Citation for published version:
Forgacs, G, Niklasson, C, Sárvári Horváth, I & Taherzadeh, MJ 2014, 'Methane production from feather waste pretreated with Ca(OH)2: Process development and economical analysis', Waste and Biomass Valorization, vol. 5, no. 1, pp. 65-73. https://doi.org/10.1007/s12649-013-9221-3

DOI:
10.1007/s12649-013-9221-3

Publication date:
2014

Document Version
Early version, also known as pre-print

The final publication is available at Springer via http://dx.doi.org/10.1007/s12649-013-9221-3

Methane Production from Feather Waste Pretreated with $Ca(OH)_2$: Process Development and Economical Analysis

Gergely Forgács[1,2*], Claes Niklasson[2], Ilona Sárvári Horváth[1], Mohammad J. Taherzadeh[1]

[1]School of Engineering, University of Borås, 501 90, Borås, Sweden

[2]Department of Chemical and Biological Engineering, Chalmers University of Technology, 412 96 Göteborg, Sweden

*Corresponding Author: Gergely Forgács

Phone: +46 33 435 5972

Fax: +46 33 435 4008

E-mail: gergely.forgacs@hb.se

Abstract

This study investigated the industrial application of feather waste as a substrate for anaerobic digestion. Feather was pretreated with 0-0.2 $Ca(OH)_2$ g/g $TS_{feather}$ (Total Solids of feathers) for 30-120 min at 100-120°C, in order to increase the digestibility, and to enhance the methane yield in a subsequent digestion at 55°C. Based on the results of the batch digestion, an industrial process was developed, which can achieve 0.40 Nm^3/kg $VS_{feather}$ (Volatile Solids of feathers) methane yield from the pretreated feathers, while it fulfills the animal by-product hygenization requirements as well. This base case of the industrial pretreatment process was designed using SuperPro Designer® for utilizing 2,500 tons of feathers per year, which is the waste stream from an average slaughterhouse with a capacity of 60,000 broilers per day. The production cost of the methane is estimated to be 0.475 EUR/Nm^3, while the investments on the pretreatment unit requires 0.97 million EUR as total capital investment, and 0.25 million EUR/year for operating cost. However, the process is sensitive to the plant capacity. Changing the plant capacity from 625 to 10,000 tons of feather per year, results in reducing the biogas production cost from 1.177 to 0.203 EUR/Nm^3. In addition, sensitivity analysis was performed on the base case to investigate the effect of the value of the incoming feather on the overall process profitability. The results showed that the proposed investment could be considered as being financially viable in the case of production of upgraded biomethane even without the current gate fee system.

Keywords: feather; anaerobic digestion; alkaline pretreatment; process development; economical analysis

Introduction

Biogas production through anaerobic digestion (AD) is an attractive waste management concept, in which renewable energy in the form of methane is produced [1]. The main advantage of AD is that all types of organic wastes can be used as substrate, including sewage sludge, food waste, organic fraction of household waste, farm waste, and commercial organic wastes [2]. Moreover, the produced biogas has a wide range of applications in heat and electricity generation; additionally, it can be upgraded to vehicle fuel as well [3].

Slaughterhouse waste is considered to be an ideal substrate of anaerobic digestion, since it has a high methane potential [4]. According to the Food and Agriculture Organization of the United Nations, worldwide chicken consumption has exceeded 86 million tons during the year 2010. During the slaughtering process, approximately 25% of the total animal weight remains as waste [5,6]; consequently, among the poultry slaughterhouse waste, feather wastes create a major concern. The feathers are generated in large amounts, and are poorly degraded under anaerobic conditions [7]. Feather is composed of 90-95% keratin protein, which makes it highly recalcitrant to biological degradation [8]. Although, several physical, physicochemical, enzymatic, and biological pretreatments were reported to improve the digestibility of feather [9-12], only a few studies were dedicated to its pretreatment for anaerobic digestion [13,7].

Forgács *et al*. [13] reported a significant enhancement in the methane production of feathers (from 0.18 Nm^3/kg VS to 0.40 Nm^3/kg VS) using recombinant *B. megaterium* strain, although the treatment process required several days. However, the application of genetically modified organisms is strongly regulated and not widely accepted. According to Salminen *et al*. [7], enzymatic pretreatment with Multifect P-3000® enzyme increased the methane yield of feather by 21%. However, high enzyme load (10 g/L) was necessary to achieve this result. In the same study, alkaline pretreatment with 1% NaOH at 35°C resulted in 32% increase in methane yield, from 164 mL/g VS to 216 mL/g VS. Alkaline pretreatment at a higher temperature may further improve the yield of methane because the temperature has a crucial effect on feather degradation under alkaline conditions. Coward-Kelly *et al*. [10] reported extremely low keratin hydrolysis (2-6%) at low temperature (50°C), but it greatly increases at elevated temperatures.

The main objective of this study was to develop a simple and feasible industrial process for the utilization of feather waste through anaerobic digestion. Chemical pretreatment with $Ca(OH)_2$ was applied to increase the digestibility of keratin, thus, improve the biogas yield from the feather within the subsequent anaerobic digestion process. Based on the experimental data obtained, an industrial process was designed using SuperPro Designer® (v8.5) computer program. The process was then analyzed regarding economical feasibility, investigating the effects of major parameters, including the capacity and the value of feather on the overall profitability.

Materials and methods

Raw materials

Chicken feather waste was obtained from a poultry slaughterhouse (Borås, Sweden). The waste was washed 3 times with water, and then air-dried at room temperature. The dried feathers were then ground into 2-3 mm particle size (Retsch GmbH SM 100 comfort miller, Germany) and stored at 5°C until use. The inoculum sludge was obtained from a large-scale municipal waste digester (Borås Energy & Environment AB, Sweden) operating at thermophilic conditions. The inoculum was stored for 3 days at 55°C before starting up the batch experiments.

