Technical, environmental, and economic evaluation of semi-continuous anaerobic digestion of pre-treated organic fraction municipal solid waste: effect of the organic loading rate on process performance

F. Demichelis[1], F. Deorsola[1], E. Robotti[2], T. Tommasi[1], D. Fino[1*]

[1]Department of Applied Science and Technology (DISAT), Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy
[2]Department of Sciences and Technological Innovation, University of Piemonte Orientale, Viale Michel 11, 15121 Alessandria, Italy
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Presenting author email: francesca.demichelis@polito.it

Anaerobic digestion (AD) is an established biotechnology able to stabilise the organic waste and convert it into biogas. Nowadays, the global warming challenge is boosting the application of renewable alternative sources of energy. Biogas is a bio-energy which can be stored and used directly without conversions and is able to face the problem of peak requirement and power failure (Scherzinger and Kaltschmitt, 2021). Due to these properties, AD faces climate change and resource depletion and produce clean energy (Hai et al., 2022) according to the Sustainable Development Goals.
The Organic Fraction Municipal Solid Waste (OFMSW) are a suitable feedstock for AD due to its organic matter availability and annually present. OFMSW is a heterogeneous substrate and made up of hard biodegradable components (as 18.6 % cellulose, 9.7 % lignin and 8.6 % hemicellulose) in accordance with (Pleissner and Peinemann, 2020), hence pre-treatments are required.

The aim of the present study is the investigation of AD of OFMSW in a semi-continuous stirred tank reactor under mesophilic conditions to test the effect of 6 different organic loading rates (OLR) on AD performances. The effect of OLR is studied on three different configurations of AD: hydrodynamic-cavitated OFMSW, enzymatically pre-treated OFMSW and non-treated OFMSW. The novelty of this study is the analysis of semi-continuous AD by considering the technical feasibility, economic profitability, and environmental sustainability and the optimal conditions of semi-continuous AD are detected through multivariate analysis.

The adopted approach consists of both experimental and modelling activities. The OFMSW used in the experimental test comes from a North Italy waste plant and it was pre-treated with hydrodynamic-cavitation and enzymatically, which have been selected in previous works of (Demichelis et al, 2023 under review).
Hydrodynamic cavitation (HC) was performed using a rotor/stator HC unit (Rotocav®, E-PIC srl – Mongrando, Italy) at 55 °C for 10 min according to (Bruni et al., 2010). by requiring 0.073 kWh/L.
Enzymatic pre-treatment was performed with enzyme 1 mL/g TS UltraPract® P2 (UPP2) which is a mix of cellulases, hemicelluloses, pectinases, and protease.
Semi-continuous AD is carried out in 1 L reactor (Duran, Germany) with a working volume of 0.8 L at 37 °C and the top of the reactor has three ports: one as inlet to feed the OFMSW in the reactor, the second to remove the digestate and the third to collect the biogas into a Tedlar (Germany) 5 L-gas bag. The tested OLR are selected by changing the hydraulic retention time (HRT) from 16 d to 6 d, which means OLR variations between 3.38-9 kg $_{VS}$/ m^3 d. Each AD configuration is tested in triplicate for a total of 9 reactors and each HRT was maintained at least for a period of time equivalent to two HRT to allow the pseudo-steady state could be achieved.
The starting HRT was selected according to the results obtained in batch AD of OFMSW carried out in (Demichelis et al., 2022). To evaluate the semi-continuous AD performance, the feed OFMSW and the removed digestate are characterised through the elemental analysis CHNSO (Elemental Macro Cube system (Vario, Germany), the total and volatile solids according to (APHA, 2006), total and soluble COD and total nitrogen were detected through a COD LCI 400 and a LCK 338 (HACH LANGE GHB, Germany) and quantified by a spectrophotometer 5000 D, (HACH, Canada), pH with a pH340 WTW pH-meter (Mettler Toledo, Germany), Biogas was analysed qualitatively by a biogas-analyser (GA5000, GMBH, Germany) and quantitatively by water displacement. After proving the technical feasibility, the economic profitability will be studied through CAPEX, OPEX and revenues analysis, and environmental sustainability will be studied through Life Cycle Assessment (LCA) with SimaPro 9.2.

