Energy Recovery from Used Disposable Diapers by Co-Digestion with Waste Activated Sludge

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Abstract
The results presented in this paper are part of a project aimed at designing an original solution for the treatment of used disposable diapers permitting the recycling of materials and the recovery of energy. Diapers must be collected separately at source and transported to an industrial facility to undergo special treatment which makes it possible to separate plastics and to recover a biodegradable fraction (BFD) made up mainly of cellulose. The methane yield of BFD was measured and found to be 280 ml CH_4/g VS_{fed} on average. 150 kg of dry BFD can be retrieved from the treatment of one ton of used disposable diapers, representing an energy potential of about 400 kWh of total energy or 130 kWh of electricity. As the treatment process for used diapers requires very high volumes of water, the setting up of the diaper treatment facility at a wastewater treatment plant already equipped with an anaerobic digester offers the advantages of optimizing water use as well as its further treatment and, also, the anaerobic digestion of BFD. The lab-scale experiments in a SBR showed that BFD co-digestion with sewage sludge (38% BFD and 62% WAS on VS basis) was feasible. However, special attention should be paid to problems that might arise from the addition of BFD to a digester treating WAS such as insufficient mixing or floating particles leading to the accumulation of untreated solids in the digester.

Keywords
Anaerobic digestion, co-digestion, diaper, waste activated sludge, energy recovery

INTRODUCTION

A process has been patented for the treatment of absorbent sanitary paper products, including disposable diapers, which makes it possible to separate such products into their different components in a form suitable for recycling or re-use (Conway et al., 1996). At the end of the treatment, plastics and the cellulosic material (called BFD – Biodegradable fraction of diapers) are recovered in separate streams. A research programme, based on the Conway patent, has been launched whose aim is to divert used diapers from municipal solid waste streams and classic disposal methods such as incineration or land filling by designing an original approach involving material recycling and energy recovery. To this end, used disposable diapers must be separated at source, collected separately and sent to an industrial centre for treatment according to the process patented by Conway et al. (1996). As this treatment process requires the use of large volumes of water, the industrial centre could be set up at a wastewater treatment plant (WWTP) to optimize water use and further post-treatment. Indeed, the effluent at the outlet of the WWTP could be used in the treatment of the diapers and then recycled back to the start of the wastewater treatment line for pollution removal. Furthermore, the biodegradable fraction of diapers could be co-digested with waste activated sludge for energy recovery in pre-existing anaerobic digesters. Co-digestion would be an advantageous option for anaerobic digesters treating waste activated sludge, particularly in the case of under-loaded digesters, as it should make it possible to increase the anaerobic treatment's overall methane production.

The work presented in this paper was part of the research programme aimed at evaluating the technical feasibility of the treatment at an industrial centre of used disposable diapers for the recovery of their plastic fraction for recycling as raw material and of their biodegradable fraction for energy production. The experiments focused first, on the assessment of the methane yield of the biodegradable fraction of diapers (BFD); and second, on the co-digestion of the BFD with waste activated sludge (WAS) in a lab-scale reactor.

RESULTS AND DISCUSSION

For the application of the patented process (Conway et al., 1996) to the separation of the constituents of used disposable diapers, the process presented at figure 1, made up of three major successive steps (coarse shredding, pulping and plastics separation, SAP separation and BFD recovery), was set-up.

