Energetic assessment of extrusion as pre-treatment to improve the anaerobic digestion of agricultural ligno-cellulosic biomasses

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Abstract
In 2013 the energy produced by renewable sources in Italy will be subjected to a reduction of the economic incentives supplied by the government. Consequently, to pledge to biogas plants an appreciable gain, the anaerobic process has to be optimized, improving the organic matter digestion of the biomasses. The extrusion, as feedstock pre-treatment, could be a valid solution to reach this aim. A biogas plant common blend feeding and the different biomasses composing it, were pretreated by an extruder and analysed in batch to determine the effect of the pre-treatment on the CH_4 yield increase. For biomasses positively affected by the pre-treatment also a simple energetic analysis was performed to evaluate the real energetic efficacy of the extrusion.

Introduction
In 2013 the energy produced by renewable sources in Italy will be subjected to a reduction of the economic incentives supplied by the government. Also the energy produced by anaerobic digestion plants (ADPs) was interested by these new regulations. National law (DM Sviluppo Economico 6th July 2012) further introduced a disincentive for ADPs using dedicated crops as feedstock. As a consequence, improving organic matter (OM) degradation and enlarging by-products amount in the digester diet, will be surely a necessity in future. This goal can be reached by the introduction of a biomass pre-treatment, as extrusion, before their inlet into the digester. Due to the defibration of the biomasses, extrusion process can improve OM digestibility and enhance hydrolysis, increasing the access for bacteria and enzymes to organic and edible compounds [1,2]. This can result in a biogas and energy production increase or in an acceleration of the anaerobic digestion process. At the same time, extrusion pre-treatment can limit problems related to mixing system and crust formation inside the digester, since extruded biomasses can be mixed more easily. Extrusion as a biomass pre-treatment in ADPs has been very less analysed in international scientific literature.
The aim of this study was to evaluate the real efficacy and the energetic efficiency of the extrusion, used as pre-treatment to improve the anaerobic digestion of different biomasses. The biochemical methane potential (BMP) test and the energetic evaluation were both performed on the blend feeding and on single feedstock composing it.

Material and Methods
Samples collection and extrusion pre-treatment
Biomasses and inoculum were collected in an ADP located in the Piemonte Region (north-west Italy), where no animal manures were used to feed the digester, but only agricultural silages: maize (MS), ryegrass (RS) and rice straw (SS). Extrusion was performed on each biomass and on their blend (BLEND), according to the ADP blend feeding composition, 53% of MS, 36% of RS and 11% of SS. The extruder used for the pre-treatment was produced by Lehmann Maschinenbau GmbH, Pöhl, Germany and developed by BTS Italia srl, Brunico, Bolzano, Italy. This machinery is composed of two twin-screws rotating in opposite directions that apply a thermo-mechanical strain on the biomasses, thanks to an electric engine of 74kW power. For each sample the pretreated amount was approximately 100kg of fresh matter. By means of an adjustable opening present at the outlet of the extruder it was possible to modify the extrusion intensity level. The extrusion effect was assessed at two different treatment intensities: exit slit opened at 100% and 60%, following indicated respectively as 100 and 60.

BMP test and chemical analysis
Batch measurements on the ultimate gas yield were carried out in a laboratory according to Stardard methods [3]. Each sample was mixed with the inoculum in a 3:1 ratio calculated on the basis of the volatile solids content, in 2 litres glass reactors connected to Tedlar® gas bags for collection of the produced biogas. Batches were flushed with N_2 and incubated at 40°C for 42 days. All samples were analysed in triplicate. A control sample with by inoculum alone was also digested in batch and its produced biogas volume was subtracted from the sample yields. During the experiment, batches were manually stirred at least once per day. Biogas and methane yields were monitored daily during the whole period of the experiment. Biogas composition was analysed by a Draeger XAM 7000 analyser with infrared sensors, whereas the biogas volume was determined by a Ritter Drum-type Gas Meter type TG05/5 volume meter. The daily biogas and methane yields were normalized to 0°C and 1013kPa. Each feedstock was analysed for pH, dry matter (DM), volatile solids (VS), NDF, ADF, ADL, proteins, lipids, starch and sugars by AOAC methods [4].
Biogas and methane yields of untreated and pretreated samples were statistically analysed through the one-way ANOVA test after confirmation that the variances were homogeneous by the Levene test. Samples showing significant differences were further analysed using the post-hoc Tukey's test (α=0.05).

