The influence on biogas production of three slurry-handling systems in dairy farms

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Abstract

Handling systems can influence the production of biogas and methane from dairy farm manures. A comparative work performed in three different Italian dairy farms showed how the most common techniques (scraper, slatted floor, flushing) can change the characteristics of collected manure. Scraper appears to be the most *neutral* choice, as it does not significantly affect the original characteristics of manure. Slatted floor produces a manure that has a lower methane potential in comparison with scraper, due to: a lower content of volatile solids caused by the biodegradation occurring in the deep pit, and a lower specific biogas production caused by the change in the characteristics of organic matter. Flushing can produce three different fluxes: diluted flushed manure, solid separated manure and liquid separated manure. The diluted fraction appears to be unsuitable for conventional anaerobic digestion in completely stirred reactors (CSTR), since its content of organic matter is too low to be worthwhile. The liquid separated fraction could represent an interesting material, as it appears to accumulate the most biodegradable organic fraction, but not as primary substrate in CSTR as the organic matter concentration is too low. Finally, the solid-liquid separation process tends to accumulate inert matter in the solid separated fraction and, therefore, its specific methane production is low.

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Introduction

Anaerobic digestion is a robust and widely applied biochemical conversion process for the production of energy from biodegradable organic matter (Appels *et al.*, 2011). Livestock and agricultural waste, and energy crops are commonly used as substrates for their abundance and availability: in particular, dedicated energy crops (*e.g.,* maize, triticale, sugar beet, *etc.*) emerged in specific situations as a cost-effective option in order to increase the return of the invested capital (Gissén *et al.*, 2014). However, the ethical issues regarding energy crops have been the subject of continuous debate in the last years. In fact, the demand for energy crops appears to increase the direct and indirect competition among energy, land and food (Fritsche *et al.*, 2010). It becomes therefore important to enhance the energetic conversion of other low value substrates, in particular of abundant organic waste. In livestock farming, this approach corresponds to both digestion processes that efficiently converts organic matter into methane, and manure/slurry management systems that allows a complete and prompt recovery of fresh excreta (Holm-Nielsen *et al.*, 2009). As already outlined in the literature (Larney *et al.*, 2006; Martinez *et al.*, 2009), different handling systems can determine the *freshness* of the available organic matter (*i.e.*, the time elapsed between faeces deposition and collection/utilisation), influencing the quality of manure. Freshness is a key element, as biodegradation can occur also before the introduction of manure in the anaerobic reactor. Consequently, the longer the interval between the excretion and the beginning of the anaerobic process, the higher the amount of non-collected biogas (Møller *et al.*, 2004a; Gopalan *et al.*, 2013). From a practical point of view, manure collection is strictly related to housing systems and bedding options. Conveyance cleaning systems like scraping, flushing-scraping and flushing are common in free stall sheds with solid floors, while in sheds with slatted floors manure is removed by gravity, and litter is manually renewed if present in resting areas (Meyer *et al.*, 2011). Scrapers mechanically collect excreta preserving their characteristics, while flushing systems collects excreta hydraulically, diluting them. In housing facilities equipped with scrapers or flushing systems, the collection of faeces and urine is frequent (1-2 times per day), and manure freshness is always guaranteed. On the contrary, when slatted floors with underlying deep pits are adopted, a longer time interval occurs between faeces production and utilisation, and the biogas potential is reduced as a function of the retention time (Moset *et al.*, 2012). A decrease of the potential methane production of 4.3-6.6% after 15 days storage and of 7.7-11.9% after 30 days storage was observed (Møller *et al.*, 2004a, 2004b). When cow manure was stored for a period of 2 months, biogas losses were of 30-40% (Fabbri and Piccinini, 2012) especially during summer. In farms with deep litter, faeces are not removed for long periods (months) and undergo complex degradation processes that can be either aerobic, where oxygen is available, or anaerobic (Tait *et al.*, 2009). In both cases, a fraction of organic substance is converted into non-collectable carbon dioxide (aerobic process) or biogas (anaerobic process). It was observed that, in a litter of 6 months, the biogas potential of excreta was reduced by 40-50% if compared to the same fresh dairy manure (Fabbri and Piccinini, 2012). This loss can be partly balanced by the increased presence of straw in the litter (Garlipp *et al.*, 2011), even if the high content of lignocellulosic compounds represents a strong limit for the biologic degradation of materials such as straw or maize stalks (Song *et al.*, 2014). Only few fragmentary and disaggregated data are available regarding the correlation between manure management system and methane production. Applied technologies are rarely specified in scientific publications. In addition, the few available data in literature are difficult to compare, since obtained under different operative conditions. Comprehensive works that compare the influence of housing system are therefore rare (Rigolot *et al.*, 2010). The aim of this research was to discuss the methane potential production of manure samples from different handling systems.

