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MONITORING SEASONAL EFFICIENCY OF DRY ANAEROBIC DIGESTION PLANT

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ABSTRACT: The lack of specific monitoring tools is a hurdle for dry anaerobic digestion plant performance studies, particularly for biochemical methane potential assessment. The work aims to suggest a solid-state BMP protocol to monitor the full-scale dry anaerobic digestion process. Physicochemical analyses, biomethane potential, and degradability data of different seasonal mixes fed in the reactor are provided.

Keywords: Dry anaerobic digestion; Biomethane Potential, Organic Loading Rate, Specific Methane Production; Full-scale plant efficiency

1. INTRODUCTION

Compared to wet anaerobic digestion, dry anaerobic digestion (AD) has a low energy requirement for heating and pumping, and less effluent production requiring dewatering, and it has been employed using various technologies; single or multistage operations (Rocamora et al., 2020). The Kompogas system originated in Switzerland in the 1980s and is a modified horizontal plug flow system with a slowly rotating internal axial mixer. The adopted mixing system increases the contact between microorganisms and organic substrate and degases the digestate (DG) before removal; the total solids in the reactor are held in the range of 23 – 28% to facilitate the flow.

The monitored plant is located in Trentino province (Northern Italy), for the organic fraction of municipal solid waste (OFMSW) and lignocellulosic green waste treatment. The thermophilic dry AD process is carried in two horizontal continuously stirred and mixed tank reactors (CSTR) (D1 and D2) (length 32 m) with a constant feed system (mixture of OFMSW and lignocellulosic material used as a bulking agent) for 21 days at 51°C (Bona et al., 2020). Part of the DG is anaerobically recirculated as inoculum; the other part is sent to the subsequent aerobic composting section after addition with yard waste to balance the C/N ratio of the starting mix. The composting process occurs in eight aerated biocells (intensive bio-oxidation phase) followed by the maturation phase in aerated static piles. Aerobic treatment of DG lasts about 24 days.

Monitoring of full-scale plants is strongly recommended to ensure proper management, energy exploitation, and biological stability. Still, the AD monitoring tools are configured mainly for the liquid and the gaseous phases (Andrè et al., 2017). The biomethane potential (BMP) assessment is a basic monitoring tool in AD. Still, the methods refer to wet samples in mesophilic conditions and the BMP test and it's not there yet an accepted standard protocol, that considers the very different conditions of the anaerobic process (Ohemeng-Ntiamoah and Datta, 2019; Hollinger et al., 2016). Moreover, very few studies investigated the scaling effect of methane production on specific substrates and the comparison of laboratory-scale BMP results with full-scale biogas production is little reported (Holliger et al., 2017).

The OFMSW is very heterogeneous: its composition in terms of biodegradable compounds (carbohydrates, proteins, and lipids) depends on several aspects, such as social and economic (related to the food availability), seasonal, consumer customs, generating source, collection time, and presence of touristic areas (Kobayashi et al., 2012). Recent work demonstrates that the geographical origin, the type of collection source, and the season might explain 24% of the food waste variations (Fisgativa et al., 2016). More recent studies have shown the quantitative and qualitative seasonal effects of organic waste on the AD process (Edwiges et al., 2018; Mozhiarasi et al., 2019; Arhoun et al., 2019; Trujillo-Reyes et al., 2022).

This work aims to use a test dry BMP protocol to monitor the seasonal performance of a dry AD plant of OFMSW.

2. MATERIALS AND METHODS

2.1 BMP tests and seasonal biodegradability of the feedstock

The BMP was assessed for the samples collected in the four seasons (Autumn 2017 – Winter 2017 – Spring 2018 – Summer 2018). The tests were done in three 20 L experimental reactors modified to sustain a dry AD process with the biowaste mix used in the full-scale AD Kompogas plant. The protocol adopted was the same as described in Bona et al., 2020. A perforated basket was used in each reactor to guarantee proper gas exchange. The biogas production is derived from the pressure changes measurement inside the reactor over time.

The feeding mix was prepared with DG as inoculum, screening green lignocellulosic material (SM) separated downstream the (anaerobic and aerobic) processes and used as a bulking agent (20% v/v), and OFMSW. The used materials were sampled in the plant at each season monitored. The VS ratio of inoculum and fresh matter was about 0.5.

