Environmental perspectives on using cast seaweed for biogas production

Fredenslund, Anders Michael; Møller, Henrik Bjarne; Christensen, Thomas Budde; Kjær, Tyge

Publication date: 2012

Document Version
Peer reviewed version

ENVIROMENTAL PERSPECTIVES ON USING CAST SEAWEED FOR BIOGAS PRODUCTION

A. M. FREDENSLUND*, H. B. MØLLER**, T. B. CHRISTENSEN* AND T. KJÆR*

* ENSPAC, Department of Environmental, Social and Spatial Change, Roskilde University, Universitetsvej 1, 4000 Roskilde, Denmark
** Department of Engineering, Aarhus University, Finnlandsgade 22, 8200 Aarhus N, Denmark

SUMMARY: Solrød Municipality, Denmark is working towards building a biogas plant utilizing locally available organic wastes including cast seaweed, which is collected each year, since the local inhabitants see this material as a nuisance. A preliminary study suggested favorable conditions for constructing a mixed substrate biogas plant. Continuously fed reactor experiments showed that the intended mix of substrate including cast seaweed could be used as raw material for a biogas plant in thermophilic operation. The environmental analysis suggests existence of several positive benefits of utilizing cast seaweed in Solrød, among which are: Production of renewable energy, greenhouse gas reduction, nutrient recycling and odor reduction.

1. INTRODUCTION

Solrød Municipality located 20 km south of Copenhagen, Denmark is working towards building a mixed substrate biogas plant, which will be utilizing organic industrial wastes, manure and cast seaweed. This is done to reduce greenhouse gas emissions.

The bay of Køge Bugt, which comprises the eastern border of Solrød Municipality and is in the eastern part of the Baltic Sea, is nutrient rich, and eutrophication causes an increased production of sea algae. This leads to a large amount of seaweed washing up on the shores of the bay each year. Local inhabitants have a strong wish to have the material removed from the beach and water. This is being done, causing thousands of tons of waste, which needs to be treated each year. Now, this material is being used for soil improvement, which results in a recycling of the nutrients. Another option is anaerobic digestion, where the collected cast seaweed is used for biogas production, whereby both nutrient recycling and energy production is possible.

Accumulation of large amounts decomposing macroalgae on shores is not a problem affecting only Solrød or the Baltic Sea. Ye et al., 2011 reviews the current status of these macroalgal blooms or so-called “green tides”, where they map the occurrence of this phenomenon on a global scale. They describe the worlds’ largest recorded green tide as having occurred in the Yellow Sea of China in 2008 where an estimated more than 1 million tons of drifting biomass covered an area of 13,000 to 30,000 km². The review also lists identified negative effects citing various
studies. These negative effects include occurrence of toxins, production of antifouling agents causing loss of macroinvertebrates, decline in tourism, anoxic conditions, sulfide poisoning of faunal species and odor nuisance (Ye et al., 2011).

Utilizing cast seaweed for bioenergy purposes has been the subject of several studies through the years, whereas recently cultivating macro-algae for bioenergy has been the main focus point. Cecchi et al., 1996 concluded through reactor experiments that anaerobic co-digestion of macro algae harvested from the Venice lagoon and sewage sludge could be feasible and could “contribute to the solution of the final disposal of the 50,000 m³ of macrophytes harvested each season”. Nkemka and Murto, 2010 studied methane production from anaerobic digestion of cast seaweed from Trelleborg, Sweden, which is located approximately 60 km from Solrød. They measured methane potentials of cast seaweed in batch tests and in an up flow anaerobic sludge blanket (UASB) digester combined with a chemical removal of heavy metals. Removal of heavy metals was tested since they had identified elevated concentrations of cadmium in samples of cast seaweed from Trelleborg, which would hinder use of the digestate as fertilizer.

In 2010-2011 Solrød Municipality in cooperation with Danish universities, consultants, local businesses as well as neighbouring municipalities performed a preliminary study on possibilities of realizing a biogas plant using locally available wastes including cast seaweed. The study, which methods and results are described in Fredenslund et al., 2011, concluded that it would be feasible to construct a biogas plant, where co-digestion of approximately 150,000 tons year⁻¹ of industrial wastes (mainly from a local pectin and carrageenan production facility), cast seaweed and manure would result in biogas production of 5.4M m³ CH₄. Several positive environmental effects were quantified – many of which were attributed to the utilization of cast seaweed. Recommendations on further studies were listed, among which were further development or gathering of knowledge regarding seaweed “harvest” methodology and further methane production experiments with the identified available materials in continuously fed reactor tests. This paper concerns results of these studies with emphasis on potential benefits and challenges regarding utilizing cast seaweed for anaerobic co-digestion.

