *digestate, drying, combustion, anaerobic digestion, waste, bioenergy.

I. INTRODUCTION

The continuously increasing organic solid waste generation worldwide calls for management strategies that integrate concerns for environmental sustainability [1]. Due to the growing demand of meat in the world, the contribution of organic solid waste from meat industries to the global waste production is increasing [2]. Approximately, a fraction between 20% and 50% of animals' weight is not suitable for human consumption, and only a quota of this waste (depending on the applied technologies, the socio-economic context, etc.) can be used in other non-food applications. Considering that the bovine meat production reached 68 10^6 t (the overall meat production was estimated at $312\cdot10^6$ t) during the year 2014 [3], the amount of related organic waste is not negligible [4, 5].

It is well known that organic solid waste from meat producing industries is considered a suitable substrate for biogas production via anaerobic digestion, because of its high content of fat and protein [6, 7].

Nevertheless, anaerobic digestion process produces relevant amount of a solid residue (digestate) that contains all the recalcitrant substances that can't be converted into biogas. Digestate gained a controversial reputation in the last years. On the on hand, it contains nutrients and stabilized organic matter, and can be used as organic fertilizer and/or soil conditioner [8].

On the other hand, an excessive or non-optimized use of digestate in agriculture can have a negative impact on the environment. For example, digestate can emit relevant amount of residual methane, ammonia, and nitrous oxide, contributing to climate change and local pollution [9]. Moreover, digestate can pollute surface water and groundwater through nitrate runoff and leaching [10] and can contain pathogens and antibiotic residues [11].

Up to now, the agricultural use of digestate derived from anaerobic digestion has not been specifically regulated by the European Community and only local guidelines have been proposed, with the exception of the application of Good Agricultural Practices [12], as well as the European "Nitrate Directive" (91/676/EEC) that strongly limits the amount of zootechnical nitrogen that can be applied per hectare of agricultural soil.

In particular, in Italy, the limits for the application of digestate in agriculture are still controversial, especially when digestate comes from a co-digestion process that includes also organic waste such as wastewater treatment plants sludge. For these reasons, many industries that co-digested organic waste are required to dispose (in landfills or municipal solid waste incinerators) or post-treat their digestate; these practices have a significant economic impact.

This paper discusses an alternative approach based on the *in-situ* combustion of digestate, as already suggested by [13], in order to minimize the production of waste and allow the recovery of energy and of a fraction of the nitrogen for agricultural purposes. A demonstrative-scale plant was installed and operated for two years in an important cattle slaughterhouse in the north of Italy. The plant also included all the necessary facilities for the control of air pollutants.

II. MATERIAL AND METHODS

2.1 Anaerobic digestion plant

A wet mesophilic anaerobic digester serves a slaughterhouse in the north of Italy managing 750 heads of cattle per day. It treats approximately 40-50 t of organic waste per day. This corresponds to the daily production of organic waste of about 150,000-200,000 persons in Italy [14].

The waste is structured as follows: 50% liquid rumen digesta (SS = 5%), 20% centrifuged rumen digesta (SS = 20%), 20% centrifuged biological sludge from the internal wastewater treatment plant (SS = 18 %), 7% waste of fat processing (SS = 23 %), and 3% waste of pasta production from a nearby factory (SS = 21%).

The overall volume of the two working reactors is 2,000 m^3 and the electrical power generated is 500 kW.

The specific production of biogas of the treated waste was measured equal to 550±50 Nm^3 per kg of volatile solids. A centrifugal separator performs the solid-liquid separation of digestate.

The daily production of solid digestate is 12±2 t/d. The solid digestate is, at present, used in agriculture at a cost of about 60 €/t. The liquid fraction of digestate is treated in a conventional nitrification-denitrification wastewater treatment plant and then discharged into the public sewer.

2.2 Digestate drying and combustion

A third (4.2±0.2 t/d, 175±8 kg/h) of the daily overall production of solid digestate was treated in a full-scale moving conveyor dryer (provided by Scolari s.r.l., Ospitaletto, BS, Italy).