The elemental composition (CHNO content) analysis has been assessed to calculate the theoretical stoichiometric biomethane potential (BMP_{th}). The ratio between BMP_{th} and experimental BMP (BMP_{exp}) provides information about the % of biodegradability (α) of the organic matter content of the biomass considered. The % of biodegradability (α) was calculated for OFMSW on each season.

$$\alpha = \mathrm{BMP_{th}}/\mathrm{BMP_{exp}} \times 100 \tag{1}$$

2.2 Seasonal monitoring plan of the full-scale AD plant

The full-scale plant was monitored yearly, from the Summer of 2017 until the Summer of 2018, considering five seasons: First Summer (June– July - August), Autumn (September – October – November), Winter (December – January – February), Spring (March – April – Mai), Second Summer (June – July – August).

For each season, the data collected focused on (a) plant performance, (b) feedstock properties used for feeding digesters, and (c) the BMP of the mixes feeding in the reactors.

The feedstock considered was OFMSW, recirculated DG as inoculum in the plant, and SM. The feedstock ratio feed in the plant was 60% OFMSW, 10% SM, and 30% recirculated DG. Each feedstock was analysed regularly (monthly), for pH, total solid content (TS), and volatile solid content (VS).

The biogas production, methane content in the biogas, and organic loading (OFMSW) data of the plant were measured daily. Organic loading rate (OLR), Hydraulic Retention Time (HRT), and Specific Methane production (SMP) have been calculated both monthly and seasonally. The equations used were:

$$\mathrm{OLR} = \mathrm{kgVS_{OFMSW}}/\mathrm{V}^{*}\mathrm{day} \tag{2}$$

$$HRT= V/\ kgVS_{OFMSW}/V*day \tag{3}$$

$$SMP=Nm^3CH_4/kgVS_{OFMSW} \tag{4}$$

The Methane production potential (MP) and the efficiency (η) were assessed by applying the following equation (modified from Hollinger et al., 2017).

$$MP\ (Nm^3CH_4) = QVS_{OFMSW}*BMP \tag{5}$$

$$\eta=[[(Q_{OFMSW}*VS_{OFMSW})+(Q_{SW}*VS_{SW})+(Q_{DG}*VS_{DG})]-(Q_{OUT}*VS_{OUT})]/ \\ [(Q_{OFMSW}*VS_{OFMSW})+(Q_{SW}*VS_{SW})+(Q_{DG}*VS_{DG})] \tag{6}$$

3. RESULTS AND DISCUSSION

3.2 BMP results and biodegradability of the feedstock

The protocol adopted allowed the measurement of the BMP of OFMSW by simulating the conditions of the Kompogas reactors. The BMP data are in Table 1 and the cumulative BMP results are in Figure 1.

Table 1. Biogas production and BMP results for each monitored season.

	Autumn	**Winter**	**Spring**	**Summer**
Biogas [Nm^3/kg_{SV}]	0.51 ± 0.09	0.57 ± 0.13	0.56 ± 0.02	0.59 ± 0.06
BMP [Nm^3CH_4/kg_{VS}]	0.27 ± 0.05	0.31 ± 0.09	0.33 ± 0.01	0.30 ± 0.04
α - OFMSW [%]	62± 12	73± 22	76 ± 2	71± 11

