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EFFECTS OF MECHANICAL PRETREATMENT ON BIOGAS PRODUCTION FROM WASTE PAPER

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Abstract

In the anaerobic digestion of lignocellulosic materials such as waste paper, the accessibility of microorganisms to the fermentable sugars is restricted by their complex structure. A mechanical pretreatment with a Hollander beater was assessed in order to reduce the biomass particle size and to increase the feedstock' specific surface area available to the microorganisms, and therefore improve the biogas yield. The mechanical pretreatment has been applied to a batch of office paper previously shredded and inoculated with sludge from a biogas production plant. A response surface methodology (RSM) was used in order to evaluate the effect of the beating time (BT) and digestion time (DT) on the biogas production; these effects were estimated and discussed using the statistical software Design-Expert v.9.

Keywords: Biogas, Waste paper, Pretreatment, Anaerobic digestion

1 INTRODUCTION

Paper and cardboard are a heterogeneous mixture of plant material such as cellulose, hemi-cellulose, and lignin and and filling material such as clay and calcium carbonate. Chemical additives (i.e. rosin, alum, starch) are added to modify quality of the material ans its properties such as brightness, opacity, or glossiness. Some paper such as currency paper is camposed by almost 100% cellulose. Residual contents of chemicals used during processing, such as talc or sodium silicate from may still be found in the paper product and consequently also in waste paper [1].

In Europe the per capita consumption of paper and board was 137 kg in 2012, in United Kingdom the total consumption was 1,0095,000 tonnes, being the sixth country in the world consumption [2]. The biggest source of recovered paper is industry and businesses with the 52% of the total, this covers also the converting losses (cuttings and shavings) and returns of unsold newspapers and magazines. Around 10% comes from offices, and the remaining 38% from households [3].

Although waste paper is mainly derived for recycling in paper mills, some other uses are being investigated such as construction materials [4], [5]; animal bedding [6], composting [7] or as a fuel [8], [9]. Many studies have been carried out about the anaerobic digestion of pulp and paper sludge [10]–[13] and municipal solid waste (MSW) (partially composed by paper and cardboard) [14], [15]. Biogas production from waste paper is in most cases studied as co-digestion with another substrates to increases the methane yields [16], [17].

Paper materials have a carbon-to-nitrogen (C/N) ratio ranging from 173/1 to greater than 1000/1 [18], these values are very high for anaerobic digestion, while the suggested optimum C/N ratio for anaerobic digestion is in the range of 20/1 to 30/1. Adding as inoculum sewage sludge that has a C/N ratio ranging from 6/1 to 16/1 [19] help to balance the C/N ratios in the reactor. Only two pretreatments have been studied to improve the biodegradability of paper and cardboard: mechanical and biological. The mechanical pretreatment consisted in shred the paper and cardboard fraction of municipal solid waste before anaerobic digestion but no significant effect on biogas yields and on kinetics [20]. Better results was obtained when filter paper (FP), waste office paper (OP), newspaper (NP), and cardboard (CB) were pretreated with a thermophilic cellulose degrading consortium (MC1), after 55 days of anaerobic digestion, the methane yield of pretreated FP, OP, NP, and CB were 277, 287, 192, and 231 ml CH4/gVS respectively, with corresponding increases of 33.2%, 34.1%, 156.0%, and 140.6% [19].

This paper investigates the improvements provided by a Hollander beater pretreatment. This technique is based on the same 'comminution' concept proposed by all other

mechanical treatments and increases biogas production. The Hollander beater has never been used as mechanical pretreatment machine on seaweed biomass. Seeing that this proposed pretreatment has already proved its effectiveness when applied to maize silage [21] gaining up to 29% extra biogas volume, in this study it has been applied to seaweed biomass in batch mode.

2   MATERIALS AND METHODS

2.1 Hollander Beater

The machine is composed of an oval vessel divided along its major axis by a partition that did not reach the walls, so an elliptic channel is formed (Figure 1). In one of the sides of the channel is placed a bladed drum that spins above a bedplate, churning pulp up over the back fall where it slides down creating momentum to round the curve and continue the loop [22]–[24].
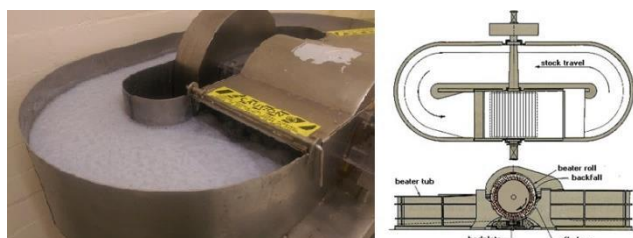

Figure 1. Hollander beater in operation with waste paper and working scheme [25].

2.2 Feedstock and Inoculum

Waste paper was collected from recycle bins at the School of Computing and Engineering at the University of West of Scotland (UWS). This paper was mostly one side printed and was cut by an office shredder in 0.6 x 29.7 cm pieces. Sludge was collected from the Scottish and Southern Energy (SSE) Barkip Biogas Plant, Ayrshire, Scotland.

