

Article



# Feasibility Study of Biogas Production from Hardly Degradable Material in Co-Inoculated Bioreactor

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Abstract: Anaerobic technology is a well-established technique to wean the fossil fuel-based energy off with various positive environmental inferences. Biowaste treatment is favorable due to its low emissions. Biogas is merely regarded as the main product of anaerobic digestion with high energy value. One of the key concerns of the waste water treatment plants is the vast amount of cellulosic residuals produced after the treatment of waste waters. The fine sieve fraction, collected after the primary sludge removal, has great energy value. In this study, the economic performance of a biogas plant has been analyzed based on net present value and pay-back period concepts. The plant in the base scenario produced 309,571 m<sup>3</sup> biogas per year. The annual electricity production has been 390,059 kWh. The producible heat energy has been 487,574 kWh or 1755 GJ per year. The plant depicts a positive economic situation with 11 years pay-back time, earning low profits and showing a positive net present value of 11,240 €.

Keywords: anaerobic digestion; fine sieve fraction; financial modeling; biogas plant

# 1. Introduction

Current environmental and political pressures, the wobbling price of the fuels, and the depleted energy derived from fossil fuel reserves such as crude oil, coal, and natural gas have increased the industrial focus to bioenergy derived from biowaste, and encouraged technological progress in the biogas production sector in the EU [1–3]. In the Netherlands, a vast amount of waste water is yearly treated in WWTPs. Several abatement techniques are applied to treat organic waste, with the anaerobic digestion (AD) technology being widely used for biogas production [4–6].

The AD process comprises four main steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. During AD, bioenergy is produced in the form of a gaseous fuel, the so-called biogas, with an approximate composition of 66% CH<sub>4</sub>, 33% CO<sub>2</sub>, 0.5% N<sub>2</sub>, 0.1% O<sub>2</sub>, and 103 mg/L biogas H<sub>2</sub>S [7,8]. Biogas can be used for electricity and heat generation or as a vehicle fuel [9–11]. Several studies focus on the potential of biogas in fuel cell systems [12,13]. AD is an appealing technique playing a key role in the bioenergy sector within the EU [14–17]. Co-digestion had been extensively investigated and reported as an alternative solution to treat simultaneously various waste streams [18,19]. The benefit from co-digestion is that the optimal carbon to nitrogen (C:N) ratio (20:1 to 30:1) can be arranged by mixing different substrates.

However, an alternative technique was recently reported for the improvement of AD performance. Co-inoculation with two or more inocula provides a vast and wide consortium of microorganism within the bioreactor [20]. The source of the microbial inoculum will influence the degradation efficiency, the bioreactor stability as well as the biogas yield and composition [21–23]. A preceding study cited that the inoculum also provided macro- and micronutrients enhancing the microbial activity and thus augmenting the biogas yield [24]. To date, materials recovery and energy management are

pivotal issues to corroborate sustainability [25,26]. Organic material, rich in cellulosic residuals, can be collected with sieves from the influent of a waste water treatment plants [27]. These residuals or FSF can be digested in anaerobic digesters for energy recovery [28].

This study continues the work of Achinas and Euverink [20] and focusses on the feasibility of combined inoculation through experimental tests and financial assessment. Cash flow analysis was performed to evaluate the viability of a biogas plant. PFSF was selected as substrate and two different inocula were used in the experiments. The biogas yield, methane content, pH, redox, FAN and FOS/TAC ratio were determined to assess the efficiency of the co-inoculation. It is notable that a techno-economic assessment on the treatment of PFSF has not been previously conducted and reported, thus this study may provide new realistic insight on the exploitation of a different waste material. The two specific objectives of this study were to (1) evaluate the AD performance of co-inoculated bioreactors treating PFSF in semi-continuous mode and (2) examine the profitability of pilot biogas unit treating PFSF in combination with co-inoculation using the NPV analysis.

## 2. Materials and Methods

#### 2.1. Inocula and Substrate

The PFSF was obtained from the Blaricum sewage treatment plant in The Netherlands, and was stored at 6  $^{\circ}$ C to prevent possible hydrolysis. The inocula used in the experimental tests were collected from three different sources and their characteristics are shown in Table 1.