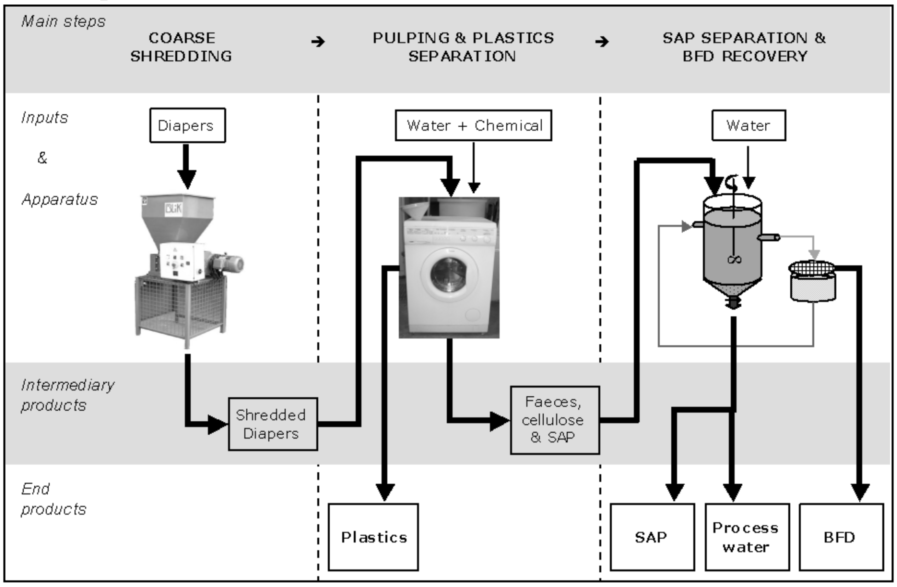

Figure 1: Lab-scale process used for the separation of the constituents of used disposable diapers (SAP: Super Absorbent Polymer; BFD: Biodegradable Fraction of Diapers)

Assessment of the BMP of BFD, WAS and different mixtures of the two substrates

The biochemical methane potentials (BMP) of the biodegradable fraction of the diapers and the waste activated sludge alone were evaluated in a first stage. The BMPs of the two substrates were quite close, with 275 ml CH_4/g VS_{fed} for BFD and 300 ml CH_4/g VS_{fed} for WAS. However, the methane potential per g of raw substrate was much higher for BFD compared to WAS, due to the higher VS content of BFD, with 29 ml of CH_4 per g of raw BFD but only 9.3 ml of CH_4 per g of raw WAS. In a second stage, the BMPs of different mixtures of BFD and WAS were measured. The BMPs of the different mixtures ranged between 239 – 340 ml CH4/g VS but without any clear influence on the BMP value of the ratio of the two substrates. This might be explained by the difficulty in obtaining satisfactory reproducibility with small quantities of inhomogeneous substrates. The average BMP of the six mixtures was 283 +/- 36 ml CH_4/gVS_{fed} which is close to the average value of the BMP of the two substrates alone. This indicates that there was no effect on the BMP, either positive or negative, when the two substrates were mixed.

Assessment of the methane yield of BFD and WAS in batch reactors

Two 6 l reactors were operated in fed-batch mode, one fed the biodegradable fraction of diapers alone, the other with waste activated sludge alone in order to measure the methane yield of each substrate individually. Several batches were done for each substrate (14 for BFD and 8 for WAS) in order to measure the methane yield with acclimatized biomass. For BFD, the same substrate as that used for the measurement of the BMP was used while for WAS a new batch of substrate was used. For BFD, the methane yield was 285 ml CH_4/g VS_{fed}, which is very close to the value measured in 550 ml flasks using the BMP protocol (275 ml CH_4/g VS_{fed}). However, for WAS, a much higher value was found with 485 ml CH_4/g VS_{fed}. The different result obtained for WAS can be explained by the use of a new batch of WAS. The very high methane yield suggests that this WAS contained a high proportion of primary sludge, probably with a significant quantity of fat and greases.

Results with a SBR fed with a mixture of BFD and WAS

A SBR was fed for 118 days with a mixture of 32 % BFD and 68 % WAS based on TS mass, that is to say 20%/80% on mass basis and 38%/62% on VS basis. The reactor was run at incremental organic loading rates (OLR): 0.92 gVS/l.d for about 5 weeks (days 1 to 34), then 1.61 gVS/l.d for about 6 weeks (days 35 to 76) and finally 2.03 gVS/l.d for the last 6 weeks of the experiment (days 77 to 118). OLR was not increased beyond 2 gVS/l.d as this OLR was the maximum OLR planed for application at an industrial scale. The hydraulic retention time was 42 d, 23 d and 19 d at, respectively, OLRs of 0.92, 1.61 and 2.03 gVS/l.d.