2. CO-DIGESTION OF CAST SEAWEED AND OTHER WASTES IN SOLRØD, DENMARK – PROJECT STATUS

2.1 Preliminary study

The overall aim of the study performed in 2010-2011 was to develop a bioenergy concept in a region with a relatively low amount of livestock, and thereby manure, by including “alternative” biomass fractions such as cast seaweed and organic waste from production of pectin and carrageenan. Specific aims included: (Fredenslund et al., 2011)

- Determination of availability and suitability of organic materials for anaerobic digestion.
- Optimization of collection and pretreatment of organic materials.
- Development of technological and economical optimal incorporation of energy production in the local energy supply infrastructure.
- Environmental assessment.
- Evaluation of possibilities of utilization of degassed biomass.

Based upon a publicly available database maintained by the Danish Ministry of Food, Agriculture and Fisheries, amounts of manure from nearby farms were estimated. Amounts of cast seaweed were estimated based upon records kept by the local contractor, who collects seaweed in Solrød Municipality. Interviewing the production manager at the local pectin and carrageenan manufacturer provided data on amounts and compositions of pectin and carrageenan wastes. The amounts of locally available organic materials suitable for anaerobic digestion were
quantified. The available amounts were: pectin waste (77,000 tons year⁻¹), carrageenan waste (2,400 tons year⁻¹), cast seaweed from Køge Bugt (22,200 tons year⁻¹), manure from pigs and cattle (52,800 tons year⁻¹) and horse manure and grass cuttings in lesser amounts.

The overall production of biogas was estimated to be 5.4M m³ CH₄, based on measured methane potentials of the different waste fractions and assuming that 75% utilization of the methane potential would be achieved. The bulk of the biogas production will be caused by digestion of pectin waste, which is due to relatively high methane potential, high material availability and a high content of volatile solids (VS: 98-99%).

Three biogas plant concepts, which differed in type of energy utilization were considered: Use for process energy at the pectin and carrageenan production facility, biogas upgrade and supply to the natural gas grid and combined heat and power (CHP). These biogas plants were evaluated with regards to construction costs, running costs, energy production and consumption, income as well as environmental consequences with emphasis on net reduction in green house gas emissions. Net reduction of green house was found to be highest for the CHP plant concept. Factors considered when calculating the net reduction were substitution of fossil fuels, reduction in chemical fertilizer use, reduction of uncontrolled methane emissions, transportation of biomass and energy demand of the biogas plant.

Necessary actions prior to constructing the biogas plant were identified. These included testing the mix of materials in a pilot scale digester, preparation of a final, detailed plant design, securing contracts with biomass suppliers and energy companies, securing necessary permits and establishing a bioenergy company, which will be responsible for building and operating the biogas facility (Fredenslund et al., 2011).

2.2 Biogas production study

2.2.1 Aims of the study

It was considered to be very important to demonstrate that the mixture of materials intended for the biogas plant was usable for anaerobic co-digestion. The overall aim of the study was to determine the feasibility of co-digestion of seaweed, pectin waste, carrageenan waste and manure including testing this mix of materials in a continuously stirred reactor.

Secondary aims were to study the following:
- Potential gas yields for the materials and mix of materials (batch tests).
- Gas production under thermophilic and mesophilic conditions (reactor tests).
- Effects of adjustments on feeding rates (reactor tests).
- Possible solutions to inhibition of anaerobic digestion, if inhibition was observed.

2.2.2 Materials and methods

Solrød Municipality provided samples of cast seaweed consisting mostly of eelgrass (Zostera marina) from Solrød beach, pectin waste and carrageenan wastes from CPKelco. Pig manure was collected from the slurry storage pit of pig farm at the Research Centre Foulum, Denmark. Inoculum for both batch and continuous experiments were taken from the commercial biogas digester at Research Centre Foulum, Denmark, running with co-digestion of manure, maize silage and industrial bio-wastes and operating at a thermophilic temperature (52 °C).

Batch experiments were carried out to measure biogas potential of the different substrates, as well as the mixture of substrates in the mixing wet weight ratio expected at the biogas plant - 4:57:2:37 for seaweed, pectin waste, carrageenan waste and manure. The batch experiments were done as described by Møller et al., 2004. 500 mL Infusion glass bottles fitted with butyl rubber stopper were used. 200±1 g of degassed inoculum was used. The inoculum had been kept
in an incubator at $50 \, ^\circ C$ for 3 weeks followed by filtration through a 500μm sieve (5564470 D-42759 Haan, Germany) and the liquid fraction was used in the experiment. After sealing each infusion bottle, the headspace was flushed with 99.9% nitrogen gas for 2 min. After preparation, the bottles were kept in a closed incubator at $35 \, ^\circ C \pm 1 \, ^\circ C$. The experiment was carried out for 94 days. All materials were tested in triplicates. Gas composition was measured using a gas chromatograph (7890A GC system, Agilent Technologies, California, USA) equipped with a thermal conductivity detector. Helium was used as carrier gas.