Parameter	Unit	IN1	IN2	PFSF
pН	-	7.52	7.27	ND
TS	$g \cdot kg^{-1}$	47.3 (0.8)	112.9 (1.5)	202.4 (12.9)
VS	$g \cdot kg^{-1}$	29.6 (0.4)	61.5 (1.0)	174.8 (6.3)
VS/TS	-	0.63	0.55	0.94
COD	$g \cdot kg^{-1}$	50.3 (2.2)	81.8 (3.9)	ND
VS/COD	-	0.59	0.75	ND

Table 1. Characteristics of the inocula and substrate used in the batch tests.

IN1: digestate from reactor treating activated sludge, IN2: digestate from reactor treating organic fraction of MSW, ND: not determined. Values are the average of three determinations. In parentheses is given the standard deviation.

The first inoculum (IN1) was obtained from an anaerobic digester treating anaerobic activated sludge from the WWTP of Garmerwolden (Groningen, The Netherlands). The second inoculum (IN2) was collected from an anaerobic bioreactor treating the organic fraction of MSW in the MSW treatment plant of Attero (Groningen, The Netherlands). All inocula were stored at 6 °C to maintain freshness and microbial activity and reactivated at 37 °C for two days prior to use.

## 2.2. Semi-Continuous Tests

Two identical 380 mL single-stage continuously stirred reactors (R1, R2) (BioBLU single-use vessels, Eppendorf, Nijmegen, The Netherlands) with working volumes of 304 mL were established to perform the semi-continuous digestion tests [29]. The OLR and process conditions used in the semi-continuous experiment are given in Table 2.

The vessels were placed in a temperature-controlled water bath (36 °C) and fed once a day. The PFSF solution was impelled with a syringe pump (NE1000, World Precision Instruments, Sarasota, Florida, USA), 30 mL syringes (inner diameter 23.1 mm Terumo) and tubing (Teflon, outer diameter 1.37 mm, inner diameter 1.07 mm).

Reactors	IN1 (%)	IN2 (%)	Organic Load (g VS <sub>substrate</sub> ·L <sup>-1</sup> )	Temperature (°C)	HRT (d)
R1	25	75	1.5	36	20
R2	25	75	1.5	36	20

Table 2. Process conditions applied in the semi-continuous tests.

IN1: digestate from reactor treating activated sludge, IN2: digestate from reactor treating organic fraction of MSW, IN3: digested cow manure.

#### 2.3. Analytical Methods

Total and volatile solids  $(g \cdot kg^{-1})$  were estimated according to the Standard Methods of APHA (2005) [30]. pH was calculated using a pH meter (HI991001, Hanna Instruments, Woonsocket, Rhode Island, USA). Chemical oxygen demand  $(g \cdot kg^{-1})$  and ammonium  $(g \cdot kg^{-1})$  were estimated using assay test kits (Hach Lange GmbH, Germany) and were quantified by a spectrophotometer (DR3900, Hach, Loveland, Colorado, USA). Free ammonia nitrogen (FAN;  $g \cdot kg^{-1}$ ) was calculated based on the equation [31]:

$$N - NH_3 = \frac{TAN \times 10^{pH}}{e^{(\frac{6344}{273.15+T})} + 10^{pH}}$$
(1)

Total alkalinity (g CaCO<sub>3</sub>·L<sup>-1</sup>), total volatile fatty acids (TVFA; mg acetate/L), FOS/TAC (TVFA/TA) ratio were determined using Nordmann titration method. The biogas volume (mL·g VS<sub>substrate</sub><sup>-1</sup>·day<sup>-1</sup>) was measured according to the methodology followed by Achinas and Euverink [20]. The methane content was determined with a micro gas chromatography (GC) device (single channel 2-stream selector system, Thermo Fisher Scientific Inc, Waltham, MA, USA) equipped with a chromatographic column (PLOT-U). Helium was used as carrier gas at a total flow of 10 mL·min<sup>-1</sup>. A gas standard consisting of 50% (v/v) CH<sub>4</sub>, 20% (v/v) CO<sub>2</sub> and 30% (v/v) N<sub>2</sub> was used to calibrate the micro GC device.

## 2.4. Statistical Analysis

Statistical significance of the data was determined by one-way ANOVA using Microsoft Office Excel (Microsoft, Redmond, WA, USA) with a threshold p-value of 0.05.