The moisture content (MC) of pulp is calculated to provide a biogas production in term of volume per gram of total solids (TS = 1 - MC (%)) and is obtained by drying 100 ml of paper pulp at 105°C until constant weight.

2.3 Bioreactors

The bioreactor consists of flasks of 500 ml connected through a system of valves and plastic pipes to airtight plastic bags for biogas collection (Figure 2). To clear up any trace of oxygen from the system and preserve the anaerobic conditions, nitrogen is flushed for triplicate for 5 minutes into the reactors. The reactors are placed in water-bath to keep the temperature at 37°C.

Figure 2. Reactors with collection systems.

Reactors are feed with 150 ml of pulp (beated paper) and 200ml of sludge (inoculum), 200ml of water, 1 g of sugar and 2.3 g of Potassium Dihydrogen Phosphate (KDP). Sugar is used to boost the action of microorganisms at the start of the digestion; sludge is collected from a thermophilic plant and the process in the study is under mesophilic conditions so the microorganisms need to acclimatize and sugar is an easy substrate to degrade and start the process. KDP is added as buffer solution to maintain the pH around 8 at the start of anaerobic digestion. The reactors corresponding to the untreated samples are feed with 3g of paper and controls are prepared in the same way except for the paper addition in order to assess their contribution to the biogas production. Flasks are gently shaken during the process in order to favour the degasification of the substrate and the contact between the biomass and the inoculum.

2.4 Design of experiments

The experiment is planned according to a response surface methodology (RSM) for two factors, beating time (BT) and digestion time (DT) with three levels; the response is the biogas production pre g of dry paper (Table 1). The statistical study is performed using the software Design Expert v.9. A second order polynomial is used,

$$Y = b_0 \sum b_i x_i + \sum b_{ii} x_{ii}^2 + \sum b_{ij} x_i x_j \qquad (1)$$

where the values of the model coefficients b_0, b_i, b_{ii} and b_{ij} are estimated using regression analysis.

The adequacy of the models is tested through the analysis of variance (ANOVA). The statistical significance of the models and of each term is examined using the sequential F-test and lack-of-fit test. If the Prob. > F of the model and of each term in the model does not exceed the level of significance (in this case $\alpha = 0.05$) then the model may be considered adequate within the confidence interval of $(1 - \alpha)$.

3   RESULTS AND DISCUSSION

The experiment parameters, beating time (BT) and digestion time (DT) are checked in three levels. Beating time varies between 0-2 h and digestion time between 6-34 d. The response is the biogas production in ml per g of dry paper (DP). The values of the biogas volume obtained were converted into standard conditions (101.3kPa, 273.15K). As the biogas produced is saturated with water vapour, the water content was removed from the results as well. Parameters and results are presented in Table 1. The sludge contribution is obtained from the control samples and its value is given in ml of biogas per g of sludge. All the values are means of the triplicates. The sugar contribution is quantified theoretically by the following equation:

$$C_{12}H_{22}O_{11} + H_2O = 6CO_2 + 6CH_4 \qquad (2)$$
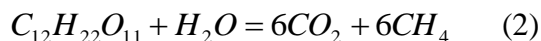
Assuming that all sugar is consumed, 1g of sucrose will produce 785.6 ml of biogas.

Table 1. Experiment parameters and results

Digestion time (d)	Beating time (h)	Biogas volume (ml/gDP)
6	0	306.54
6	1	302.67
6	2	303.71
20	0	519.22
20	1	429.92
20	2	435.85
34	0	538.01
34	1	455.40
34	2	489.93
6	Control (ml/g sludge)	0.56
20		3.67
34		4.35

The biogas production decrease when the office paper is treated in the Hollander beater for 1h compared with the untreated. Although the 2h pre-treatment reduces the biogas production compare to the untreated sample, it increase compare to 1h pre-treatment. A short beating time do not disrupt paper structure enough to lead to an improvement in biogas production. Because the waste paper has passes through refining during its preparation, its structure is already disrupted to a large degree.

In the six first days of digestion, there is less than 1.3% difference in biogas production between the three beating times. By day 20, the biogas production is 17.20% less for 1h BT and 16.06% for 2h BT compare to non-beated paper. At the end of digestion, the biogas production for 1h BT is reduced by 21.89% and for 2h BT by 15.97%. The reduction in biogas production may be due to the removal of ink and paper additives during the beating pre-treatment. These components could be metabolized and produces biogas. The removal of ink from the paper is visible to the naked eye; a layer of microbubbles accumulates near the rotor with a distinctive black colour. Rosin is an additive present both in the office paper and in the ink which does not dissolve in water, and may therefore become detached from the fibres in the paper during the Hollander beater treatment forming an immiscible layer on the surface of the suspension. Rosin is a biodegradable material [26], [27], however only aerobic degradation data is available [28]. If it assumed that rosin is anaerobically degradable as well, its removal during beating will lead to a decrease in biogas production. Beating pre-treatment seems start to be effective after 2h being that biogas production for 2h treatment is higher than for 1h. Longer beating times disrupt the feedstock structure making it more available for microorganisms. If the effect of structure disruption is higher than the loss of additives and ink, the beating pre-treatment of waste paper will be feasible.