Energetic evaluation
For the energetic evaluation, the electrical energy intensity of the extruder, expressed in ampere, and the tonnes of biomass processed per hour were recorded for each biomass and for the diet mixture during the two different intensity levels of pre-treatment (60-100).
Considering that the extruder had a triphasic electrical engine, the electric energy demand of the pre-treatment, expressed in kWh_{el}/t of fresh matter, was calculated for each sample and pre-treatment intensity level by the following equation

$$E_{extrusion} = \frac{V \cdot I \cdot \sqrt{3} \cdot \cos\varphi}{C \cdot 1000}$$

where V = 400V, cosϕ = 0.8 and I was the electrical intensity, which ranged between 48A (when screws spin freely) and 190A. C was the extruder capacity and ranged between 4.2 and 6.6t/h.
Electrical energy produced by untreated and pretreated biomasses, expressed as kWh_{el}/t of fresh matter, was calculated using the equation

$$E_{sample} = \frac{Y \cdot HHV \cdot \eta_{el}}{3.6}$$

where Y was the specific methane yield of untreated and treated samples, expressed in m^3 per tonnes of fresh matter, HHV (Higher Heat Value) was 39.79 MJ/Nm^3 and η_{el} was the co-generator (CHP) electrical efficiency estimated as 40%. The methane yield of the untreated biomasses was deducted from the yield of each pretreated biomass, to obtain the real methane yield increasing value.

Results and discussion
In Table 1 chemical composition of the blend feeding and analysed biomasses is shown. As attended, SS was the wettest biomass, since in Italy rice is cultivated in submerged soils and the straw was harvested few hours after the rice harvesting. Inorganic fraction, represented by ashes, largely prevailed in SS, which resulted in an ash content higher than 20% on DM. Proteins and fats were quite similar in RS and MS. In contrast, SS showed very lower percentage both of proteins and fats compared to the other biomasses. Also the sugar content in SS was very low, less than 1%. H-Cel and Adl prevailed in SS, respectively 43.2% and 7.1%, whereas Cel prevailed in RS, 35.5%. Considering the three analysed biomasses, MS showed the lowest content of ligno-cellulosic compounds. Blend feeding, mainly composed by MS, presented a very similar chemical composition.
Extrusion did not modify the chemical composition of the biomasses. The same results were observed in [1], where a similar machinery was employed to pretreat some biomasses. On the contrary, in [5] a reduction of 21% in Cel and Adl was observed, but in this case the extrusion was combined also to the water and CO_2 addition and heating treatment at 90°C, that caused an increase in depolymerisation.

Table 1. Chemical composition of analysed biomasses.

	DM	VS	Ash	Proteins	Fats	Sugars	Starch	H-Cel	Cel	Adl
Samples	[%]	[% on DM]								
Blend	35.1	86.9	13.1	8.1	2.7	2.6	18.1	19.4	26.9	4.1
Maize silage	36.1	96.0	4.0	8.6	2.9	1.2	27.7	15.0	23.3	2.9
Ryegrass silage	35.6	89.8	10.2	7.7	2.7	6.4	3.4	22.7	35.5	4.7
Rice straw silage	30.3	78.8	21.2	4.7	1.5	0.6	9.9	43.2	16.8	7.1

Extrusion significantly improved the CH_4 yield of analysed biomasses, except for SS (Figure 1). According to other studies [1,6], organic compounds contained in straw not digestible by anaerobic process, are very hard to be degraded by pre-treatments. Moreover the absence of more fat and solid size particles, as seeds, did not ease the extrusion action. In this trial the percentage of SS organic matter degraded during the BMP test was close to 58% both with and without extrusion. Pretreated blend CH_4 yield was higher than untreated blend of about 11.5-13.4%. Similar results were obtained also for MS, whereas RS showed a methane yield increase lower, 7.1-8.5%. Due to the homogeneity of the chemical composition of the biomasses, the CH_4 yield increase varied in a tight range for each. Results obtained in this study were comparable with the data obtained in [1] where some biomasses were extruded and then digested in anaerobic reactors for 90 days. In a previous study [7], 8-27% methane yield increases were highlighted after 30 days following extrusion respectively of grass and maize. Also in [7] the extrusion most relevant effect was observed for maize silage. Also the effect of extrusion on the CH_4 production rate was analysed. For each biomass, including SS, was observed the relevant acceleration of the organic matter degradation due to the pre-treatment both at 100 and 60 (Figure 2). Therefore, although extrusion was not able to increase the final degraded organic matter of SS, it improved SS anaerobic digestion, accelerating its organic matter degradation and reducing the degradation time of about 4 days compared to untreated SS (calculated on the production of 80% of the total CH_4 yield).