Continuous tests were performed to observe the results of the co-digestion process using the substrates; seaweeds, industrial wastes and pig manure. The experiments were carried out in three different reactors: $R_1$, $R_2$, and $R_3$. $R_1$ was a small reactor having the size of approximately 6.2 L, consisting 3 L of slurry and operating in thermophilic condition ($51 \, ^\circ C$) at hydraulic retention times (HRT) of 25, 20 and 15 days. The experiment was carried out continuously in this reactor for around 100 days operating first 14 days with HRT 25, followed by HRT of 20 for 65 days and finally with HRT of 15 for the last 21 days. $R_2$ was identical to $R_1$, but it was operated in mesophilic condition ($35 \, ^\circ C$) with HRT of 30 days. $R_3$ was a larger reactor having 25 L of volume. In this reactor, 15 L of slurry was kept and operated in thermophilic condition ($51 \, ^\circ C$) with HRT of 25 days for a period of around 2.5 months. Daily manual feeding system was done in all reactors with different composition of biomass under different conditions. Feeding the reactors was done only after removing the digested slurry from a port or outlet at the base of the digesters in equal amount to that of feeding quantity. In each feeding, the outlet of feeding pipe was submerged in substrate to avoid the ingress of air.

In the continuous experiments, biogas composition was measured using a gas chromatograph (7890A GC system, Agilent Technologies, California, USA) equipped with a thermal conductivity detector. Helium was used as carrier gas. The measurements were generally performed twice a week.
Higher than the yield from commonly used substrates like manure, grass, some domestic wastes, etc.

Figure 2: The ultimate methane yield of the substrates.

3.2 Continuous experiment
3.2.1 Methane production
The methane productions from the thermophilic reactors operating in different HRT are illustrated in Figure 3. The mean methane yield from the reactor operating with 25 days HRT was 307±45 L kgVS⁻¹ day⁻¹. Similarly, the production from the reactor operating with 20 days HRT was 294±31 L kgVS⁻¹ day⁻¹. These were the results obtained when the process was continued at least 3 times the HRT. Considering this methane yield, maximum 81% of the ultimate methane yield of substrates was possible in the continuous experiment. When the HRT period reduced from 25 to 20 days, the process proceeded normally; however, the average yield reduced by 4%. The value is comparable with Heiske and Schmidt (2011), where 11% pectin wastes was used to mix with manure. An additional test was performed by reducing the HRT to 15 days and the process continued for times almost equal to HRT period. On doing so, a problem of choking the stirrer due to high solid content of substrates was observed. Therefore, liquid fraction of slurry was separated and recirculated into the digester. During that process, some changes in the biochemical parameters were observed but surprisingly, the average yield maintained high.

Total volatile fatty acids – TVFA (C₂-C₅) measurements were performed by using a gas chromatograph (7890A GC system, Agilent Technologies, California, USA) with flame ionization detector (FID). Helium was used as carrier gas. The measurements were generally done twice a week. Similarly, the pH of the slurry sample was measured twice a week using a pH meter (Knick Type 911, Berlin, Germany). TS, VS and ash content were determined by drying the sample in 105 °C for 24 hours in a dryer and combusting the dried sample in an oven at 550 °C for 5 hours.

2.2.3 Results
The average ultimate methane yield from cast seaweed, pectin waste, carrageenan waste, pig manure, and mixture were 100, 441, 192, 308 and 375 L kgVS⁻¹ respectively (see Figure 2). The value for methane potential of pectin waste was very close to the methane potential measured under thermophilic conditions in the preliminary study (460 L kgVS⁻¹) (Fredenslund et al., 2011). The methane potential of cast seaweed consisting mainly of eelgrass (100 L kgVS⁻¹) was also comparable to results from the preliminary study, where cast seaweed from Solrød Municipality similarly consisting mainly of eelgrass was tested for methane potential (118 L kgVS⁻¹). The ultimate methane yield of the mixture of seaweed, pectin waste, carrageenan waste, and pig manure with ratio of 4:57:2:37 respectively was observed to be quite high (375 L kgVS⁻¹), which was close to the calculated value considering each material’s methane potential and mixing ratio (368 L kgVS⁻¹).

Methane production measured from the thermophilic reactor R₁ fed with the mix of materials operating in different HRT is illustrated in Figure 3. The mean methane yield from R₁ operating with 25 days HRT was 307±45 L kgVS⁻¹. Reduction of HRT led to a slight decrease in yield: 294±31 L kgVS⁻¹ or approximately 4%. The methane production observed at HRT = 20 days was 81% of the methane potential measured for the mix of materials. When reducing HRT to 15 days, the methane yield remained high in the 21 days of operation (294±24 L kgVS⁻¹), but TVFA was observed to increase sharply at these operating conditions causing decreasing pH, which may indicate instability of the process at HRT of 15 days.
Figure 3. Measured methane production and gas composition (methane content) during reactor experiment R₁ operated at thermophilic conditions.