Materials and methods

Farms and sampling

Three commercial Holstein-Friesian farms located in Lombardy (in the north of Italy) were considered during an experimental campaign lasting 18 months. During this period, the average number of cows in the considered sections of each farm was around 90. In order to reduce the influence on the biogas production among farms, all the dairy cows were fed with the same diet. Dry matter supply was 21-23 kg/d, and different feedstuffs were used in order to satisfy the productive needs of cows during seasons. During cold seasons, cows were daily fed with 26-28 kg of corn silage, 5 kg of alfalfa (*Medicago sativa*), and 10 kg of concentrate (maize and/or soy flours) with a vitamin supplement. During warm seasons, cows were daily fed with 26-28 kg of corn silage, 3-4 kg of alfalfa (*M. sativa*), and 6 kg of concentrate (cotton and/or sugar beet seeds). Samples of each effluent were taken twice a season, from summer 2012 to autumn 2013, for a total of 180 samples (three samples per sampling day, two sampling days per season, six seasons, five effluents). Samplings were carried out periodically on the same effluent every 4-8 weeks, according to the availability of free batch reactors for the determination of the biochemical methane potential (BMP). Manure samples were taken directly during the clean-up operation, from the manure collection basin, depending on the technology installed in each farm. Each representative sample was obtained mixing two sub-samples of 3 L. Samples were collected in 10-L plastic tanks and temporarily maintained (max. 24 h) at a temperature of 4°C before use.

Farm 1 - Free stall dairy system equipped with scrapers

Cows were housed in a free-stall barn divided into feeding and resting zone. Two rows of head to head free stalls were located between the two areas. The feed alley (3.5×80 m) and the resting alley (3×80 m) were covered with a rubber mat pavement and equipped with scrapers for manure removal. Scrapers were used twice a day. At the end of the alleys, manures were collected in a catch basin. Crossover passages between alleys were placed every 15 stalls. Manure in those areas was removed during daily maintenance and was not considered in this work. Samples were collected at the end of the scraper run, before the discharge.

Farm 2 - Free stall dairy barn equipped with flushing system

The feeding (5×60 m) and the resting alley (3×60 m) of cows were in convex (1.5% slope) and inclined (3% slope) concrete, in order to facilitate cleaning. The flushing flow rate in the considered section of the farm was 0.15 m^3/s. The flushing was carried out twice a day, usually at the time of milking, for 10 min. The flush system utilised mainly recycled effluent from the manure separation system or occasionally water from the municipal water supply network. The flushed wastewater was collected directly to a primary storage basin. Samples were taken just before the discharge. Wastewater was then pumped to a screw press solid-liquid separator (5 kW, treating 25 m^3/h of slurry), and both the liquid and solid separated fractions were sampled.

Farm 3 - Free stall dairy system equipped with slatted floors

Each section of the housing module consisted of a feed alley (3.5×50 m), two rows of head-to-head free stalls, a resting alley (3×50 m), and a row of single free stalls. Free stalls (128 cubicles of 185×120 cm) were equipped with rubber mats and cleaned manually. The floor of the feeding and resting alleys was made of perforated concrete with holes of 3.5 cm. Slurries were collected by gravity in deep pits located under the floor. Each housing module had its own separate pit, and every pit was emptied cyclically according to a time interval that varied from 12 to 20 days (14 days was the most common time interval). Samples were collected while emptying. During summer, foam was often present on the surface of pits, but was not sampled.