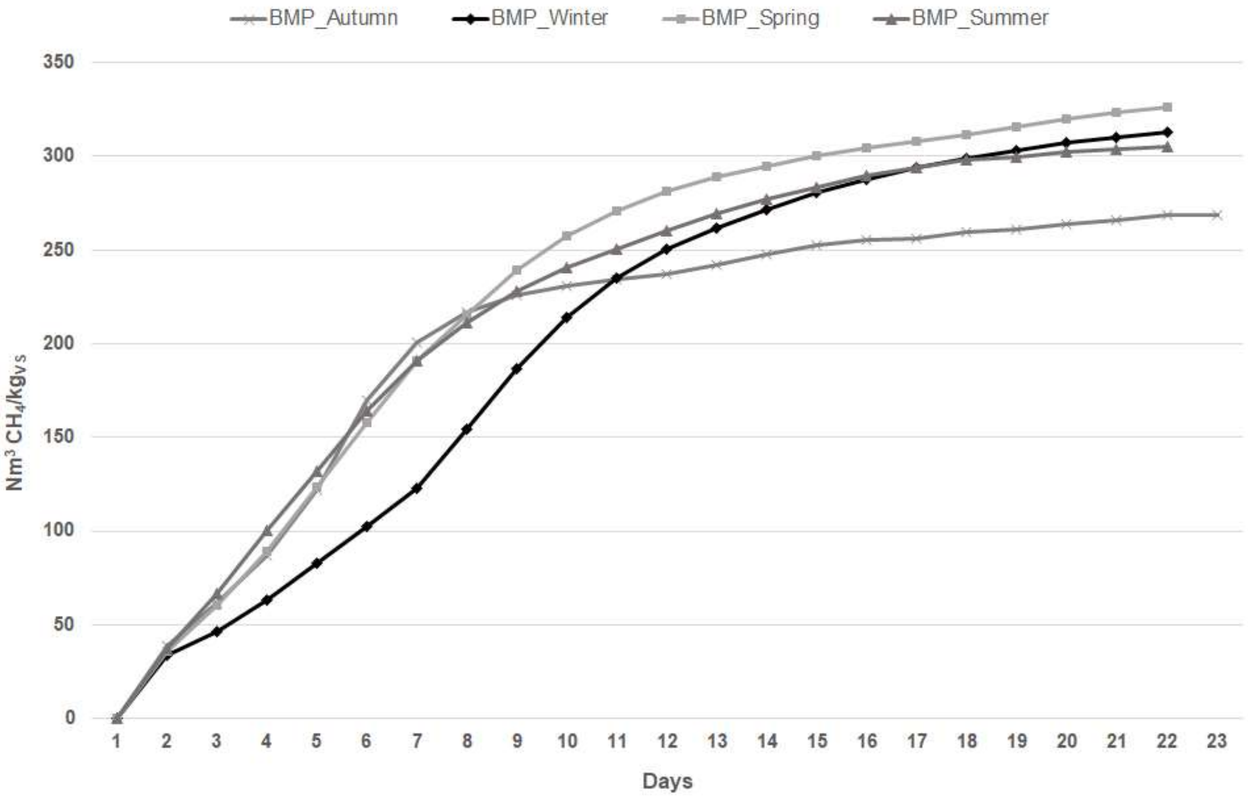

Figure 1. BMP cumulative results for OFMSW for each monitored season.

The BMP tests performed on dry conditions are challenging due to the lack of representative protocols and guidelines for very heterogeneous samples (Hollinger et al., 2016). The key issues concern the sampling methods, the inoculum origin concentration, storage and duration, and the different degradability of the lignocellulosic feedstock used as a bulking agent (Andrè et al., 2018). The obtained value (Tab. 1; Fig. 1) agreed with the results of previous works on seasonal organic waste (Edwiges et al., 2018; Trujillo-Reyes et al., 2022) and dry AD tests (Sun et al., 2019).

The protocol adopted was useful to monitor the seasonal difference of the feedstock processed at the industrial plant. The data showed very slight variations among seasons, although differences between Autumn and Spring regarding BMP and biodegradability are registered (Tab. 1).

The easily degradable compounds or slowly degradable organics in the OFMSW composition could affect the BMP (Alibardi and Cossu, 2015). As detected in previous work, the OFMSW collected in Spring has a higher methane potential (Trujillo-Reyes et al., 2022). The composition and quantity of OFMSW changed over seasons and the presence of fruit and vegetable waste seems to be the main issue (Fisgativa et al., 2016; Trujillo-Reyes et al., 2022). Differently, the higher content of lignocellulosic waste can determine a lower BMP. The concentration of lignocellulosic biomass in the dry process may result in the enrichment of hydrolytic and acidogenic microbes in the preliminary stages of the digestion and thus lead to high VS destruction and subsequently, a more apparent peak of biogas production than for wet AD (Brown et al., 2012). This could explain the higher biogas production in the Autumn and Winter BMP, compared to the other BMP (Tab. 1). The lignin content of SM can be a critical point in AD, since feedstock with high energy density compounds (such as lipids or easily degradable components of fruits and vegetables) have higher BMP value and biodegradability than compounds with high content of fibers (Li et al., 2013).

3.2 Performance of the full-scale plant during monitoring seasons

The data about the performance of the full-scale plant samples are shown in Table 2 and the monthly data of SMP and OLR are shown in Figure 2.

Table 2. Data of dry AD full-scale plant monitoring.