#### 2.5. Economics

As for all investments, the economic assessment is a pivotal factor for the final decision (go/no-go) to continue with a project. In this part, the costs and revenues of a biogas installation treating fine sieve fraction are discussed. The AD plant comprises investment costs, operation and maintenance costs, insurance and taxes. The investment costs for a biogas unit depends on the specific needs of the installation. As a result, it is difficult to clarify investment costs beforehand. For better comprehension, it is indispensable to state that the total cost of installation for a biogas power plant can vary from  $2500 \notin$  to  $7500 \notin$  per kWh/h electricity generation [32]. In this study, the equation estimating the total capital investment (TCI) is:

$$TCI = TIC \cdot P_{el}$$
(2)

where TCI is total capital investment ( $\in$ ), TIC is total installation cost per power installed ( $\notin$ /kW), and P<sub>el</sub> is total power installed (kW). It is possible to estimate also the electricity yield (E) and the heat yield (H) multiplying the total methane by specific conversion factors: for electricity the conversion factor is included between 1.8 and 2.2 kWhe [33,34], whereas the heat conversion factor could vary from 2 kWh/m<sup>3</sup> biogas to 3 kWh/m<sup>3</sup> biogas [33]. In this study, the average values are considered using the following equations:

$$E (kWhe) = Total Methane \cdot 2$$
 (3)

$$H (kWh) = Total Methane \cdot 2.5$$
(4)

To evaluate the profitability of the installation, NPV, IRR and PP concepts were used as valuation criteria. NPV analysis is a form of intrinsic valuation and is used extensively across finance for determining the value of a business project investment. The NPV is the sum of expected net cash flows measured in today's currency and is given by:

$$NPV = -I + \sum_{t=0}^{n} \frac{CAF_t}{\left(1+r\right)^t}$$
(5)

and:

$$CAF_t = p_t Y_i - v_t Z_i \tag{6}$$

where CAF is expected cash flow at time t, r is discount factor, and I is initial capital investment cost. CAF is a function of income  $p_t$  from i outputs (Y) where output relates to electricity and heat (no income from digestate sale is assumed) and cost  $v_t$  from i inputs (Z) where input include total operating and maintenance costs including labor cost (no cost for feedstock supply and digestate disposal are assumed). IRR is the discount rate for which the total present value of cash flows equals cost of investment. if the IRR is greater than or equal to the cost of capital, the investor can accept the project as a good investment.

## 3. Results

#### 3.1. Experimental Study

The batch test results showed that combined inoculation can enhance the biogas production when using digested activated sludge with digested organic fraction of MSW in a ratio of 25:75 [20]. Semi-continuous reactors were established and operated at 36 °C to evaluate the process for 95 days (4.75 HRT). The results of pH, redox, FAN, FOS/TAC, and biogas yield are depicted in Figures 1 and 2. The process stability was evaluated in terms of the aforementioned parameters, which were relatively constant for all the reactors during the experiment [35].

The co-inoculated reactor R1 reached 188 mL·day<sup>-1</sup>·g VSsubstrate<sup>-1</sup> 12.6% higher than that in reactor R2 (167 mL·day<sup>-1</sup>·g VSsubstrate<sup>-1</sup> (Figure 1). The methane content in the biogas from reactor R1 64.7% slightly higher than the methane content of 61.4% in the biogas from R2. The daily biogas production rate increased in the first 3 weeks and became stable for the next ten weeks. The pH of the reactor content is an important parameter to evaluate the AD performance. This is due to the high sensitivity of the methanogens to pH variations [36]. Several reports refer to a pH range of 6.8–7.2 as optimum for the activity of the methanogens [37,38]. The pH also affects the other microbial activities and thus the digester conversion efficiency. A low pH significantly decreases the reactor performance.



Figure 1. Cont.



Figure 1. Evolution of biogas yield, pH, and redox during the semi-continuous experiment.

The pH range for the co-inoculated reactors was between 6.84–7.28 for R1 and 6.85–7.27 for R2 (Figure 1). Preceding studies also state that different microbial species have specific pH values for optimal activity [39,40].

Concentration of volatile fatty acids and total alkalinity in the reactors were monitored daily and were plotted as FOS/TAC ratio in Figure 2.