Pretreatment process

Feather corresponding to 1.0 g TS was suspended in 10 ml of distilled water or 10 ml of 1 or 2% $Ca(OH)_2$ solution, to provide a solution with a concentration of 100 g $TS_{feather}$/L, and where the $Ca(OH)_2$ had a final concentration of 0, 0.1, or 0.2 g $Ca(OH)_2$ per g TS of the feather. The pretreatments were carried out in autoclave at temperature ranges of 100-120°C for 30-120 min. After the pretreatment, the calcium was precipitated and removed as $CaCO_3$ by sparging CO_2 through the vessel. The precipitated $CaCO_3$ was then removed by centrifugation at 4,500×g for 10 min. The supernatant was divided into five equal portions, each corresponding to 0.2 g TS feather. Three of these samples were subjected to batch digestion experiments, and the rest were used for the measurements of soluble chemical oxygen demand (sCOD) to determine the solubilization degree of the feathers as the results of the treatments.

Batch digestion experiments

All of the batch digestion experiments of pretreated and untreated feather were carried out in triplicates, using 118 mL glass bottles [14]. Inoculum of 20 mL was added to each vial containing either untreated or pretreated sample corresponding to TS value of 0.2 g. Finally, the reaction volume was adjusted to 25 ml with distillated water. A blank experiment, containing only water and inoculum, was also set up to determine the methane production of only the inoculum. The reactors were then sealed with butyl rubber props and aluminum caps and finally, flushed with a gas mixture of 80% N_2 and 20% CO_2 to obtain anaerobic conditions and then incubated at 55°C. During the 50-day long incubation period, the bottles were shaken in the incubator once a day. Gas samples of 0.25 mL were regularly taken from the headspace using a pressure-tight syringe, and the gas composition was measured directly by gas chromatograph (GC). Excess gas was released after each analysis through a needle (Sterican® Ø 0.4 X 20 mm B|Braun, Germany) to avoid increased overpressure in the headspace. The composition of the gas in the headspace of each reactor was measured again after the release. Assuming ideal gas mixtures and using the ideal gas law, the produced methane was calculated using the data from the GC measurements. Moreover, the accumulated methane production obtained from the blanks (inoculum) was subtracted in each measuring occasion from the accumulated methane production of the samples. In this way the accumulated methane production of the feather waste can be calculated [14].

Analytical methods

Methane and carbon dioxide were measured using a gas chromatograph (Clarus 400, PerkinElmer, Inc., USA) equipped with a packed column (Column 8000 PKD, PerkinElmer, Inc., USA) and a thermal conductivity detector (PerkinElmer, Inc., USA) with inject temperature of 150°C. The carrier gas was nitrogen, operated with a flow rate of 25 mL/min at 60°C. A 250-µL pressure-tight gas syringe (VICI, Precision Sampling, Inc., USA) was used for the gas sampling. A gas with a known composition was used as a standard on each measuring occasion. All methane volumes are presented at standard conditions (101.325 kPa, 0°C) [15]. The total solids (TS), volatile solids (VS), and ash were analyzed according to Standard Biomass Analytical Procedures [16]. For the determination of soluble oxygen demands (sCOD), a COD reactor coupled to a DR/2000 direct reading spectrophotometer (HACH, Germany) was used. First, the samples were digested at 150°C for 2 h in a COD reactor using Digestion Solution sCOD vials (0-15000 mg COD/L, HACH, Germany). Then, the absorbance was measured at 620 nm with the UV-VIS Spectrophotometer.

Process development and financial analysis

Process description

A continuous pretreatment process was developed, which can be easily coupled to a biogas plant operating in semi-continuous mode. The proposed industrial process is similar to the lab scale procedure; although it does not contain initial washing and drying steps. These steps were applied only in the lab-scale experiments to be able to determinate the biogas yield of feather based on its solid content. However, in a large scale process these preprocessing steps are not required. During the pretreatment, the feathers are introduced to an industrial food grinder (constructed from carbon steel) to be reduced in size. This step is followed by the hydrolysis of feather with 1% $Ca(OH)_2$ solution at 100°C with resident time of 1 h in a blending tank (constructed from SS304). The hydrolyzed feather is then pumped to another blending tank (constructed from SS304), where CO_2 is added in order to precipitate the calcium in the form of $CaCO_3$. Finally, the hydrolyzed feather is separated from the precipitated calcium carbonate in a concrete clarifier. The produced $CaCO_3$ is dried and sold on the market, while the water from the drying step is recycled as process water. The hydrolyzed feather is transported to the anaerobic digester, where it is exploited in a semi-continuous co-digestion process. Co-digestion with carbon rich substrates is recommended for the utilization of pretreated feather to ensure the ideal reactor performance by adjusting the C/N ratio to an optimal level [17]. Furthermore, the nitrogen rich digestate residue can be utilized as fertilizer [18].

Process simulation and economical calculation

SuperPro Designer® v8.5 (Intelligen, Inc., NJ, USA) was used for the simulation and sizing calculations of the main steps and equipment within the pretreatment process. The chemical and equipment costs were indexed to 2011 €. The fixed capital investment (FCI), which includes the total direct plant cost (purchase and installation of the equipment, piping, instrumentation, etc.); the total indirect plant cost (construction and engineering work); and the contractor's fee and contingency was calculated using the above mentioned software, taking the costs for the equipment from this software, or in the case of vessels the purchase cost was calculated according to Turton *et al.* [19]. The yearly operating cost was calculated as the sum of the variable operating expenses (e.g., chemicals, maintenance) and fixed operating expenses, including labor wages and insurance. The annual insurance cost were estimated to be 1.0% of the fixed capital investment [20]. The annual maintenance cost of industrial processes typically varies between 2-10% of the fixed capital investment [19]. Since this process is relatively simple and does not apply strong acids or bases (which can be harmful to the equipments), the lowest maintenance cost was chosen. The number of laborers required was calculated according to Perry and Green [21], and a lump sum wage of 50,000 EUR/employee/year was assumed [20]. The working capital (WC) was presumed to be 15% of the fixed capital investment. Table 1 summarizes the prices used in the economical evaluation.