Samples characterisation

Total solids (TS) and volatile solids (VS) were determined for each sample, according to standard methods (APHA *et al.*, 2012). Analyses were carried out in triplicate. BMP tests were performed using a custom experimental platform made up of 18 identical parallel lines at controlled temperature. Each line was equipped with a 5-L batch plexiglass reaction tank coupled to a variable volume (max. 1 L) aluminium-polyethylene gas storage. Batch reactors were housed into thermally insulated containers (6 batches per container). Gas storages were connected in through automatic valves to a main unit equipped with a condenser to remove humidity, a drum counter for the volumetric measurement of the biogas (TGO5, Ritter Apparatebau Gmbh, Bochum, Germany) and a non-dispersion infrared/fuel cell gas analyser for oxygen, carbon dioxide and methane determination [Gasboard 3200 provided by WuHan Cubic Optoelectronics, Wuhan, China; the entire platform was assembled by Ambra Sistemi, Grugliasco (TO), Italy]. Biogas was automatically pumped from the storages to the analyser when the 80% of the maximum volume was reached. Results were automatically recorded on a PC. Reaction tanks were filled with 3 L of a mixture of inoculum and substrate. The mixture respected a 2:1 ratio between inoculum and substrate VS mass, in order to avoid any accumulation of fatty acids during the early days of digestion. The inoculum was obtained from the supernatant of the effluent of a mesophilic anaerobic digestion plant, operating with 50-days hydraulic retention time and treating dairy cow manure. The inoculum was filtered at 1 mm and kept at 40°C for 72 h before use in order to remove the residual, easily biodegradable organic compounds. At least two batch reactors for each set of measurements were used as control, measuring the BMP of the inoculum. At the beginning of each test, the headspace of the reactors and the storages were washed with N_2 for 2 min at 2 bars, and then depressurised to –0.4 bars, in order to remove residual oxygen and to identify any leakage of the system. Then the internal pressure was equilibrated to atmospheric pressure at the incubation temperature of 40±0.5°C. Temperature was continuously monitored and maintained constant through electric air heaters coupled with proportional-integral-derivative logic controllers. The reactors were incubated in the dark and mechanically stirred for a minute once a day. The incubation period lasts until the cumulated production of biogas had a daily marginal increase of less than 1% and, in any case, at least for 30 days.

Statistical analyses

Statistical analysis of the characteristics of different manures was carried out using SAS statistical software (SAS version 9.3, 2012; SAS Institute, Cary, NC, USA). Correlation analyses were carried out using the CORR procedure to study the relationship between type of manure and season as a function of TS, VS, and methane production. The same data were submitted to variance analysis (PROC GLM) to evaluate the seasonal effects. Methane production, TS and VS data were analysed using the analysis of variance (ANOVA) procedure (Waller-Duncan K-ratio t-test) to study the effect of the different manure handling systems.

Results and discussion

Characteristics of manures

Lactating cows produced about 50 kg of manure per day, corresponding to about 6 kg of dry matter per day (TS=12.0±1.3%, VS=78.1±3.3%, referred to the TS content of the manure sample; average values of samples taken during various seasons in the three farms). Table 1 shows TS and VS, representing the dry and organic matter content of manures; the results suggests an certain effect of handling techniques on manure characteristics. The most relevant comparisons are discussed, assuming scraping as reference point. In fact, scraping does not affect in substantial ways the characteristics of manure, since the collection is mechanical and very frequent.

Slatted floor slurry had a lower content of TS ($P<0.001$) and VS ($P<0.001$) than scraped manure. These results were probably due to (at least) two causes: i) slatted floor slurries remained for several days in the deep pit, where the rapidly biodegradable organic matter could be partly decomposed by heterotrophic and/or anaerobic bacteria and converted to gaseous products (foams were observed on the liquid surface); ii) deep pits were not mixed, and this could have favoured sedimentation or floatation of solids (that are never removed during the usual operations of the farm, as the emptying of the pit was never complete).