The dryer was operated at mid-low air temperature (70°C), with a thermal power consumption of 150 kW. The electric power consumption was 7.5 kW, mainly for the movement of the digestate (ventilation was considered as a part of the scrubbing unit, described below).

The drying process duration was variable as a function of the residual humidity of the digestate: humidity was continuously measured and the treatment time varied in order to grant a maximum of 15%. A reference time process can be assumed around 40-50 minutes. The optimal air flow rate was empirically established at 6,400 Nm^3/h, which can assure a maximum water evaporation of 130 kg/h (design data provided by the manufacturer).

The thermal energy was provided by the combustion of the dried digestate. The combustion unit (provided by Losi Alberto s.a.s., Pegognaga, MN, Italy) was designed to provide at least 150kW, in order to assure a self-sufficient process.

The burner was externally constituted of a triple-layer steel chassis and, internally, of a monolithic ring of refractory concrete (internal diameter: 60 cm, external diameter: 80 cm, depth: 50 cm) with a high content of alumina (>50%) in order to resist to corrosion.

A countercurrent heat exchanger (efficiency: 70%) was installed in order to allow the energy transfer from the combustion chamber to the dryer. The electric power consumption for water recirculation was 2 kW. The temperature of water in the heating circuit ranged between 70 and 90°C.

2.3 Flue gas treatment

The plant generated two separated flue gas fluxes: from the drying unit and from the combustion process. The industrial facility in which the plant was located must comply with the EU-IPPC Directive (2008/1/EC), and the local competent authorities defined the emission limits reported in Table 1.

TABLE 1
EMISSION LIMITS FOR THE DRYING AND COMBUSTION PROCESSES

Emission	Pollutant	Limit [mg Nm^{-3}]^1
Drying unit	NH_3	150
	SOx (as SO_2)	350
	Total particulate matter	10
Combustion unit	CO	500
	NH_3	150
	NOx (as NO_2)	450
	SOx (as SO_2)	350
	Total particulate matter	10

^{1}: dry gas, and reference O_2 = 5%.

The gas flux from the drying unit was treated with an acid scrubbing unit (provided by AUSTEP s.r.l., Milano, MI, Italy) in order to remove gaseous ammonia and dust particles. The vertical scrubber was designed to treat a flow rate of 6,400 Nm^3h^{-1}.

The electric power consumption for the ventilation was 4 kW. The contaminated gas was treated using a solution of sulphuric acid (in order to produce $(NH_4)_2SO_4$, ammonium sulphate), in a recycle loop. pH=4 set point was defined in order to modulate the consumption of acid, operating a constant process. The empty bed contact time of the reactor was 2 seconds, with a gas velocity of 2 m s^{-1}.

The combustion emissions were treated with a series of different specific processes. NOx were controlled using a non-catalytic process based on urea (aqueous urea solution at 32.5%), directly injected in the combustion chamber.

For this process, temperature must be included between 950 and 1,100°C. Temperature was continuously controlled with a thermocouple and eventually adjusted by modifying the amount of excess air.

Dust particles and SOx were removed in a two-step baghouse filtering process.

The first filter (total surface: 11 m^2, filtration velocity: 1.5 cm s^{-1}) was designed to achieve the removal of dust particles.

Then, $Ca(OH)_2$ was added to the gas flux in order to remove SOx ,and the second filter (with the same characteristics of the previous one) allowed the abatement of the $CaSO_3$ produced in the reaction.

During the abatement of SOx, temperature did not exceed 170°C.

A scheme of the entire process is reported in Fig. 1.

A trained worker was in charge to verify the functioning of the entire system at least one time per day, and to promptly repair any evident malfunctioning.