In the experiment using the larger reactor R₃ operated at constant HRT at 25 days and also at thermophilic temperature, a slightly higher methane yield was observed (297 to 317 L kgVS⁻¹). It was possible to start the reactor feeding it with the described mix of materials without any problems.

Reactor R₂ operated at mesophilic temperature failed after approximately one week of operation, where a rapid increase of VFA (from 60 to 12,000 mg L⁻¹) and sharp reduction of pH (from 8.2 to 6.5) was observed. Restarting the reactor with new inoculum yielded similar results – moderate gas production (approximately 200 L kgVS⁻¹) for one week followed by digester acidogenesis and failure. It is noted that inoculum from a digester operating in thermophilic conditions was used in R₂ as well.

2.3 Other activities

2.3.1 Testing seaweed collection methods

High sand content in collected cast seaweed is a challenge, if the material is to be used in a biogas plant. The method presently used in Solrød, when abundance of cast seaweed is high is to scrape the cast seaweed onto the beach using front loaders, followed by collection of the material using a beach cleaner. Sand content of the material was found to be 60-90% w/w of dry solids (Fredenslund et al., 2011). This meant that either a pretreatment to remove sand will be necessary before using this material in a biogas plant, or that another seaweed collection method could be used, where sand content is kept at a minimum.

Halmstad Municipality, Sweden is working on a similar project, in which context they have developed a prototype “harvester” specifically aimed at collecting cast seaweed with a low sand content. This harvester was tested in Solrød. It was found to be able to collect approximately 30
Figure 4. Testing a prototype seaweed harvester in Solrød. The machine developed in Halmstad, Sweden is a modified pea harvester, which was developed for collecting cast seaweed in the water as well as on shore.

m$^3$ of cast seaweed per hour, and the measured sand content (23-40% w/w of dry solids) was significantly lower than the material collected with previously described method. It is, however, not yet clear if the sand content is low enough to avoid the necessity of pretreatment.

2.3.2 Environmental impact assessment

As part of securing necessary permits to be able to realize the biogas plant, an environmental impact assessment (EIA-assessment) was completed. According to Danish law, the purpose of this report was to provide the best possible basis for public debate and the final decision to proceed with the project. The EIA-assessment had to describe the biogas plants’ direct and indirect effects on:

- People, fauna and flora.
- Soil, water, air, climate and landscape.
- Material goods and cultural heritage.
- Links between these factors.

(Hansen, 2011).

Since many of the listed factors are linked to the exact location of the biogas plant, this had to be established prior to completing the EIA-assessment. The location was chosen partly through a public hearing process. Also, the final plant concept had to be decided upon regarding the type of utilization of the produced biogas. Combined heat and power was chosen, since the established exact location of the facility was close to the southern most part of a large district heating network serving households and businesses in Copenhagen and surrounding area, where utilization of heat from the biogas plants’ CHP unit would be possible the entire year.

Among the conclusions from the EIA-assessment, two major environmental advantages where pointed out: The net reduction of greenhouse gasses resulting from a realization of the biogas plant would be approximately 40,500 tons CO$_2$ eq. year$^{-1}$, which corresponded to approximately half of the municipality’s CO$_2$ reduction targets it had set for 2025 through the EU Covenant of Mayors initiative. Secondly, the use of cast seaweed causes recycling of nutrients in the same
order of magnitude as the reduction targets set for the local coastal zone from EU Water Framework Directive.

3. DISCUSSION

Anaerobic co-digestion of cast seaweed with manure and other wastes was found to be feasible in this case, based on results from reactor tests. Using cast seaweed as a part of a mix may be a solution to the problem that availability of this material varies over the year – at least in temperate climates, which may be a challenge if the material is to be used as a mono-substrate.

The tested prototype harvester was seen to be effective in collecting cast seaweed with relatively low sand content. However, the machine probably cannot operate on more rocky coasts, where other collection methods need to be used.

The prevalence of anoxic conditions in algae mats often reported suggests the occurrence of anaerobic decay, which may result in emission of methane. Assessment of avoided uncontrolled methane emissions were done in this study based partly on estimates regarding the “methane conversion factor”, i.e. how much of the potential methane production is realized when the seaweed undergoes decay. No studies were found, where these emissions were quantified using field measurements. Since reduction in methane emissions may be a significant benefit of using cast seaweed for biogas production, more quantitative studies on this subject would be useful.

ACKNOWLEDGEMENTS

Vækstforum Sjælland and Solrød Municipality funded the study. We thank the Municipality of Halmstad, Sweden with regards to cooperation in this project. Dhan Prasad Ghautam at Aarhus University is acknowledged for performing measurements described in chapter 2.2.

REFERENCES