The model assumes that the pretreatment unit is located beside an existing biogas plant. Based on the experimental results, a methane production of 360 m^3 (0.40 m^3/kg VS) per ton of feather was used in the calculations. The energy requirement of the pretreatment process is supplied by using part of the produced methane in a boiler and in a combined heat and power (CHP) unit. This model investigates two possible utilizations of the remaining methane. In the first case, biogas is utilized for heat and electricity generation through a CHP unit, while in the second case, biogas is upgraded to biomethane and sold as vehicle fuel. In the calculations for the first case, efficiency values of 41.0% and 43.0% were used for the generation of electricity and heat, respectively, within the CHP unit [2,22]. Additionally, it was also assumed that the biogas plant has green electricity certification, which allows for selling the electricity at a higher price. Moreover, according to the base model, the untreated feather, CO_2 and digestate have zero value. The main product of anaerobic digestion is biogas which is a mixture of mainly methane and carbon-dioxide. In this model, CO_2 provided from the biogas production was used for the precipitation of $CaCO_3$. The produced digestate has value as a fertilizer, but in most cases is usually just given away to farmers rather than being sold [2]. The produced calcium carbonate can be sold on the market as an additive for plastic PE blown film or for production of CaO.

Sensitivity analysis

The base case of the model was designed to utilize 2,500 tons/year of feather, which is approximately the waste stream from a chicken slaughterhouse with a slaughtering capacity of 60,000 broilers/day. Sensitivity analysis was performed to investigate both the effect of the process capacity and the effect of the value of the feather on the overall profitability. For this purpose, process sizes of 25-400% of the base case, that is, 625-10,000 tons/year feather were considered. The capital cost was calculated according to the “six-tenth” rule [19]. The sensitivity analysis included the estimation of the capital and operating costs as well as the calculation of the minimum production/selling price of the methane. Minimum selling price of the methane was calculated as a production price of methane that makes the net present value (NPV) of the process equal to zero over 20 years of plant life, considering 15% discounted cash flow rate of return.

The effect of the value (price/cost) of the feather wastes on the process viability was investigated using the base model. In Sweden, waste treatment facilities including AD plants usually get economic compensation for the service, which is also known as gate fee or tipping fee. However, it is difficult to obtain the value of the waste since the biogas plants have different agreements with different municipalities and industries, and the details of these agreements are often considered as business secrets [23]. Palm [24] estimated the gate fee for slaughterhouse waste to be between 0-35 EUR/ton. In this study, sensitivity analysis was performed in a wider range, using five scenarios, described in Table 2, where the value of the feather waste was set between -20 and 20 EUR/ton. For the analysis of the financial viability, the NPV and the internal rate of return (IRR) were calculated for the investment over a 20-year lifetime assuming market price of biomethane (1.23 EUR/Nm^3), electricity (0.071 EUR/kWh) and heat (0.040 EUR/kWh) as it is shown in Table 1. The investment was considered to be financially viable with 15% or higher internal rate of return. The IRR is the discount rate (*r*) at which the net present value (NPV) is zero, and it is calculated by manipulating the *r* value until the NPV becomes zero [2].

Results

Pretreatment of the chicken waste

Chemical pretreatments with $Ca(OH)_2$ at various concentrations and temperatures were applied to enhance the digestibility of feather waste prior to biogas production. The results are summarized in Table 3. It was found that as a result of the chemical pretreatment, the sCOD value of the feather suspension was increased to 100.3-148.1 g/L depending on the time and the concentration of $Ca(OH)_2$ used. These values are equivalent to 66.8-98.8% of solubilization degree calculated from the theoretical COD potential of proteins (*i.e.*, 1 g protein is equal to 1.5 g COD) [25]. Thermal pretreatment without $Ca(OH)_2$ addition was less effective, resulting in solubilization degrees of only 1.4-7.7% corresponding to sCOD values of 2.1-11.6 g/L. Based on the sCOD results, the following three pretreatments were selected for further investigations regarding the following biogas production: 0.1 g $Ca(OH)_2$/ g $TS_{feather}$ at 100°C for 30 min, 0.1 g $Ca(OH)_2$/ g $TS_{feather}$ at 100°C for 60 min, and 0.2 g $Ca(OH)_2$/ g $TS_{feather}$ at 120°C for 120 min.

Batch thermophilic digestion assays

In the batch anaerobic digestion series, the methane production of the selected pretreated feather samples and the methane production of untreated feathers were compared. Figure 1 presents the accumulated methane production obtained during the 50-day long incubation period. All the selected pretreated samples produced approximately two times more methane than the untreated samples. The methane of the untreated sample was 0.201±0.021 Nm^3/kg VS, while methane productions of the pretreated feathers were 0.396±0.016, 0.404±0.058, 0.412±0.034 Nm^3/kg VS after pretreatment conditions of 0.2 g/g $Ca(OH)_2$ for 120 min at 120°C, 0.1 g/g $Ca(OH)_2$ for 60 min at 100°C, and 0.1 g/g $Ca(OH)_2$ for 30 min at 100°C, respectively. Moreover, the methane production rates were also improved after the pretreatments (Figure 1). According to EU legislation of animal byproducts, slaughterhouse waste including feather must be subjected to thermal treatment *i.e.* minimum for 1 h at 70 °C, particle size < 12 mm prior to anaerobic digestion at the biogas plants, therefore pretreatment conditions of 0.1 g/g $Ca(OH)_2$ for 60 min at 100°C were used during the development of the industrial pretreatment process [26].

Process development and economical calculation

The process flow sheet of the developed pretreatment process, which can be coupled to an existing biogas plant, is presented in Figure 2. The base case of the industrial pretreatment process was sized to utilize 2,500 tons/year feather waste. Based on the results obtained by the batch digestion experiments, it was calculated that the proposed process is able to increase the biogas production of the plant by 4800 m^3 per day. The energy (heat and electricity) requirement of the process is 301 kW, which can be provided by burning 21.2 % of the produced biogas in a boiler and by using 8.2 % of the gas in a CHP unit. The remaining biogas can be used to generate 345 kW of electricity and 361 kW of heat, or can be upgraded to 2100 m^3 of biomethane and used as vehicle fuel. The total investment (FCI+WC) was estimated at approximately 970,000 EUR, which includes the total direct plant costs, the total indirect plant costs, the working capital cost, and the contractor's fee and contingency, while the operating cost was estimated to be 248,000 EUR/year. The revenue of the investment is assumed to be 369,000 EUR/year, in the case of electricity and heat production, while the income is around 402,000 EUR/year when biogas is upgraded and sold as vehicle fuel.