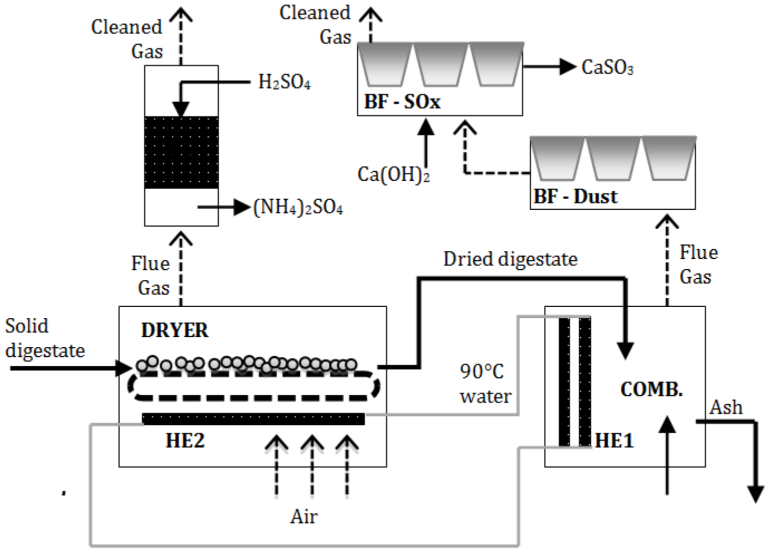

FIGURE 1: THE SCHEME OF THE ENTIRE PROCESS

2.4 Physical-chemical characteristics

Total Solids (TS) and Volatile Solids (VS) were determined for each sample of raw digestate, dried digestate, and ash, according to Standard Methods [15].

Lower heating value (LHV) was measured according to UNI EN 15400:2011.

Total nitrogen, phosphorus, potassium, copper, zinc, cadmium, chromium (total), zinc, lead, mercury, and arsenic, were measured according to EPA 3051A:2007 and EPA 6010C:2007 methods.

Analyses were carried out in duplicate, two-three times per month.

Gases characteristics were determined according to UNI 10169/01, UNI EN 13284-1/03 and EPA CTM-34, at least one times per month.

III. RESULTS AND DISCUSSION

3.1 Fluxes characterization

Table 2 reports the concentration of pollutants in the solid fraction of digestate, dried digestate, and ashes (bottom ash and fly ash are collected in a single storage and manually mixed before sampling).

TABLE 2
CHARACTERISTICS OF DIGESTATE (SOLID FRACTION), DRIED DIGESTATE AND ASHES (INCLUDING FLY ASHES FROM THE FIRST BAGHOUSE FILTER).

	U.M.	Digestate (solid fraction)	Digestate (dried)	Ashes
TS	%	25.6±1.5	92.8±2.8	98.9±0.2
VS	% TS	71.5±7.8	71.7±10.4	0.4±0.1
LHV	$\mathrm{kJ\ kg_{TS}^{-1}}$	-	17,398±1,751	-
Arsenic	$\mathrm{mg\ kg^{-1}}$	0.9±0.4	3.2±0.5	12.7±0.7
Cadmium	$\mathrm{mg\ kg^{-1}}$	<1	<1	<1
Chromium (total)	$\mathrm{mg\ kg^{-1}}$	3.0±0.7	10.6±0.9	42.3±1.1
Copper	$\mathrm{mg\ kg^{-1}}$	8.4±0.5	29.6±0.6	118.4±2.6
Lead	$\mathrm{mg\ kg^{-1}}$	<5	<5	<5
Mercury	$\mathrm{mg\ kg^{-1}}$	<0.5	<0.5	<0.5
Nickel	$\mathrm{mg\ kg^{-1}}$	2.2±0.3	7.8±0.4	31.0±0.9
Nitrogen (total)	$\mathrm{g\ kg^{-1}}$	9.6±2.0	9.7±1.8	0.50±0.7
Phosphorus	$\mathrm{g\ kg^{-1}}$	4.4±0.6	15.5±0.7	62.0±1.3
Potassium	$\mathrm{mg\ kg^{-1}}$	1,005.5±151.2	3,547.6±184.3	14,169.0±275.3
Zinc	$\mathrm{mg\ kg^{-1}}$	122.5±28.6	432.2±34.6	1,726.2±56.8

These results show that, with the exception of nitrogen, the drying and the combustion processes increases the pollutants' concentrations in the solid fractions. In the drying process, the increase is proportional to the increase of the concentration of total solids. In fact, the concentration ratio of TS is 3.62.