The significant higher buffer capacity in the co-inoculated reactors resulted in an optimal pH for the methanogenic bacteria. No extra alkalinity was added in these reactors and the inocula were considered as the only source of alkalinity. The FOS/TAC ratio in reactor R1 ranged between 0.14–0.26 whereas the ratio n in reactor R2 lied between 0.11–0.29. If the FOS/TAC ratio falls in the range of values between 0.20 and 0.3, the anaerobic digestion process is then considered as stable. With a ratio of less than 0.20, the microbes begin to "feel hungry" and require the decrease of the inoculum-to-substrate ratio, while a value greater than 0.3 indicates the beginning of "indigestion" [41–43].

The evolution of free ammonia (FAN) increased faster in reactor R1 during the experimental period and reached a 12% higher steady state value than in reactor R2 (Figure 2). FAN is partly free ammonia (NH<sub>3</sub>) that is able to penetrate a bacterial cell membrane resulting in a proton imbalance that results in an increased intercellular pH, inhibiting specific enzyme responses, and increasing maintenance energy requirements [44,45]. Inferences redounded from long-term continuously operated reactors, showed that adaptation of anaerobic digestion to high FAN (up to 1 g·L<sup>-1</sup>) is possible, most likely as a result of an increase in specific ammonia tolerant species [46,47]. Considering the above findings, the co-inoculation represents an efficient solution for digesters as well as a sustainable solution with ecological benefits. A financial evaluation is interesting to assess other factors than the mixing ratio for full-scale applications.



Figure 2. Evolution of FOS/TAC and FAN during the semi-continuous experiment.

## 3.2. Feasibility Study

The biogas yield, methane content, and AD performance from the experimental study support the financial assessment. The annual consumption of toilet paper in the Netherlands is approximately 180 kton [48]. Assuming 70% recovery, the FSF that can be annually extracted from waste water treatment plants is up to 126 kton (dry basis) or 630 kton pressed FSF (wet basis). In our study, we examined the case of 10 kton pressed FSF (wet basis) that corresponds to 1.6% of the total capacity of pressed FSF treatment potential in The Netherlands. To have a prudential assessment and avoid overestimation, the values of Table 3 were set for the base scenario of the biogas installation:

Investment is paid from own equity capital (100% down payment) with no borrowed capital (i.e., loan) or subsidy. We assumed 12 years as the average life-span of the installation with a discount rate of 7%. In addition, costs for the maintenance of digester and CHP unit are included in the for the operation and maintenance in the O&M cost.

The base scenario produces 39 kWh per ton feedstock digested based on the values of Table 4. Further to the biogas quantity, the economic analysis for the biogas plant that used pressed fine sieve fraction as a substrate has been examined for the NPV concept. Higher NPV values represent greater economic benefits. In a "no subsidy" situation, the plant has 11 years payback time (PP), and showing a positive NPV of  $11,240 \in$  and IRR of 8% (Figure 3).

Parameter	Unit	Base Scenario
Biogas yield	$m^3 \cdot g VS^{-1}$	177.5
CH <sub>4</sub> content	%	63
Electricity produced from 1 m <sup>3</sup> CH <sub>4</sub>	kWh	2
Heat produced from $1 \text{ m}^3 \text{ CH}_4$	kWh	2.5
Total installation cost (TIC)	€·kW <sub>installed</sub> <sup>-1</sup>	6000
Operational & maintenance cost	€·kWh <sup>-1</sup>	0.065
Extraordinary generator cost	€·kWh <sup>-1</sup>	0.002
Extraordinary plant cost	€·kWh <sup>-1</sup>	0.005
Transport cost	€.ton <sup>-1</sup>	2.5
Electricity price	€·kWh <sup>-1</sup>	0.11
Heat price	€·GJ <sup>-1</sup>	30
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Table 3. Average values for techno-economic r	parameters used in the NPV analysi	s.
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Table 4. Technical data for the biogas plant.

	Unit	
PFSF digested	ton·year <sup>-1</sup>	10,000
Biogas produced	m <sup>3</sup> ·year <sup>−1</sup>	309,571
Methane produced	$m^3 \cdot year^{-1}$	195,030
Operating time	hour	8040
Electrical energy produced	MWh	390
Heat energy produced	GJ	1755
Total power installed-Pel.	kW	49



Figure 3. Economic results of the base case study based on the NPV model.

Table 5 shows the investment costs, revenues, gross cash flows, net present value, internal rate return, and payback period time for the case study of the base scenario. According to Equation (6), the total capital investment is approximately estimated up to  $300,000 \notin$ . The total revenue is  $95,565 \notin$  and the net cash flow is  $37,458 \notin$  for each year. It is notable that an external subsidy might play a significant role in the profitability of the plant and makes the choice for a  $300 \notin$  investment somewhat easier.