Raw flushed manure was very diluted due to its origin, and acted like a liquid. Therefore, a TS comparison with other manures makes no sense. On the contrary, VS can be compared since expressed as referred to TS. In raw flushed manure, VS were lower than in scraped manure ($P<0.001$) probably because flushing process was operated by means of stabilised liquid fraction, which had a higher concentration of inert solids (VS=61.7±2.4%), as also observed by Wilkie *et al.* (2004). TS variability within seasons was relatively high with significant differences only between samples collected in summer 2012 and spring 2013. A probable cause was that the liquid fraction of manure was stored in an open tank utilised also for the storage of rainwater runoff, as commonly in many farms, producing anomalies in the characteristics of the fluid during washing operations. Solid-liquid separation operated differently on VS. In particular, it produced a solid fraction with a significantly increased VS concentration (up to an average value of 91.3±2.9%), and a liquid fraction with a reduced VS concentration (64.8±3.1%). This behaviour was already observed by the authors on other plants (unpublished data) and by others (Jørgensen and Jensen, 2009), and was probably due to the fact that organic solids are larger than inorganic (Levine *et al.*, 1985). A clear trend of the characteristics of manures during seasons was not observed. Statistical analyses showed no significant differences ($P>0.05$) among seasons and total and volatile solids concentrations.

Biogas yield and methane content

Specific biogas productions from different manure handling systems are reported in Table 2, and are expressed as normal litres of methane

Table 1. Total and volatile solids content of manure samples collected (%, mean value±standard deviation of the six samples taken during each season).

Effluents		Summer 2012	Autumn 2012	Winter 2013	Spring 2013	Summer 2013	Autumn 2013	Mean
Scraper	TS	14.0±1.2	13.5±0.9	11.6±1.5	12.5±1.1	13.6±1.5	13.6±1.8	13.2±0.9
	VS	79.3±2.1	80.7±3.0	83.1±2.7	76.3±2.1	75.1±1.1	83.8±2.5	77.8±4.5
Slatted floor	TS	8.5±0.9	13.5±1.2	11.1±1.1	11.2±1.0	10.8±0.9	12.0±1.0	11.1±1.6
	VS	71.9±1.5	73.5±2.1	73.4±2.0	72.1±2.3	71.1±1.8	72.1±0.9	73.0±1.4
Flushing (raw)	TS	2.3±0.5	2.3±0.6	2.8±0.5	3.0±0.6	2.9±0.3	3.0±0.4	2.3±0.5
	VS	73.2±1.8	75.1±2.5	73.9±1.5	70.1±1.9	73.0±1.7	73.1±1.8	71.9±2.3
Flushing (liquid fraction)	TS	1.9±0.3	2.0±0.7	1.8±0.4	2.3±0.5	2.5±0.4	2.6±0.5	2.2±0.3
	VS	65.2±1.8	63.0±1.9	62.5±1.5	67.0±1.2	69.7±1.7	61.6±2.1	64.8±3.0
Flushing (solid fraction)	TS	34.4±2.5	29.8±1.9	30.3±1.8	27.9±1.1	28.3±1.1	29.3±1.0	30.6±2.7
	VS	94.2±2.1	94.5±1.7	92.2±1.8	87.2±2.1	90.2±2.1	89.2±1.7	92.3±3.4

TS, total solids; VS, volatile solids.

Table 2. Specific methane production (NL/kg_{SV}, mean value±standard deviation of the six samples taken during each season).

Effluents	Summer 2012	Autumn 2012	Winter 2013	Spring 2013	Summer 2013	Autumn 2013	Mean
Scraper	175±22	188±12	177±25	193±34	192±12	183±23	185±22
Slatted floor	152±14	160±11	166±17	161±15	168±23	168±24	162±19
Flushing (raw)	174±15	129±12	163±15	186±31	173±21	188±30	169±26
Flushing (liquid fraction)	193±28	205±29	200±22	209±21	209±35	217±37	205±28
Flushing (solid fraction)	141±16	145±27	139±31	155±23	144±11	156±32	147±27

Table 3. Methane concentration in biogas (%, mean value±standard deviation of the six samples taken during each season).