		Autumn	**Winter**	**Spring**	**Summer**
OFMSW	**DM** [%]	31.5 ± 1.4	33.8 ± 1.4	37 ± 3	37 ± 6
	SV [% DM]	73 ± 7	72 ± 7	65 ± 7	74 ± 5
	pH	4.72 ± 0.06	5.7 ± 0.4	5.4 ± 0.4	5.1 ± 0.7
SW	**DM** [%]	68 ± 3	68.07 ± 0.00	68 ± 3	70 ± 6
	VS [% DM]	60 ± 7	56 ± 3	67 ± 7	73 ± 5
	pH	8.85 ± 0.25	8.94 ± 0.16	8.74 ± 0.18	8.93 ± 0.02
DG	**DM** [%]	31 ± 7	28.6 ± 1.2	26 ± 3	27 ± 0.8
	VS [% DM]	51 ± 7	52 ± 3	55 ± 3	56 ± 5
	pH	8.40 ± 0.15	8.61 ± 0.03	8.61 ± 0.28	8.33 ± 0.15
VS_{OFMSW} IN [Mg]		530 ± 80	610 ± 80	600 ± 30	680 ± 60
VS_{SM} IN [Mg]		170± 40	170 ± 40	200 ± 30	220 ± 60
HRT [day]		22 ± 1	22 ± 5	22 ± 2	21 ± 3
η - VS removal [%]		65.78	68.46	72.45	71.25

The HRT values measured for each season ranged from 22 days in Autumn to 21 days in Summer (Tab. 2). The yearly mean value was 21.98 days. The VS removal efficiency (η) calculated for each season was higher in Spring and Summer than in Autumn and was about 70%. These differences are due to the composition and properties of organic waste. As seen before, the OFMSW of Autumn has lower BMP and biodegradability, which agreed with the lower VS removal as the full-scale plant monitoring showed. The higher content of lignocellulosic compounds in the waste made the organic matter less degradable. In Spring and Summer, the VS (Mg) of OFMSW and SM were higher compared to Autumn and Winter, highlighting the seasonal differences of both quantitative and qualitative organic waste collected (Tab. 2).

The SMP of the plant was higher in the Autumn and Winter compared to Summer (Fig. 2). The OLR (of OFMSW) calculated for each season considered did not show a significant difference among the seasons but was higher in Summer and in Winter, particularly in November and December (Fig. 2) for both quantitative and qualitative differences. The reported data highlighted the effect of a better SMP and process performance in correspondence to lower OLR (Fig. 2) and higher HRT (Tab. 2).