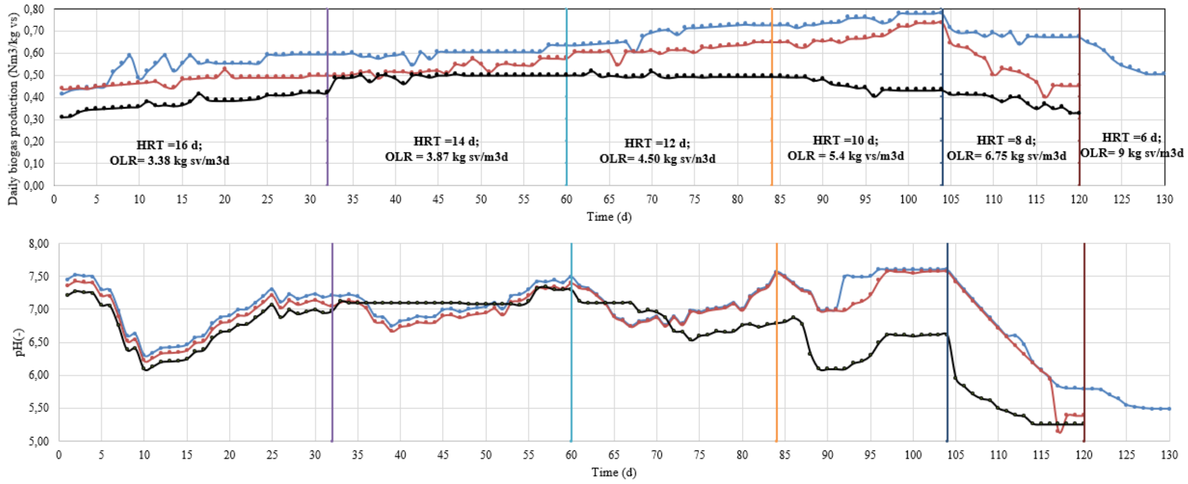
The preliminary results concern the characterisation of the OFMSW and the inoculum from mesophilic digestate of cow and agricultural sludge (CAS), which was employed to start the semi-continuous AD (Table 1).
The daily biogas productions and the pH values of the130 d of tests are depicted in Figure1.
Figure 1 proved that for HC-OFMSW semicontinuous AD the biogas production increases up to OLR=5.4 kg $_{VS}$/ m^3 d (HRT=10), whereas for E-OFMSW semicontinuous AD the biogas production increases up to OLR=4.52 kg $_{VS}$/ m^3 d (HRT=12), and for non-pre-treated OFMSW semi-continuous AD the biogas increases up to OLR=3.87 kg $_{VS}$/ m^3 d (HRT= 14). The obtained preliminary results proved that the pre-treatments have a positive effect on

semi-continuous AD, because they allow to work with higher OLR rather than non-pre-treated OFMSW. The pre-treatments make available the organic matter to micro-organism under higher OLR and lower HRT, without acidification accumulations as proved by the trend of pH values.
Specifically, among the two tested pre-treatments, the HC pre-treatment allows to work with the highest OLR which means the possibility to treat higher amount of OFMSW by considering the same reactor volume.
For HRT lower than 10 d the pH values drop due to the fatty acids accumulation which destroys the methanogen population.

Table 1. Physical and chemical properties of OFMSW and inocula.

	TS	VS	pH	C	H	N	S	C/N	TOC
	(%)	(%)	(-)	(%)	(%)	(%)	(%)	(-)	(g/kg)
OFMSW (mean)	19.32	96.76	5.31	48.42	6.76	2.97	0.20	16.3	24,995.82
OFMSW (dev.st)	0.61	0.53	0.22	0.51	0.70	0.32	0.12	1.4	114.92
CAS (mean)	5.82	70.3	7.74	40.62	3.09	7.92	0.03	5.12	12.04
CAS (dev.st)	0.12	1.0	0.12	0.61	0.07	0.11	0.01	0.12	0.24

Figure 1: Biogas and methane productions and pH values of the semi-continuous AD of HC-OFMSW (blue), E-OFMSW (red) and non-pre-treated OFMSW (black).



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