The same ratio about the other pollutants gives results included between 3.52 and 3.55.

Regarding the combustion process, the behavior of the pollutants is obviously different, since VS are burnt and converted into energy and gaseous products. Nevertheless, the mass balances of each pollutant (not reported) demonstrated that more than the 98% of the initial mass is concentrated into the ashes.

The entire process, therefore, concentrates the non-volatile pollutants in the ashes while nitrogen is converted to gaseous compounds and is conveyed with the flues gases.

Table 3 reports the characteristics of the flue gases coming from the drying and combustion processes, before and after the abatement units.

It can be observed that the emissions are below the limits reported in Table 1, meaning that the implemented technologies are adequate to respect the regulatory limits.

After the start-up period during which the treatment procedures were calibrated, the ammonia removal efficiency of the acid scrubber reached 97%, while the SOx removal efficiency of the $Ca(OH)_2$ process reached 80%.

The abatement of nitrogen oxides will be discussed in paragraph 3.2, since it occurs in the combustion chamber.

TABLE 3
CHARACTERISTICS OF THE FLUE GASES, FROM DRYING AND COMBUSTION PROCESSES (PRE- AND POST-SPECIFIC TREATMENTS, WHERE MEASURED).

		Drying		Combustion	
		Pre-scrubbing	Post-scrubbing	Pre-filters	Post-filters
Gas flow rate	$Nm^3\ h^{-1}$	-	6,465±314	-	566±32
Temperature	°C	68±4	47±5	223±26	148±24
CO	$mgCO\ Nm^{-3}$	-	-	-	248±63
NH_3	$mg_{NH3}\ Nm^{-3}$	227.3±18.7	7.0±0.5	-	<0.5
NOx (as NO_2)	$mg_{NO2}\ Nm^{-3}$	-	-	-	415±28
SOx (as SO_2)	$mg_{SO2}\ Nm^{-3}$	-	Udl*	1,630±269	297±41
Total particulate matter	$mg\ Nm^{-3}$	-	1.0±0.5	-	7.2±2.1

***udl: under detection limit.**

3.2 Mass and energy balances

Figure 2 reports the mass balances for digestate and nitrogen (excluding the contribution of urea for the abatement of NOx).

The drying process allowed an average reduction of the digestate weight of the 72% (mainly water evaporation, 125-130 kg h^{-1}, as expected from the technical characteristics of the dryer).

At the same time, the process removed the 70% of the nitrogen of the digestate.

It was measured that the nitrogen in the dried digestate was 92% organic, meaning that almost all the ammonia was stripped.

Regarding the chemicals utilization, the consumption of sulfuric acid for the ammonia abatement in the scrubber was measured at 130 kg d^{-1} (3.65 $kg_{H2SO4}\ kg_{NH3,removed}^{-1}$, +27% with respect to stoichiometric ratio).

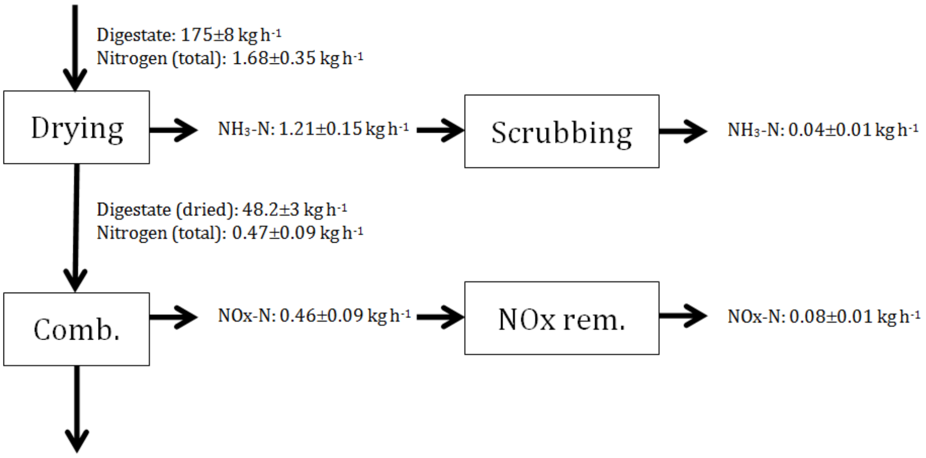

FIGURE 2 THE MASS BALANCES FOR DIGESTATE AND NITROGEN

After being dried, the organic solids were burnt in the combustion chamber and converted into ashes, CO_2, CO, SOx, NOx, and other oxidation products.