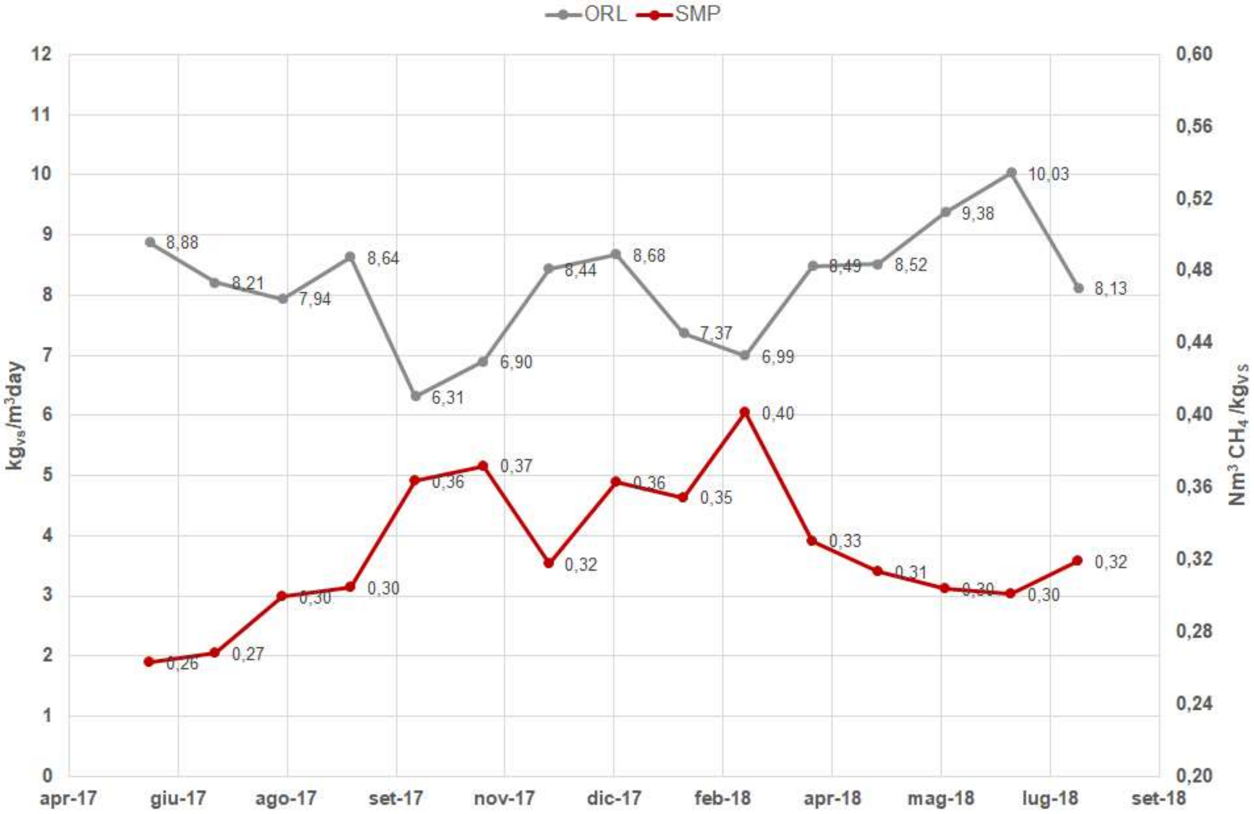

Figure 2. SMP and ORL of full-scale dry AD plant during the monitoring seasons.

3.2 Performance of the full-scale plant during monitoring seasons

The comparison of the BMP results and the data collected from the full-scale plant monitoring was calculated by seasonal MP value. The MP value was compared to the effective methane production of the plant (registered monthly). The percentage reported in Table 3 represents the average of the efficiency of methane production calculated for each season.

Table 3. Methane potential (MP) compared to Methane produced from the full-scale plant for each monitored season.

	Autumn	**Winter**	**Spring**	**Summer**
Methane produced: MP [%]	94 ± 4	80 ± 3	84 ± 10	69 ± 8

The efficiency of methane production (Methane produced: MP) was better in the Autumn; the methane production of the dry full-scale plant was in line with the BMP results (Tab. 2; Tab. 3). The reasons are due both to better process performance in full-scale plant and to the lower BMP of the OFMSW in Autumn. In Autumn the lower OLR and higher HRT guarantee a better exploitation and anaerobic degradation of the OFMSW, but at the same time, the lower BMP of the OFMSW collected in Autumn guarantees better process performance. Differently, in the Spring and Summer, the higher OLR and lower HRT determined lower yields, but also the higher methane potential and biodegradability of the OFMSW could have affected the process.

In recent years, many works aim to improve the knowledge of dry AD and the analysis of the performance of the process at full scale (Li et al., 2019; Rocamora et al., 2020; Zou et al., 2022). The BMP tests could provide useful information for full-scale process efficiency monitoring; recently it has assessed the suitability of the extrapolation coefficient of at least 0.8–0.9 (based on the BMP data and organic loads) to estimate the methane production of a full-scale AD plant (Holliger et al., 2017).

The OFMSW biodegradability and methane potential showed slight seasonal variability. However, the proper awareness of the seasonal trend of both, process efficiency and OFMSW properties, can be very useful to improve the management of an industrial AD plant.

From the data collected, the operational management and good biological process resilience were able to manage the qualitative and quantitative changes in incoming organic waste. Recent studies demonstrated that the redundancy of the microbial groups, which occurs when the communities significantly differ in composition, but all can carry out similar roles, was considered the major strategy to ensure the stability of methane production (Niu et al., 2015; Andrè et al., 2016; Pasalari et al., 2021).

Moreover, the work confirms the importance of proper knowledge of the feedstock combined with the knowledge of process operation to become a stable dry AD process (Rocamora et al., 2020).

4. CONCLUSIONS

The work suggests a protocol to perform a dry batch test to monitor the performance of a full-scale AD plant. The data highlighted slight seasonal differences (in plant performance, biodegradability, and BMP), probably related to the organic waste composition and the different lignocellulosic input and content of the organic mix fed into the plant. The standardization of plant operating conditions helps in maintaining high performances in terms of biogas production. The BMP results gave information about the degradability of the feeding mix and can be used to improve the operational management of the plant.

Combining the knowledge (qualitative and quantitative) of all the input feedstock loaded in the plant with the data of the monitoring plan is important to guarantee the stability and efficiency of the biological process.

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