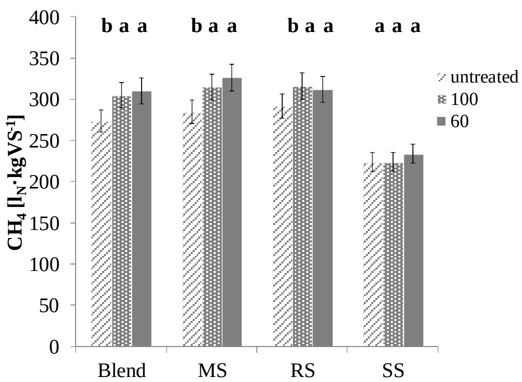

Figure 1. Mean methane yields of untreated and extruded (exit slit opened at 100% and 60%) biomasses in batch reactors. Values with different letters indicate significant differences.

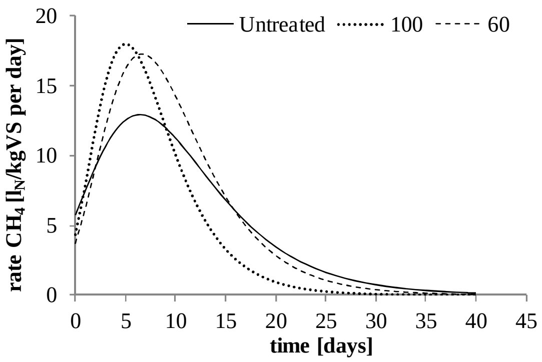

Figure 2. CH_4 production rate of untreated and pretreated rice straw silage (SS)

Energy requirement for the biomasses extrusion ranged between 9.2 and 23.8kWh$_{el}$ and it was well correlated to the extruder capacity (R^2=0.8610), expressed in tonnes of fresh matter extruded per hour (Table 2). According to the sample moisture, extruder capacity varied from 4.2 and 6.6 t/h, and no relevant differences were observed between 100 and 60. Extruder capacity, during blend pre-treatment, was low and highly affected by SS amount which reduced it. As attended, extrusion energy demand was higher when the exit slit was reduced to only 60%. This energy demand increase (*ΔE100-60*), expressed as percentage, was well correlated to the extruder capacity (R^2=0.9947), but only when the single biomasses were considered. Considering the low extrusion capacity during the blend pre-treatment, a higher *ΔE100-60* was expected. For the other biomasses, *ΔE100-60* was 10.9% for MS, 11.5% for RS and 20.0% for SS. This data confirmed SS high resistance to the pre-treatment, in fact the energy input to pretreat SS was considerably higher than the one necessary for RS and MS.

According to obtained results, the extrusion energetic simple balance resulted positive for MS, RS and blend. For SS only the energy input was calculated, since no significant differences were observed in CH_4 yield improvement. Extrusion efficiency was lower for RS, compared to MS, which showed an energy output twice as high as RS and lower energy input for the extrusion. Blend feeding efficiency was quite close to MS efficiency, but lower, due to the influence of other two biomasses, that increased the energy input for extrusion. Since no significant differences between the two pre-treatment intensity levels were observed, the extrusion efficiency was higher when the exit slit was completely opened, due to the lower pre-treatment energy demand.

Table 2. Energetic evaluation of the extrusion pre-treatment performed on the biomasses at two different intensity levels (exit slit opened at 100 and 60%).

Samples	Extruder Capacity $t \cdot h^{-1}$	Energy input* $kWh_{el} \cdot t^{-1}$ of fresh matter	Energy output**	Efficiency***
Blend 100	5.2	12.0	66.5	5.5
Blend 60	5.2	12.9	66.5	5.2
MS 100	6.6	9.2	74.3	8.0
MS 60	6.6	10.2	74.3	7.2
RS 100	6.2	11.7	33.4	2.9
RS 60	6.2	13.0	33.4	2.6
SS 100	4.2	19.8	n.d.	n.d.
SS 60	4.2	23.8	n.d.	n.d.

*Energy input: energy demand by extrusion pre-treatment

**Energy output: energy increase calculated as difference between energy produced by pretreated sample and energy produced by untreated sample

***Efficiency: calculated as ratio between energy output and energy input

Conclusions

Extrusion has a potential to improve digestibility of some biomasses usually employed as feedstock in anaerobic digestion plants, because it causes a structural disruption which makes the degradable compounds more easily digestible. In particular, it can improve the degraded organic matter amount of tender biomasses with whole seeds which can be broken during the process. But it is also able to improve the anaerobic digestion of more resistant biomasses, as rice straw, accelerating the CH_4 production time. The simple energetic balance of extrusion resulted positive and it would be surely further more effective, considering also that extrusion simplifies the stirring of the biomasses within the anaerobic digester. The physical and technical advantages of extrusion in a continuous stirring AD should be surely investigated to better analyse the employment of extruder in ADPs.

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