Volume of gas produced and methane yield. The volume of biogas produced during each batch was monitored on-line. As the duration of batch treatment was not constant during the week, with four 24 h batches and one 72 h batch, the volumes of biogas and methane produced were reported per week. Figure 2 presents the evolution over time of the total quantity of VS fed per week and of the volumes of biogas and methane produced per week. In week 14, the quantity of VS added was lower because the reactor was fed only 4 times. As a consequence, the volumes of biogas and methane were lower compared to the other weeks.

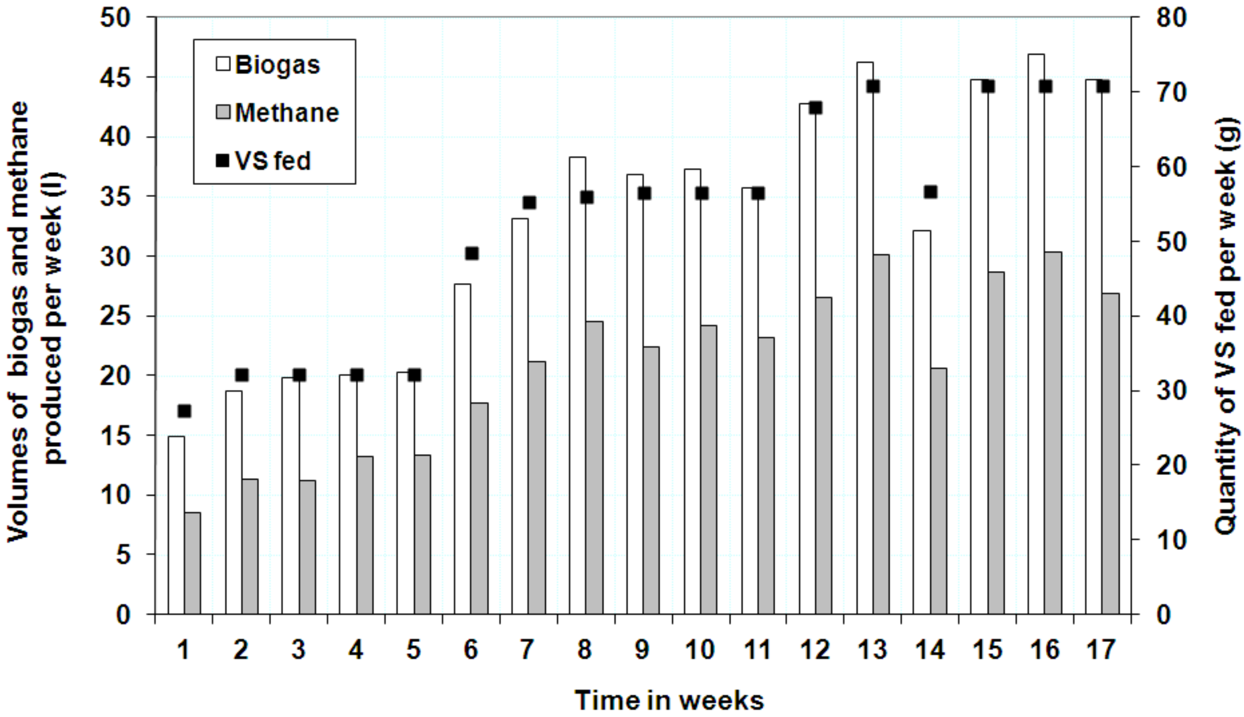

Figure 2: Evolution over time of the quantity of VS and of the volumes of biogas and methane produced per week in the SBR fed with a mixture of 32% BFD and 68% WAS (as a percentage of VS)

Figure 2 shows clearly that the volumes of biogas and methane produced increased rapidly after each increase in the organic loading rate, with a weekly methane production of 32 l at 0.92 gVS/l.d, 57 l at 1.61 gVS/l.d and 71 l at 2.03 gVS/l.d. The average methane content of the biogas produced was 63 +/- 2.9 %. The methane yield of the mixture 32% BFD/68% WAS was 411 ml CH_4/g VS_{fed}. This value is in total agreement with the expected value calculated using the methane yields measured for each individual substrate in the batch reactor. Indeed, the methane yield was 285 ml CH_4/g VS_{fed} for BFD and 485 ml CH_4/g VS_{fed} for WAS, and considering the proportion of each component (38% for BFD and 62% for WAS as a percentage of VS), the expected methane yield was 409 ml CH_4/g VS_{fed}. This mixture had a much higher methane yield than that measured in the first part of the experiment using the BMP protocol (around 283 ml CH_4/g VS_{fed}) because of the use of a new batch of WAS in the experiments in the reactor, with a much higher methane yield than that of the first batch (485 ml CH_4/g VS_{fed} instead of 300 ml CH_4/g VS_{fed}).