The mass of ashes was significantly lower than the initial mass of digestate (the reduction was about 93%). At the same time, nitrogen was almost completely converted to NOx. The non-catalytic process for the abatement of NOx requests the dosage of urea. The consumption of urea was estimated at 47.3 kg d^{-1} (1.58 $kg_{CO(NH2)2}\ kg_{NO2,removed}^{-1}$, +102% with respect to stoichiometric ratio).

The removal of SOx implied an average consumption of $Ca(OH)_2$ of 43.8 kg d^{-1} (2.41 $kg_{Ca(OH)2}\ kg_{SO2,removed}^{-1}$, +117% with respect to stoichiometric ratio). The plant produced about 140 kg d^{-1} of $(NH_4)_2SO_4$ and 72 kg d^{-1} of $CaSO_4$.

Regarding the energy balance, the LHV of dried digestate was measured equal to 17,398±1,751 kJ kg_{TS}^{-1}. This value appears quite low if compared to the most energetic solid fuels, such as anthracite (~30,000 kJ kg^{-1}), but it can be considered equivalent to other common low-value fuels such as lignite (~16,000 kJ kg^{-1}) or wood pellets (~15,000-20,000 kJ kg^{-1}) [16]. The thermal power generated by the combustion can be estimated at 778±80 MJ h^{-1}.

The hot combustion flue gases flux represents a heat loss: considering an average volume composition of 9% CO_2, 12% O_2, and 79% N_2, a heat capacity of 1.1 kJ kg^{-1} K^{-1}, and a temperature of 223±26 °C after the heat exchanger (average external air temperature: 15°C), it can be estimated a thermal flux of 171±39 MJ h^{-1} with the flue gases. The dryer requests a thermal power of 150 kW, which corresponds to 540 MJ h^{-1}. The overall average energy balance appears to be therefore positive (778 MJ h^{-1} – 171 MJ h^{-1} - 540 MJ h^{-1} = +67 MJ h^{-1}) but, since the thermal flux through the surfaces was not estimated and therefore considered, this value is also inevitably overestimated.

Nevertheless, the plant was self-sufficient for at least the 85% of the operation time, with exception of the cold season (external air temperature below 5°C) when it was not possible to reach the correct temperature of the water in the heat exchanger.

During winter (for about 45 days per year), it was therefore necessary to integrate the dried digestate with wood pellets in order to compensate the heat losses. In general, the amount of wood pellets necessary to guarantee the functioning of the process was 2.5 kg h^{-1}, which assured an additional heat flux of about 50 MJ h^{-1}. Probably, a better thermal insulation of the structure, or a heat exchanger with a higher efficiency, could avoid the need of this additional fuel.

Another possible solution could be the pre-heating of combustion air using the residual thermal power of the co-generator of the anaerobic plant or of the combustion unit itself.

3.3 Economic evaluation

The described cost analyses derive from the budget of the research program and to budget offers of vendors, refer to Italian prices and conditions, and are reported in Table 4 (two scenarios: the monitored demonstration-scale plant, treating a third of the digestate production, and a designed full-scale plant).

A life-span of 15 years, with a replacement of the bag house filters after 7.5 years and a 5% discount rate for the capital costs were assumed. For the chemicals, the following costs were considered: urea = 300 € t^{-1}, $Ca(OH)_2$ = 120 € t^{-1}, and sulfuric acid = 120 € t^{-1}.