Sensitivity analysis

The changes of the total investment cost and operating costs versus the capacity of the plant are presented in Figures 3A and B. The total investment (FCI+WC) cost does not linearly increase with the plant capacity (Figure 3A). By doubling the capacity to 5,000 ton/year, the total investment increased to 1.47 million EUR, making the cost 52% higher than that for the base case (0.97 million EUR). The operating cost varied between 168,000 and 410,000 EUR/year depending on the capacity of the process (Figure 3B). Furthermore, the minimum production price for the methane was estimated between 0.203 and 1.177 EUR/ Nm^3 depending on the process size (Figure 3C). For the base case capacity, the selling price of methane was determined to be 0.475 EUR/Nm^3. By doubling the plant capacity, the production cost is reduced by 34.7% to 0.310 EUR/Nm^3 compared to the base case.

The result of the sensitivity analysis is presented in Figure 4. According to the model investment, generating an IRR of 15% or above is considered to be a profitable activity. The different scenarios calculated showed that the production of vehicle fuel generates a slightly higher IRR compared to the case of heat and electricity generation. For the production of vehicle fuel, the different scenarios generated an IRR of between 10.7 and 23.7%, while for heat and electricity generation the IRR values of the different scenarios varied between 5.6 and 19.6%. If biogas is used for generation of heat and electricity, the process can be profitable when feather has a gate fee (Scenario 1 and 2). On the other hand, when biogas is upgraded for the production of vehicle fuel, the process can be economically feasible if the feather has a gate fee, or at minimum with zero gate fee (Scenario 1-3).

Discussion

This paper deals with the utilization of chicken feather waste for methane production. Earlier investigations has confirmed that the compact and resistible structure of feather results in a low methane production [13,7]. However, suitable pretreatment on feather can increase its digestibility and methane yield [13,7]. In this study, batch digestion assay of untreated feather at thermophilic condition showed a methane production of 0.201 Nm^3/kg VS, which is comparable to results reported in previous studies [13,7]. Chemical pretreatment with $Ca(OH)_2$ significantly solubilized the feather, resulting in an improved methane production of 0.394-0.412 Nm^3/ kg VS, corresponding to 80% of the theoretical methane potential from proteins. According to the sCOD measurements, addition of lime even in very low concentration (0.1 g $Ca(OH)_2$/g $TS_{feather}$) was able to dramatically increase the biodegradability of feather after treatments at temperature ranges of 100-120°C. Coward-Kelly et al. [10] also reported that low amounts of $Ca(OH)_2$ can significantly improve the solubilization of feather. In the case of animal feed production from feather, the authors recommended 5 h hydrolysis time in the presence of 0.1 g $Ca(OH)_2$/g dry feather at 100°C in order to obtain 95% solubilization. However, the feather hydrolyzate in this study was utilized in an anaerobic digestion process, and our data showed that shorter pretreatment times, *i.e.* between 0.5 – 1 h are sufficient for opening up the keratin structure, which can result in an enhanced methane production, achieving 80% of the theoretical methane production of feathers [13].

Based on the batch digestion experiment, an industrial pretreatment process was developed for treating the feather waste generated by a poultry slaughterhouse with a slaughtering and processing capacity of 60,000 broilers per day. The process is able to treat 2,500 tons of feather waste per year, and it can increase the production of the biogas plant by approximately one-million m^3 methane per year.

As presented in Figure 3C, the production price for the methane highly depends on the processing capacity. The price of biomethane, utilized as vehicle fuel, follows the oil price and it varies based on the economical situation during that time as well as the location where it is produced. Currently in Sweden, the biomethane price is 11.1 SEK/Nm^3 (*i.e.*, about 1.23 EUR/Nm^3) without VAT; therefore, it needs to be sold below this price to be competitive on the market. However, the upgrading, distribution, and sales costs could be as high as 0.730 EUR/Nm^3 [24]. Therefore, only those processes that can deliver methane at a cost of less than 0.50 EUR/Nm^3 (0.049 EUR/kWh) can be economically feasible. According to this assumption, the pretreatment process considered viable with minimum process capacity of at least 2,500 tons feather/year. However, the sensitivity analysis on the base case (2,500 tons/year) confirmed, that if feather utilized in the process is associated with any cost (Scenario 4 and 5 in Figure 4) the process is not considered to be profitable (IRR<15%). On the other hand, in the case of heat and electricity production, the current price of heat and electricity are 0.040 and 0.071 EUR/kWh (without network cost), respectively, which means that a profitable process should produce energy at a price less than 0.111 EUR/kWh. It is noteworthy that during the heat and electricity generation using biogas, 58-60% of the energy is lost during the conversion. As a result, the methane production cost for economical process will be limited to around 0.046 EUR/kWh (0.463 EUR/Nm^3). Therefore, a process with a capacity of 5,000 or 10,000 tons feather/year is assumed to be viable on the Swedish heat and electricity market (Figure 3C). The base case with a capacity of 2,500 tons feather/year can deliver methane at minimum cost of 0.475 EUR/Nm^3, which is slightly higher than the market price, thus this investment scenario is not recommended. However, according to the sensitivity analysis with the current gate fee system (Scenario 1 and 2) the developed pretreatment unit becomes profitable even at capacity of 2,500 ton feather/year (IRR≥15%, Figure 4).

Currently, feather is either used for the production of animal feed or it is incinerated [27]. However, its application as animal feedstock has been declining in recent years because production of animal feedstock is relatively costly and in addition, the legislation for its utilization has become tighter [8]. Incineration is a common waste handling technology in Sweden [23]; however, the gate fee for incineration is high, fluctuating between 24-60 EUR/ton [28,23]. The economic analysis in this study proved that utilization of feather waste as substrate for AD can be an attractive option since it can be economically viable at lower gate fees than the current incineration fees. Moreover, as demonstrated in the case of biomethane production, the proposed process can be economically viable even without the current gate fee system, which can be crucial in the future, since it is not guaranteed whether this gate fee system will continue to be used. In some countries, for example, Germany, the gate fees for certain waste streams have already dropped to zero, as a result of the competition between the waste management sites [2].