For the optimization through the RSM, a resulted p-value of $7.68805 \cdot 10^{-05}$ indicates model terms are significant. The model terms of $R^2 = 0.9004$, adjusted-$R^2 = 0.8672$, predicted-$R^2 = 0.7297$, all these values are very close to 1 and so indicate the adopted model is adequate. The adequate precision, which measures the signal to noise ratio is 14.9547. A ratio greater than 4 indicates an adequate signal. The analysis of variance indicates that the digestion time (DT), the beating time (BT) and the second order effect of digestion time (DT) are the most significant factors affecting the biogas yield. The

final mathematical model associated to the response in terms of actual factors determined by the software is shown below.

$$Biogas\ yield = 220.46 + 21.01DT$$
$$- 29.88BT - 0.34DT^2 \qquad (3)$$

The response surface obtained from the model illustrated in Fig. 3 shows that the optimal condition was located outside the factorial design boundary, at higher digestion times.
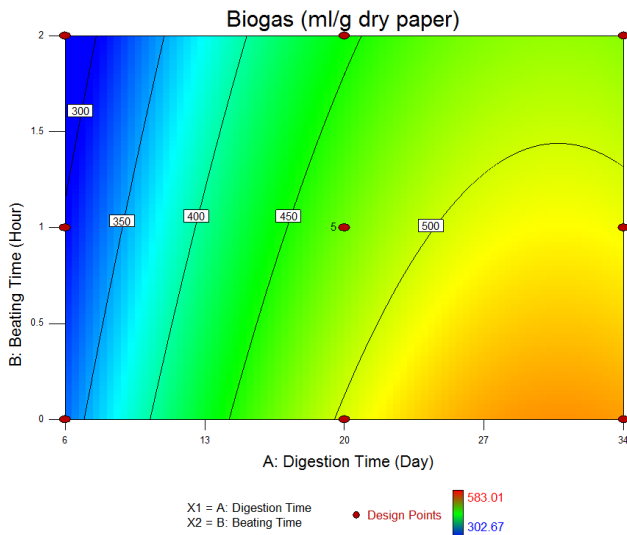

Figure 3. Response surface plot showing the effect of BT and DT on biogas yield.

The predicted vs. actuals plot (Fig. 4) shows that these values were distribute near to a straight line and a satisfactory correlation between them is observed. This demonstrates that the model can be effectively applied for mechanical pretreatment with a Hollander beater for office paper.
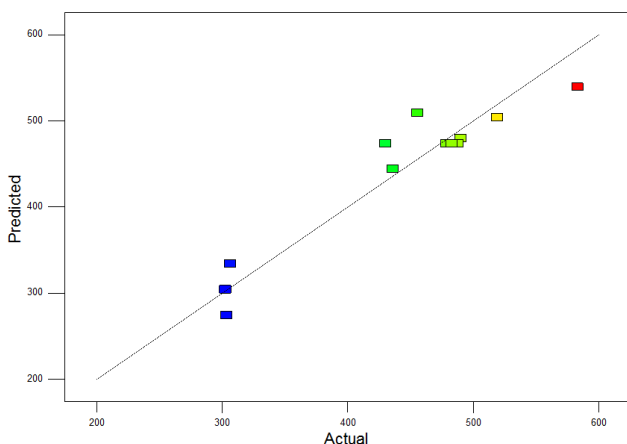

Figure 4. Scatter diagram of biogas yields.

The perturbation plot in Fig. 5 shows how the biogas yield is affected by the input variables BT

and DT. Digestion time affect the biogas yield in an exponential way and beating time affects it in a linear way. Increasing the beating time has a negative effect on the biogas yield while an increase in the digestion time has a positive effect.
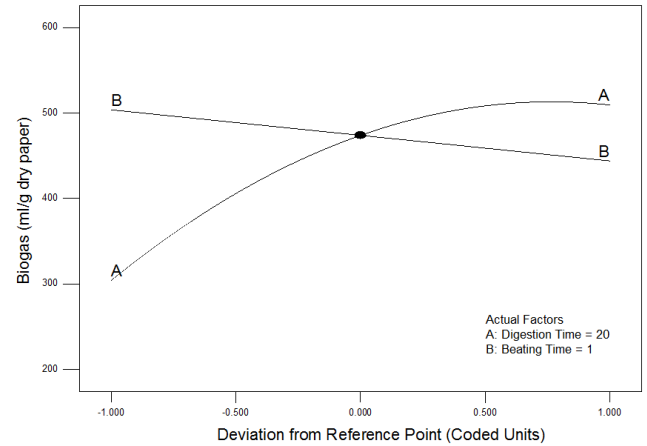

Figure 5. Perturbation plot showing the effect of BT and DT on biogas volume.

4 CONCLUSIONS

The experimental work shows the biogas yields obtained from the digestion of office paper inoculated with sludge from a biogas production plant. Pre-treated office paper with a Hollander beater for 2h has a negative effect on the biogas production through anaerobic digestion. Loss of ink and paper additives during the pre-treatment can occur. Longer beating times have to be investigated in order to evaluate the positive effects on biogas production.

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