The cost of the electric energy was assumed at 0.15 € kWh^{-1}. The cost of wood pellet was 195 € ton^{-1}. The yearly maintenance cost was estimated at the 5% of the demonstrative-plant cost, while it is reasonable to assume a 3% for the full scale plant. For the pilot plant, 30 minutes per day of a skilled worker at 30 € h^{-1} were necessary. For a full-scale plant it can be estimated 1 h d^{-1}.

The ash disposal cost was calculated considering that ash needs to be landfilled as special waste (100 € t^{-1}).

TABLE 4
COST ANALYSES REFER TO ITALIAN PRICES AND CONDITIONS

	Demonstrative plant (real)		Full plant (designed)	
	Equipment cost, €	Yearly cost, € y^{-1}	Equipment cost, €	Yearly cost, € y^{-1}
Dryer	105,000	10,115	250,000	24,085
Scrubber	60,000	5,780	120,000	11,560
Combustion	75,000	7,225	160,000	15,415
Other devices[1]	20,000	1,930	35,000	3,370
Plant costs	260,000	**25,550**	565,000	**54,430**
Urea	-	5,180	-	15,540
$Ca(OH)_2$	-	1,900	-	5,700
Sulphuric acid	-	6,510	-	19,530
Electric energy	-	17,750	-	55,000
Wood pellet	-	550	-	-
Maintenance	-	13,000	-	16,950
Personnel	-	4,680	-	9,360
Ash disposal	-	10,860	-	32,600
Running costs	-	**60,430**		**154,680**
Total costs	-	**85,980**		**209,110**

[1]: electric connections, storage of chemicals, …

At present, the slaughterhouse spends 270,000 € y^{-1} in order to dispose the anaerobic digestate in agriculture. The economic feasibility of the plant is therefore a function of its dimension. The studied demonstrative-scale plant treats a third of the overall production of digestate at a cost of 85,980 € y^{-1}, that is roughly the same cost of the disposal in agriculture (90,000 € y^{-1}), and the drying-combustion solution appears to be not particularly interesting. On the contrary, the designed full-scale plant would allow an estimated saving of 60,000 € y^{-1}, with a specific treatment cost of about 45-50 € t^{-1}. In this balance are not included the products of the process, $(NH_4)_2SO_4$ and $CaSO_4$. These products could have a destination in, respectively, fertilizers and cements production. However, due to the presence of impurities, it is much more plausible that these materials will have no economic value on the market. Moreover, the economic balance does not consider the cost of a building devoted to the plant. In the present study, a suitable warehouse was already available.

It should also be observed that the removal efficiency of NOx is high (80%) for a non-catalytic technology (typical range: 60-80%) and was obtained after a careful optimization of the process (positioning of the nozzles, urea solution concentration …). The reproducibility of a similar result could be not possible in other plants. For this reason, it was also evaluated a secondary scenario based on a catalytic process (titanium dioxide, honeycomb structure). A similar reactor could easily reach a NOx removal up to 90%, but the cost can be around 150,000 € (14,450 € y^{-1}) without a significant saving of chemicals (that are requested also in this configuration), reducing the economic interest of the drying-combustion solution.

IV. CONCLUSION

The present research shows that it is possible to minimize the production of solid waste from the anaerobic digestion process and, at the same time, to recover a fraction of nitrogen under a chemically stable form (ammonium sulfate). The process can be self-sufficient, even if it requires some particular attentions. It is in fact necessary to verify if the LHV of the dried digestate is high enough. From our results, it appears that the LHV should be higher than 17,000-18,000 kJ kg^{-1} in order to avoid the need of an additional fuel. Accordingly, an efficient thermal insulation is also required in order to minimize any heat loss. Nevertheless, the cost of the plant structure and of the reagents resulted high, and this solution appears feasible only for large anaerobic plants and/or particular conditions that imply an expensive disposal of the digestate (for example, when the digestate is considered a waste and cannot be used in agriculture). In the conditions of the present study, it was observed that the *in-situ* drying-combustion process is feasible for a digestate production higher than 10 t d^{-1} and for a conventional digestate disposal cost higher than 50 € t^{-1}.

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