It can be concluded that in Sweden, the utilization of biogas as a vehicle fuel is economically more feasible (higher IRR) compared to heat and electricity production, in spite of the high costs of upgrading, distribution, and sales. Moreover, these costs can be reduced by using cheaper technologies or by having onsite biomethane filling stations, which can further increase the profitability. However, in Europe, the price of renewable heat and electricity defers noticeably. Thus, production of these utilities may be preferable. For example in Italy, the price of the renewable energy in the form electricity is 3–4 fold higher than the price in Sweden. Moreover, in most of the European countries the usage of biogas as a vehicle fuel is not widespread; therefore, generation of heat and electricity is the only possible application.

This study presents a possible process for the utilization of feather waste by introducing a chemical pretreatment process prior to biogas production. The pretreatment process significantly improves the methane yield of the feather, while at the same time fulfills the hygienization conditions, which are necessary to consider when treating animal by-products in an anaerobic digestion process. The developed process offers an environmental friendly and economically feasible method for the utilization of feather waste to produce renewable energy.

ACKNOWLEDGEMENTS

This work was financially supported by the Swedish Excellence Center, Waste Refinery, and by the Research and Education Board of the University of Borås. The authors thank Karthik Rajendran for his useful comments regarding the economical analysis.

Table legends:

Table 1: Economic conditions for the calculations concerning the developed chemical pretreatment process

Table 2: Description of the different plant scenarios considered within the sensitivity analysis

Table 3: The soluble chemical oxygen demand (sCOD), solubilization degree obtained after the different pretreatment conditions

Figure captions

Fig. 1: Accumulative methane production, expressed in Nm^3 /kg VS feather, determined during anaerobic digestion of untreated vs. selected pretreated feather samples. The pretreatment conditions are described in the figure.

Fig. 2: Schematic diagram of the proposed continuous pretreatment process, utilizing 2,500 tons of feathers per year.

Fig. 3: The prediction of the distribution of the total investment cost (A), the operating cost (B), and the production cost for the produced methane (C) in the function of the capacity of the plant.

Fig. 4: Sensitivity analysis for the value of the feather using the base model (*i.e.*, capacity of 2,500 tons of feather per year) for 5 different plant scenarios. The internal rate of return target (IRR) was set at 15% for this investment.

Materials and products	Cost or Value	Unit	References
Raw materials			
Feather/ CO_2	0.00	EUR/ton	Based on the model
Fresh water	0.067	EUR/ton	[29]
$Ca(OH)_2$	90	EUR/ton	[30]
$CaCO_3$	80	EUR/ton	Market price[1]
Other costs			
Labor	50,000	EUR/employee/year	[20]
Maintenance	2	% FCI	[20]
Insurance	1	% FCI	[20]
Products			
Electricity	0.071	EUR/kWh^{-1}	Market price[2] +green electricity certificate[3]
Heat	0.040	EUR/kWh^{-1}	Market price
Digestate	0.00	EUR/ton	[2]
Biomethane	1.23	EUR/Nm^3	Market price[4]

[1]AB Termidor, http://www.termidor.se/
[2]2011 Average market price of electricity was used. www.nordpool.com
[3]2011 Average market price of green electricity certificate was used. http://www.skm.se/priceinfo/
[4] FordonsGas Sverige AB, http://www.fordonsgas.se/

Table 1

Examined scenarios	Gate fee or cost of the feather (EUR/ton)
Scenario 1	20 (gate fee)
Scenario 2	10 (gate fee)
Scenario 3	0
Scenario 4	-10 (cost)
Scenario 5	-20 (cost)

Table 2

$Ca(OH)_2$ concentration (g/ g TS feather)	Time (min)	100°C		110°C		120°C	
		sCOD (g/L)	Solubilization degree (%)	sCOD (g/L)	Solubilization degree (%)	sCOD (g/L)	Solubilization degree (%)
0	30	2.1	1.4	6.9	4.6	4.3	2.8
0.1	30	100.3	66.8	110.0	73.3	134.4	89.6
0.2	30	113.4	75.6	124.4	82.9	131.5	87.7
0	60	2.5	1.7	10.0	6.7	6.6	4.4
0.1	60	105.4	70.3	112.9	75.3	110.6	73.8
0.2	60	116.8	77.8	124.0	82.7	138.1	92.1
0	120	2.6	1.7	10.8	7.2	11.6	7.7
0.1	120	123.1	82.1	118.4	78.9	114.6	76.4
0.2	120	140.9	93.9	146.1	97.4	148.1	98.8