Soluble matter and solids concentration in the reactor. Soluble COD in the reactor always remained very low, with a maximum of 1.75 g/l at the end, and VFA concentration was always very low (< 100 mg/l) indicating no overloading nor accumulation of non-eliminated soluble matter. As the reactor was operated in SBR mode with a settling phase prior to withdrawal, SS and VSS concentrations increased quite rapidly during the first 8 weeks of the experiment, reaching about 40 g/l and 30 g/l respectively for SS and VSS concentrations. This result shows that non-degraded solids accumulated in the reactor. At such high concentrations, sludge no longer settled in two hours and solids concentrations began to decrease after week 12, reaching 35 g SS/l and 22.5 g VSS/l in week 17.

Mass balance and solids removal efficiency. At the end of the experiment, the reactor was emptied in order to evaluate the quantity of solids remaining in the reactor. A solid black mass had accumulated around the agitation blade. A volatile solids mass balance was calculated for the entire period to evaluate VS removal efficiency: (i) the total quantity of VS fed for the entire period was 894 g; (ii) the quantity of VS accumulated in the liquid phase between the beginning and the end of the experiment was 90 g (10% of the VS fed); (iii) the quantity of VS accumulated around the agitation blade was 57 g (6% of the VS fed); (iv) the quantity of VS removed from the reactor with the treated effluent was 286 g (32 % of the VS fed). The quantity of VS eliminated was then calculated to be 461 g which represented a VS removal efficiency of 52 % for the entire period.

Implementation of the treatment process at industrial scale. The treatment of one ton of used diapers made possible the separate recovery of, on average, 150 kg of dry plastics, to be recycled as raw material, and 150 kg of dry biodegradable fraction (BFD) to be further treated by anaerobic digestion for energy production. The energy potential of used disposable diapers was calculated from the methane yield of BFD as measured in this work (280 ml CH_4/g VS_{fed} on average). 150 kg of dry BFD with a VS/TS ratio of 95 % can be transformed by anaerobic digestion into 40 m^3 of methane. This corresponds to a total energy production from one ton of used diapers of about 400 kWh and, thus, to 130 kWh of electricity/ton of used diapers taking into account an electricity yield of around 33% for a combined heat and power unit. Because the treatment of used diapers requires very high volumes of water, setting up a diaper treatment facility at a WWTP equipped with an anaerobic digester for waste activated sludge treatment offers two main advantages: (i) first, it makes it possible to use the treated effluent as process water during the pulping phase. After use, this water, contaminated mainly by urine and faeces, can be sent back to the aerobic tank for pollution removal; (ii) second, the existing anaerobic digester can be used for the digestion of BFD. Indeed, the lab-scale experiments in reactors showed that BFD co-digestion with sewage sludge (38% BFD and 62% WAS on VS basis) was feasible. 1.5 tons of BFD at 10% TS can be recovered from the treatment of 1 ton of used diapers and further co-digested with about 6 tons of sewage sludge, depending upon sludge TS content. This mixture has a TS content of 5 to 6%, well adapted to classic WWTP anaerobic digesters. This approach could be particularly advantageous in the case of under-loaded digesters as it would make it possible to increase the overall methane production obtained by the anaerobic treatment. However, special attention should be paid to the design and operating requirements of an industrial-scale continuously-fed liquid reactor digesting such a mixture of BFD and WAS: agitation system should not entrap solids, nor should it cause the accumulation of floating material at the top of the digester; also, the organic loading rate should be maintained below 2 kg VS/m^3.d to avoid irreversible imbalance in the process.

ACKNOWLEDGEMENTS
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Conway M. E., Jooste F., Smith M. D. (1996). Treatment of absorbent sanitary paper products. United States patent. Patent number: 5,558,745. Date of patent: sep. 24, 1996.