**Application**

Identify the importance of operational parameters for optimising biogas production from an anaerobic digestion (AD) plant using silage and slurry as feedstock. Additionally, assess the potential profit from biomethane considering different biomethane prices and the emissions savings criteria from the Renewable Energy Directive.

**Introduction**

AD plants using agricultural feedstock offer an opportunity to increase renewable energy production, diversify the energetic matrix and land use, and secure the local energy supply. The co-digestion of crops and residues improves the robustness of the process and biogas production while improving waste management and mitigation of greenhouse gas (GHG) emissions. AD process has been continuously studied since 1980, with exponential growth in publications from the 2000s (Ampese et al., 2022) and several models have been developed to predict the behaviour of AD systems. Nevertheless, more recently statistical methodologies such as principal component analysis (PCA) are gaining attention as they can summarise complex data sets and indicate the crucial parameters to help operators (Kim et al., 2022). However, the optimisation of operational parameters on the efficiency of biogas production in full-scale AD plants using agricultural feedstock, considering also economic aspects and sustainability criteria from the Renewable Energy Directive (RED), is still incipient.

**Materials and Methods**

The analysis of operational parameters was performed on 6 months of data from an AD full-scale plant fed with grass silage and cattle slurry. The AD system was composed of two continuously stirred tank reactors (CSTR) working in series, C1 and C2, with working volumes (WV) of 2112 ± 37 m3 and 2611 ± 20 m3, respectively. The raw data provided are: daily feeding with silage (t/day) and slurry (m3/day), silage fraction in the feed (xSilage – dimensionless), feedstock flow rate (Q – m3/day), feedstock organic loading (OL – kg-VS/day) in terms of volatile solids (VS), biogas production rate from both reactors combined (BPR – m3/day), and percentage of methane (%CH4) in the biogas. The following operational parameters and dependent variables from the system were calculated considering the combined WV of the system (WVCS = WVC1 + WVC2):

Hydraulic Retention Time (HRT – day): $HRT = \frac{WV\_{CS}}{Q}$

Organic Loading Rate (OLR – kg-VS/m3 per day): $OLR =\frac{OL}{WV\_{CS}}$

Methane Production Rate (MPR – m3-CH4/day): $MPR=BPR×\%CH\_{4}$

Methane Yield (MY – m3-CH4/t-VS): $MY=\frac{MPR}{OL/1000}$

The analysis was performed as follows: i) descriptive analysis of data, ii) removal of outliers based on quartiles criteria, iii) standardisation of data, iv) PCA analysis, v) desirability function for optimisation of both profit and emissions savings for heat and only profit. The profit calculation considered a biomethane facility, with a digester of 4723 m3 of working volume, producing biogas with 55% methane from silage with 25% of VS in the wet weight. The price of the silage was fixed at €35 per t-wet. Data for capex and opex and emissions savings were obtained from Beausang et al. (2024). The statistical analysis was performed in RStudio 2023.12.1 Build 402.

**Results**

The PCA analysis indicated a higher correlation for OLR, OL and MY in the PC1. The absolute value of the correlation was similar for all variables, but OLR and OL were inversely correlated to MY. HRT had the highest correlation for PC2, followed by xSilage and %CH4. The PC3 was strongly correlated to MPR and followed by %CH4 and xSilage. Investigating the correlation among the variables identified for each PC, it was found that MY can be estimated by linear regression of OLR, with the MY increasing with a decrease of the OLR.

The desirability function results were plotted (Fig.1) against the price of biomethane and the OLR for different fractions of silage. The contour plots considering profit and emissions savings (Fig.1A) shows the desirability increases as the silage fraction and OLR decrease. As demonstrated by Beausang et al. (2024), the maximum silage in terms of VS in the feeding mix should be 70% to achieve emissions savings required for heating. Emissions savings lower than 80% resulted in desirability equals to 0. The minimum price of biomethane for a breakeven profit is €0.10 per kWh when 60% or 70% of silage in VS is used, as long as the OLR is lower than 2.12 kg-VS/m3 per day. For a gross profit margin of 33%, a biomethane price of €0.14 per kWh with 60% and OLR lower than 1.96 kg-VS/m3 per day. However, the MY using a low percentage of silage might be overestimated due to the lack of data in the data set with silage lower than 80% after the removal of outliers.

Figure 1: Contour plots of desirability function values obtained by maximising profit and emissions saving for heat (A) and only profit (B) for different prices of biomethane (Price CH4), organic loading rates (OLR) and fractions of silage (xSilage) in the feeding mix.

When the objective is only optimising the profit (Fig.1B), the silage fractions of 80 and 90% can also be considered. The minimum price for breakeven would be €0.11 per kWh for 90% of silage fraction and OLR lower than 2.17 kg-VS/m3 per day. However, a minimum price of €0.16 per kWh would be required to ensure a 33% gross profit margin.

**Conclusions**

The data analysis demonstrated that higher methane yield (MY) and profits from the AD of grass silage and slurry can be improved using organic loading rate (OLR) below 2.0 kg-VS/m3. The desirability function indicated that the minimum biomethane price of €0.16 per kWh is required to achieve a minimum 33% gross profit margin for all silage fractions. However, 70% of silage should be used to optimise profits and emissions savings. These findings can help the biomethane industry to optimise the operation of AD digesters to increase the profit while attending the renewable energy criteria. Besides, it highlights the opportunities for farmers to improve the slurry management and diversify activities by providing grass as feedstock to AD plants.

**References**

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