Table 3

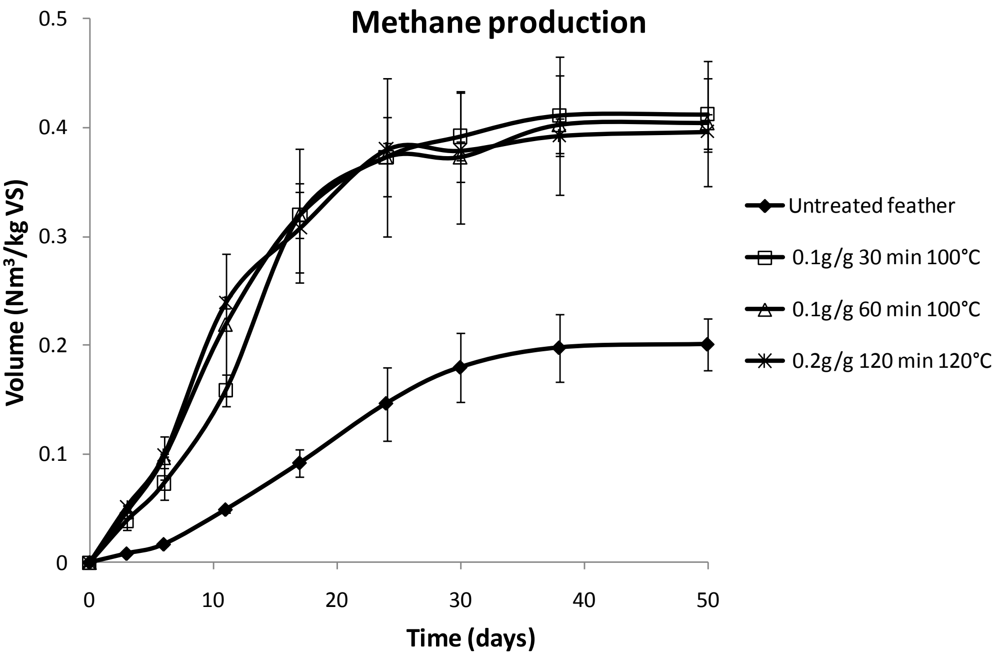
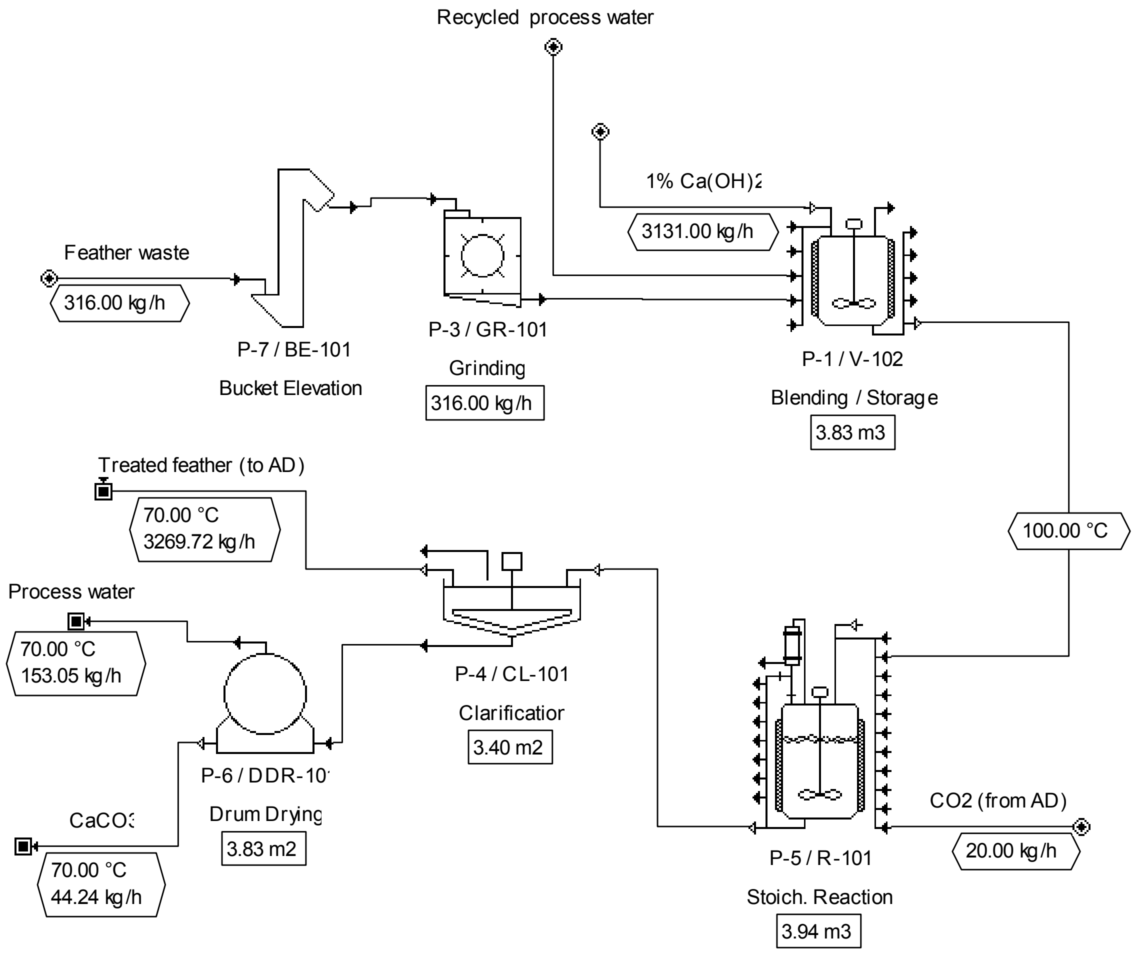

Methane production
Volume (Nm³/kg VS)
Time (days)
0
0.1
0.2
0.3
0.4
0.5
0
10
20
30
40
50
Untreated feather
0.1g/g 30 min 100°C
0.1g/g 60 min 100°C
0.2g/g 120 min 120°C

Fig. 1



Recycled process water
1% Ca(OH)2
3131.00 kg/h
Feather waste
316.00 kg/h
P-7 / BE-101
Bucket Elevation
P-3 / GR-101
Grinding
316.00 kg/h
P-1 / V-102
Blending / Storage
3.83 m3
Treated feather (to AD)
70.00 °C
3269.72 kg/h
100.00 °C
Process water
70.00 °C
153.05 kg/h
P-4 / CL-101
Clarificatior
3.40 m2
P-6 / DDR-10
Drum Drying
3.83 m2
CaCO
70.00 °C
44.24 kg/h
CO2 (from AD)
20.00 kg/h
P-5 / R-101
Stoich. Reaction
3.94 m3