Effluents	Summer 2012	Autumn 2012	Winter 2013	Spring 2013	Summer 2013	Autumn 2013	Mean
Scraper	54.1±1.1	53.4±0.8	52.0±1.0	53.8±0.9	56.5±1.1	52.5±0.5	53.7±1.6
Slatted floor	48.1±0.9	48.6±1.2	50.9±0.8	53.2±1.0	55.5±0.7	51.3±1.3	51.3±2.8
Flushing (raw)	57.3±1.0	55.1±0.8	55.5±1.1	57.0±1.3	55.3±0.8	56.4±1.1	56.1±0.9
Flushing (liquid fraction)	50.3±0.7	49.1±1.3	51.3±1.0	51.0±1.1	49.7±0.8	50.8±1.1	50.4±0.4
Flushing (solid fraction)	56.9±0.9	55.8±1.2	60.5±1.1	57.4±1.1	59.3±0.9	58.7±1.1	58.1±1.7

produced per kg of VS subjected to anaerobic digestion. Little or no surface accumulation of solids was observed in samples before and during biochemical methane potential tests. Since biogas losses can be considered negligible after a few hours from excretion (Møller *et al.*, 2004a; Kirk and Faivor, 2012), manure handling systems that allow a frequent collection, such as scraping and flushing, was expected to preserve the specific methane potential. Instead, significant differences ($P<0.001$) in the specific production of methane of flushed manure was observed. This was probably due, as discussed in the previous paragraph, to use of stabilised liquid separated fraction of slurry during flushing, that lower the specific production of methane. Statistical significant differences ($P<0.001$) can be observed among raw flushed manure, flushed liquid fraction and flushed solid fraction. This behaviour was probably due to the washing process and, in particular, to the separation process. Highly biodegradable VS appeared to be concentrated in the separated liquid fraction that had a high specific production of methane. This result suggests that the solid-liquid separation process did not distribute VS equally, but operated a selection: the most productive fraction of VS appeared to be contained in the liquid fraction. This result was already observed by other authors (*e.g.* Liao *et al.*, 1984; El-Mashad and Zhang, 2010), that supported their findings considering the composition of the separated fraction. It was observed that fibrous (poorly degradable) compounds tend to accumulate in the separated solid fraction, lowering the specific production of methane. The valorisation of the liquid separated fraction cannot be performed in completely stirred reactors (CSTR), since the low concentration of solids. Other authors, *e.g.* Wilkie *et al.* (2004) and Rico *et al.* (2007), obtained interesting results using fixed-film anaerobic digesters.

Slatted floor manure was expected to produce a lower amount of methane. In fact, the observed specific production was 162±19 NL_{CH4}/kg_{VS}, significantly ($P<0.001$) lower in comparison with scraped manure (185±22 NL_{CH4}/kg_{VS}). As previously discussed, this was probably due to the long retention time in the deep pit. The slow but constant production of small bubbles of gas and foam was always observed in the deep pit. However, when considering the concurrent reduction of VS in the slatted floor manure (Table 1), we observed a more pronounced depletion in the methane yield. If the methane production is expressed as a function of TS (in order to include in the analysis also the variation of VS), scraper and slatted floor manure produced 144±17 and 118±14 NL_{CH4}/kg_{TS}, respectively. This aspect is not clearly visible if only specific biogas production (referred to the mass of VS) is considered. Nevertheless, when a substantial change in the characteristics of the solids occurs (especially when dealing with a transformation of similar manures), the specific production could be a misleading parameter during a farm scale evaluation. For example, considering negligible the effect of evaporation in the deep pit during the period of storage (Costa *et al.*, 2015, unpublished data), the calculated methane yield of 1 kg of raw scraped manure was 18.8±4.3 NL_{CH4}, while for 1 kg of slatted floor manure was 13.2±3.3 NL_{CH4}.

The methane content in biogas is reported in Table 3. The values remained between 50 and 58%, an interval that is comparable with that in the literature (Hill, 1984; Møller *et al.*, 2004b; El-Mashad and Zhang, 2010). Again, the lower values were observed in manure that was partially stabilised (slatted manure). No evident seasonal effects were observed.

Table 4. Waller grouping of different technologies and parameters.