		Present	Year 1	Year 2	Year 3	Year 6	Year 9	Year 12
Investment								
Paid capital		-291,089	-	-	-	-	-	-
O&M cost			-25,354	-25,354	-25,354	-25,354	-25,354	-25,354
EGM cost			-780	-780	-780	-780	-780	-780
EPM cost			-1950	-1950	-1950	-1950	-1950	-1950
Transport cost			-25,000	-25,000	-25,000	-25,000	-25,000	-25,000
Total		-291,089	-53,084	-53,084	-53,084	-53,084	-53,084	-53,084
Revenues								
Electricity revenue			42,907	42,907	42,907	42,907	42,907	42,907
Heat revenue			52,658	52,658	52,658	52,658	52,658	52,658
Total revenues			95,565	95,565	95,565	95,565	95,565	95,565
Cash flows								
Gross cash flow			42,480	42,480	42,480	42,480	42,480	42,480
EBITDA			42,480	42,480	42,480	42,480	42,480	42,480
Asset value			268,698	246,306	223,915	156,740	89,566	22,391
Fiscal depreciation			22,391	22,391	22,391	22,391	22,391	22,391
EBIT			20,089	20,089	20,089	20,089	20,089	20,089
Tax			5,022	5,022	5,022	5,022	5,022	5,022
Net cash flow (NCF)			37,458	37,458	37,458	37,458	37,458	37,458
Cumulative NCF			-248,033	-210,575	-173,117	-60,743	51,631	164,005
Net discounted CF (NDCF)			32,717	30,577	28,577	23,327	19,042	15,544
Cumulative NDCF			-248,033	-210,575	-173,117	-99,949	-38,732	11,240
Net present value (NPV)	11,240							
Internal rate of return (IRR)	8%							
Payback period (PP)	11							

Table 5. Economic results of the case study based on the NPV model.

The NPV analysis revealed insights of the viability of a biogas plant treating PFSF. Electricity and heat prices, transport and operation cost as well as the biogas yield are pivotal decision parameters. These parameters allow model users to determine whether certain changes in the given situation (base scenario) might affect the profitability. A change of  $\pm 5\%$  and  $\pm 10\%$  on these parameters was applied to examine how they influence the profitability. Their impact on the NPV value is depicted in Figure 4.



**Figure 4.** The influence of a 5% and 10% change of the parameters in on the profitability of a biogas plant.

## 4. Conclusions

This study aimed at exploring the feasibility of electricity generation and heat recovery from a biogas plant treating the fine sieve fraction available in The Netherlands. The NPV model was used in this study to facilitate the economic assessment. PFSF was anaerobically treated in semi-continuous mode with two different inocula. The reactors were run for 4.75 HRT and produced an average biogas

yield of 177.5 mL·day<sup>-1</sup>·g VSsubstrate<sup>-1</sup>. The results from the semi-continuous mode were used in the economic analysis to evaluate the feasibility of a biogas unit treating PFSF. The potential producible electricity energy and heat energy from a biogas plant treating PFSF have been 390 MWh and 1755 GJ per year respectively. In The Netherlands, biogas is mainly produced from the sludge that is produced in aerobic wastewater treatment and combusted for electricity generation. In addition, AD technology and policy drivers might reinforce the implementation of alternative AD pathways. This study can be further expanded to incorporate and address the assumptions and uncertainties associated with the operation costs, funding, price of feedstock purchase (if available), and the price of digestate sale and disposal. Notwithstanding, environmental and ecological assessment would be interesting in order to examine other factors than the techno-economic for full-scale applications.

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# Abbreviations

AD	anaerobic digestion
EBIT	earnings before interest and tax
EBITDA	earnings before interest, taxes, depreciation and amortization
EGM	extraordinary generator maintenance
EPM	extraordinary plant maintenance
EU	European Union
FAN	free-ammonia nitrogen
FOS/TAC	fatty acids/total alkalinity
FSF	fine sieved fraction
HRT	hydraulic retention time
IRR	internal rate of return
MSW	municipal solid waste
NPV	net present value
O&M	operation and maintenance
OLR	organic loading rate
PFSF	pressed fine sieve fraction
PP	payback period
TCI	total capital investment
TIC	total installation cost
WWTP	waste water treatment plant

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