Fig. 2

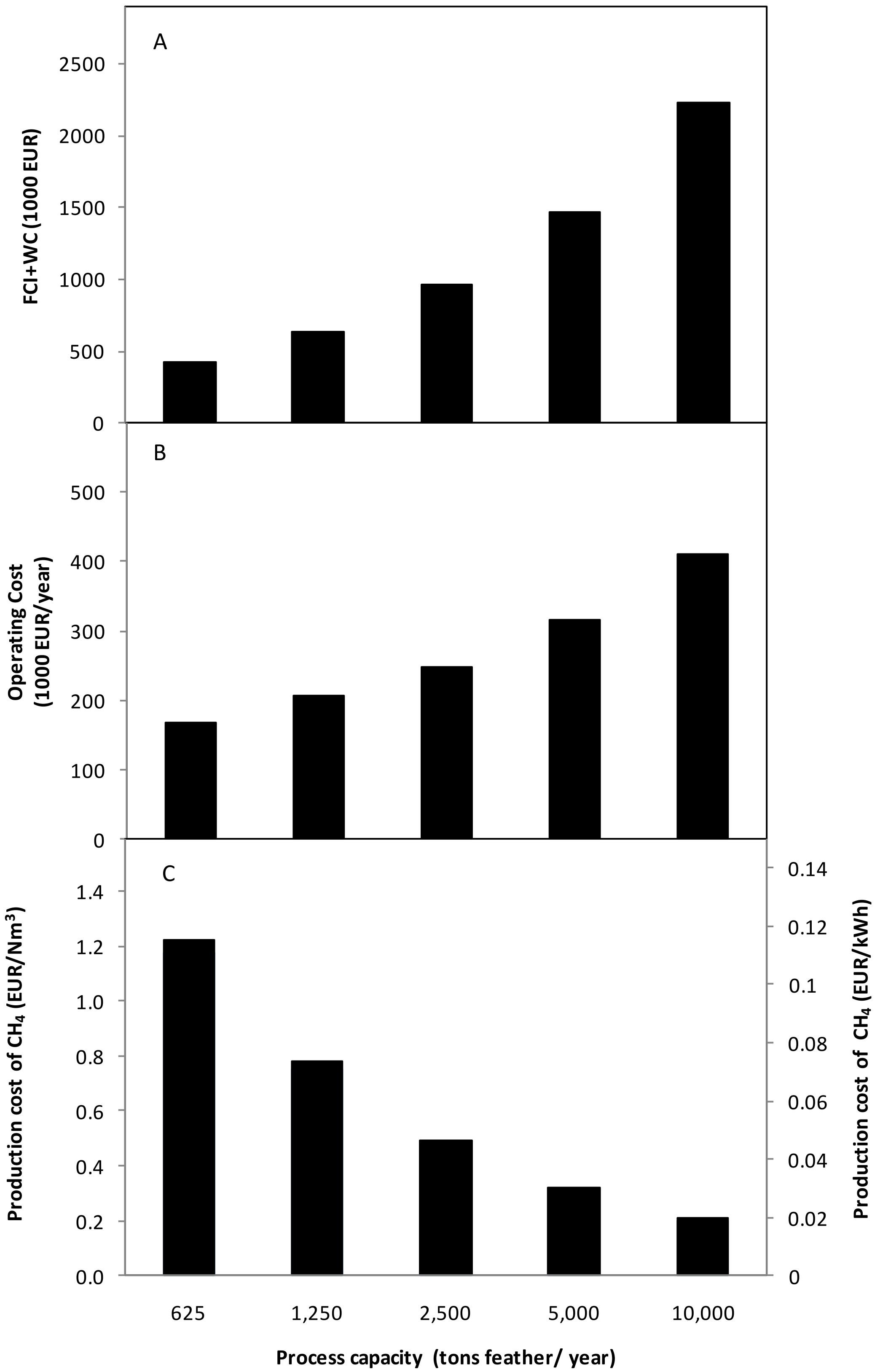

A
B
C
2500
2000
1500
1000
500
0
FCI+WC (1000 EUR)
Operating Cost
(1000 EUR/year)
400
300
200
100
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Production cost of CH4 (EUR/Nm3)
0.14
0.12
0.1
0.08
0.06
0.04
0.02
Production cost of CH4 (EUR/kWh)
625
1,250
2,500
5,000
10,000
Process capacity (tons feather/ year)

Fig. 3

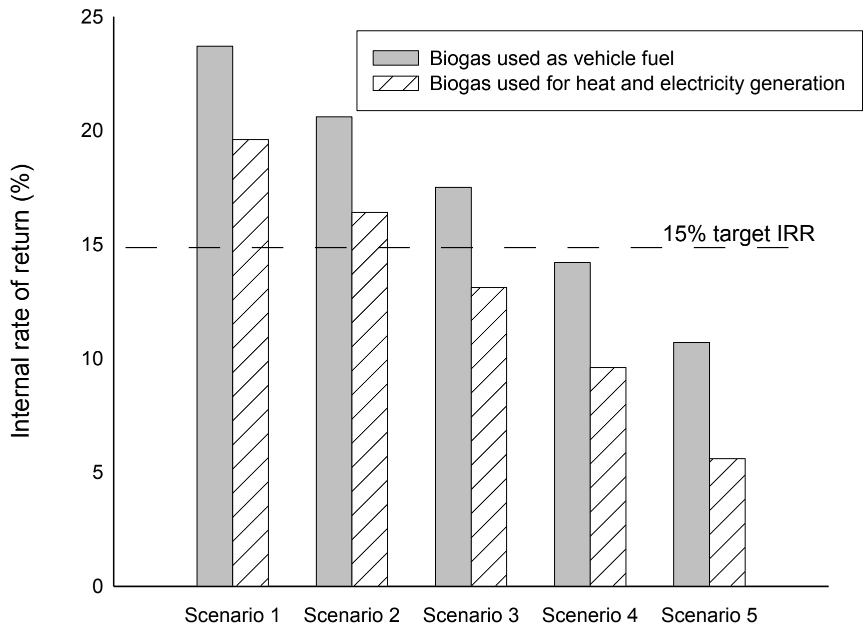

Biogas used as vehicle fuel
Biogas used for heat and electricity generation
15% target IRR
Internal rate of return (%)
0
5
10
15
20
25
Scenario 1
Scenario 2
Scenario 3
Scenerio 4
Scenario 5

Fig. 4

References:

1. Poeschl, M., Ward, S., Owende, P.: Environmental impacts of biogas deployment – Part II: life cycle assessment of multiple production and utilization pathways. J. Cleaner Prod. **24**, 184-201 (2012)
2. Dolan, T., Cook, M.B., Angus, A.J.: Financial appraisal of wet mesophilic AD technology as a renewable energy and waste management technology. Sci. Total Environ. **409**(13), 2460-2466 (2011)
3. Tippayawong, N., Thanompongchart, P.: Biogas quality upgrade by simultaneous removal of CO_2 and H_2S in a packed column reactor. Energy **35**(12), 4531-4535 (2010)
4. Cuetos, M.J., Gómez, X., Otero, M., Morán, A.: Anaerobic digestion of solid slaughterhouse waste (SHW) at laboratory scale: Influence of co-digestion with the organic fraction of municipal solid waste (OFMSW). Biochem. Eng. J. **40**(1), 99-106 (2008)
5. Hejnfelt, A., Angelidaki, I.: Anaerobic digestion of slaughterhouse by-products. Biomass Bioenergy **33**(8), 1046-1054 (2009)
6. Salminen, E., Rintala, J.: Anaerobic digestion of organic solid poultry slaughterhouse waste - a review. Bioresour. Technol. **83**(1), 13-26 (2002)
7. Salminen, E., Einola, J., Rintala, J.: The methane production of poultry slaughtering residues and effects of pre-treatments on the methane production of poultry feather. Environ. Technol. **24**, 1079-1086 (2003)
8. Korniłłowicz-Kowalska, T., Bohacz, J.: Biodegradation of keratin waste: Theory and practical aspects. Waste Manage. **31**(8), 1689-1701 (2011)
9. Onifade, A.A., Al-Sane, N.A., Al-Musallam, A.A., Al-Zarban, S.: A review: Potentials for biotechnological applications of keratin-degrading microorganisms and their enzymes for nutritional improvement of feathers and other keratins as livestock feed resources. Bioresour. Technol. **66**(1), 1-11 (1998)
10. Coward-Kelly, G., Chang, V.S., Agbogbo, F.K., Holtzapple, M.T.: Lime treatment of keratinous materials for the generation of highly digestible animal feed: 1. Chicken feathers. Bioresour. Technol. **97**(11), 1337-1343 (2006)
11. Park, G.-T., Son, H.-J.: Keratinolytic activity of Bacillus megaterium F7-1, a feather-degrading mesophilic bacterium. Microbiol. Res. **164**(4), 478-485 (2009)
12. Ramnani, P., Gupta, R.: Keratinases vis-à-vis conventional proteases and feather degradation. World J. Microbiol. Biotechnol. **23**(11), 1537-1540 (2007)
13. Forgács, G., Alinezhad, S., Mirabdollah, A., Feuk-Lagerstedt, E., Sárvári Horváth, I.: Biological treatment of chicken feather waste for improved biogas production. J. Environ. Sci. **23**(10), 1747-1753 (2011)
14. Hansen, T.L., Schmidt, J.E., Angelidaki, I., Marca, E., Jansen, J.l.C., Mosbæk, H., Christensen, T.H.: Method for determination of methane potentials of solid organic waste. Waste Manage. **24**(4), 393-400 (2004)
15. ISO: Stationary source emissions - Measurement of velocity and volume flowrate of gas streams in ducts. In, vol. ISO 10780:1994. (1994)
16. APHA: Standard methods for the examination of water and wastewater 21th ed. American Public Health Association Wasington DC (2005)
17. Forgács, G.: Biogas Production from Citrus Wastes and Chicken Feather: Pretreatment and Co-digestion. Ph.D. thesis, Chalmers University of Technology (2012)
18. Lansing, S., Martin, J.F., Botero, R.B., Nogueira da Silva, T., Dias da Silva, E.: Wastewater transformations and fertilizer value when co-digesting differing ratios of swine manure and used cooking grease in low-cost digesters. Biomass Bioenergy **34**(12), 1711-1720 (2010)
19. Turton, R., Bailie, R.C., Whiting, W.B., Shaeiwitz, J.A.: Analysis, Synthesis, and Design of Chemical Processes Third ed. Prentice Hall, Upper Saddle River (2009)

20. Lohrasbi, M., Pourbafrani, M., Niklasson, C., Taherzadeh, M.J.: Process design and economic analysis of a citrus waste biorefinery with biofuels and limonene as products. Bioresour. Technol. **101**(19), 7382-7388 (2010)
21. Perry, R.H., Green, D.W.: Perry`s Chemical Engineers` Handbook. 7th ed. McGraw-Hill Inc., New York (1997)
22. Walla, C., Schneeberger, W.: The optimal size for biogas plants. Biomass Bioenergy **32**(6), 551-557 (2008)
23. Lantz, M., Svensson, M., Björnsson, L., Börjesson, P.: The prospects for an expansion of biogas systems in Sweden—Incentives, barriers and potentials. Energy Policy **35**(3), 1830-1843 (2007)
24. Palm, R.: The economic potential for production of upgraded biogas as vehicle fuel in Sweden. Technical report no FRT 2010:03, Chalmers University of Technology. (2010)
25. Palatsi, J., Viñas, M., Guivernau, M., Fernandez, B., Flotats, X.: Anaerobic digestion of slaughterhouse waste: Main process limitations and microbial community interactions. Bioresour. Technol. **102**(3), 2219-2227 (2011)
26. European Parliament: Regulation (EC) No 1774/2002 of the European Parliament and of the Council of 3 October 2002 laying down health rules concerning animal by-products not intended for human consumption. In: Official Journal 10/10/2002;L273. (2002)
27. Xia, Y., Massé, D.I., McAllister, T.A., Kong, Y., Seviour, R., Beaulieu, C.: Identity and diversity of archaeal communities during anaerobic co-digestion of chicken feathers and other animal wastes. Bioresour. Technol. **110**(0), 111-119 (2012)
28. Sundberg, J., Nilsson, K.: Markedet for avfallsforbrenning i Sverige og Norge (Waste market in Sweden and Norway). Avfall Norge, (2009)
29. Shafiei, M., Karimi, K., Taherzadeh, M.J.: Techno-economical study of ethanol and biogas from spruce wood by NMMO-pretreatment and rapid fermentation and digestion. Bioresour. Technol. **102**(17), 7879-7886 (2011)
30. Tao, L., Aden, A., Elander, R.T., Pallapolu, V.R., Lee, Y.Y., Garlock, R.J., Balan, V., Dale, B.E., Kim, Y., Mosier, N.S., Ladisch, M.R., Falls, M., Holtzapple, M.T., Sierra, R., Shi, J., Ebrik, M.A., Redmond, T., Yang, B., Wyman, C.E., Hames, B., Thomas, S., Warner, R.E.: Process and technoeconomic analysis of leading pretreatment technologies for lignocellulosic ethanol production using switchgrass. Bioresour. Technol. **102**(24), 11105-11114 (2011)