Effluents	TS	VS	Methane production	Methane concentration
Scraper	B	B	B	C
Slatted floor	C	C	C	D
Flushing (raw)	D	C	C	B
Flushing (liquid fraction)	D	D	A	D
Flushing (solid fraction)	A	A	D	A

Technologies with the same letter (referred to a parameter) are not significantly different (level of significance for the comparison among the means =0.05). Letters are ordered from the highest to the lowest mean value (refer to Tables 1, 2 and 3). TS, total solids; VS, volatile solids.

Table 4 reports the Waller grouping from the ANOVA procedure, describing the statistical differences among different technologies and parameters, and supporting the previous discussion.

In general it should be considered that some minor differences among manures can probably be explained by other factors like feedstuff quality, genetic variety, conservation, microclimate, geopedology and soil structure of the areas where feedstuffs were produced, which can slightly influence the amount of undigested residuals even if the amount of feed was constantly monitored.

Energy consumption

Different manure handling techniques requires the installation and operation of different technologies. The scrapers were moved by two 3 kW electrical engines, twice a day (overall operation time: 80 min). The daily consumption of energy was 4 kWh. Assuming an average live weight (LW) of 700 kg/cow, the daily specific consumption of energy can be estimated at 65 Wh/t_{LW}. Flushing was operated through a centrifugal pump of 15 kW, twice a day (overall operation time: 20 min). The overall flushed manure (300 m^3/d) was then treated in a screw press solid-liquid separator (5 kW, operated 12 h per day). The overall daily consumption was estimated at 65 kWh. Since the farm was subdivided into two barns, and we considered only one of them, the daily energy consumption of the studied section was 32.5 kWh. Therefore, the daily specific consumption of energy can be estimated at 515 Wh/t_{LW}, which is a much higher value with respect to scraper. It can also be observed that the management of the flushing process is discretional (see, for example, the brief review reported in Wilkie *et al.*, 2004, where it is highlighted that differences of 2-4 times in flow rates are possible among farms with similar characteristics). Therefore, the value obtained in the present study should be considered as site-specific, even if the flushing can in any case considered as a technology with a high-energy and water consumption. In the studied farm, in fact, an average water consumption of ~2500 L/t_{LW} was calculated, and can be compared with other literature values (*e.g.*, 2260 L/t_{LW}, Williams and Frederick, 2001; 935 L/t_{LW}, Chastain *et al.*, 2001; 4000 L/t_{LW}, Kay Camarillo *et al.*, 2012).

Slatted floor handling system did not require any specific device, since it is based on gravity. The energy consumption for the transport of manure to the storage was not considered here, as the pump was operated every two weeks and the specific energy consumption was negligible. These values can slightly be varied as a function of the dimension of the farm, but the proportion between them should remain quite constant.

Conclusions

Manure handling can have an effect on the overall energetic balance of anaerobic digestion process. Scraping appears to be the most effective technology, as it does not significantly affect the characteristics of manure (that is adequate to be digested *as it is*) nor its energy content, and requires a minimal energetic consumption for collection. Slatted floor is a simpler technology that does not require the operation of any specific equipment, but a significant loss of methane can occur during the period of storage of manure in the deep pit. Finally, flushing requires much more energy than the other technologies, and the liquid fluxes produced are not fit to be directly introduced in the digesters commonly installed in Europe (mesophillic, wet technologies, CSTRs), since too diluted. The relatively high specific methane production of the liquid separated fraction could suggest its utilisation in other types of reactors, such as fixed film anaerobic digesters, even if the low solid concentration remains a problem. The solid separate fraction from flushing tends to accumulate the VS with the lower methane potential and therefore could be considered as suitable co-substrate only under particular circumstances, such as the adjusting of the humidity. In general, flushing appears to be a technology scarcely compatible with conventional anaerobic digestion processes: the unavoidable dilution makes the characteristics of the slurry unfit to be conveniently converted into methane. Also from the environmental point of view, the prompt recovery of slurries is an important aspect. In fact, methane losses between excreta deposition and collection have not only an energetic drawback, but also a clear environmental consequence: the emission of greenhouse gases. The proper management of slurries is therefore a primary issue in order to optimise the environmental sustainability of livestock farms.

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