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Optimised biogas production from the co-digestion of sugar beet with pig slurry: Integrating energy, GHG and economic accounting

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A B S T R A C T

Several countries have established a number of increased targets for energy production from renewable sources. Biogas production, which will play a key role in future energy systems largely based on renewable sources, is expected to grow significantly in the next few decades. To achieve these ambitious targets, the biogas production chain has to be optimised to obtain economic viability and environmental sustainability while making use of a diversified range of feedstock materials, including agricultural residues, agro-industrial residues and, to some extent, dedicated energy crops. In this study, we integrated energetic, GHG and economic analysis to optimise biogas production from the co-digestion of pig slurry (PS) and sugar beet pulp silage (SB). We found that utilising SB as a co-substrate improves the energy and GHG balances, mostly because of increased energy production. However, utilising SB negatively affects the profitability of biogas production, because of the increased costs involved in feedstock supply. The scale of the processing plant is neutral in terms of profitability when SB is added. The results indicate that medium-to large-sized biogas plants, using low shares of SB co-substrate, may be the preferred solution.

1. Introduction

Anaerobic digestion (AD) is one of the most efficient technologies for extracting clean and renewable energy from biomass with high water content [1]. In addition, AD is useful for recycling nitrogen (N) and phosphorus (P) from animal manure, which is in great need worldwide [2,3], and it is also considered to be the most effective technology for reducing greenhouse gas (GHG) emissions from manure management and at a low cost [4,5]. AD is fully integrated into Denmark's long-term strategy to be independent of fossil fuels before 2050 [6,7]. In accordance with this strategy, 50% of all animal slurry must be used in AD by 2020 [8], and 60% of organic waste from public services (up from the current level of 17%) will be collected and utilised for biogas production by 2018 [9]. In 2050, biogas plants are expected to be processing about 42 PJ of biomass, corresponding to >7% of all energy input for Denmark, while 16–22% of all biomass will be routed to energy production [10].

Abbreviations: AD, anaerobic digestion; BMP, biochemical methane potential; CHP, combined heat and power; CSTR, continuous stirred tank reactor; EF, emission factor; GHG, greenhouse gases; HRT, hydraulic retention time; PS, pig slurry; SB, sugar beet pulp silage; TC, total cost; TI, total income; TNI, total net income; TS, total solids; VS, volatile solids; VS_D, degradable volatile solids; VS_{ND}, non-degradable volatile solids; ww, wet weight.

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The AD of animal manure is in focus for two reasons: 1) large amounts of manure are available in Denmark [11] and 2) it allows for the better management of N and P nutrients at the regional level. In Denmark, manure is currently collected in the form of slurry, with a water content of about 95% and an organic matter content of ca. 4% [12]. Owing to this high water content, manure can only be used at the present time for biogas production, though hydrothermal liquefaction may represent an alternative to anaerobic biogas production in the future. Manure has a low biogas production potential [13], meaning that its digestion needs to be boosted by a more energetic co-substrate [14]. Suitable co-substrates include other agricultural residues, organic industrial by-products (e.g. from the food industry) and dedicated bioenergy crops.

The amounts of biogas to be produced and the portfolio of biomass materials to be used represent important logistical and management challenges, the combination of which hinders environmentally sustainable and economic viable biogas production in the country. Environmental and energetic issues related to biogas production are depicted rather comprehensively in the available literature, focusing for example on the digestion and/or co-digestion of manure (e.g. Hamelin et al. [15]; De Vries et al. [16]; Lansche & Mueller [17]), municipal organic waste (e.g. Møller et al. [18]; Bernstad et al. [19]; Boldrin et al. [20]; Levis & Barlaz [21]), industrial co-products (e.g. Berglund & Börjesson [22]; Tufvesson et al. [23]), sewage sludge (e.g Tarantini et al. [24]; Lederer & Rechberger [25]; Nakakubo et al. [26]), energy crops and/or cropping systems (Amon et al. [27]; Gerin et al. [28]; Jury et al. [29]; Schumacher et al. [30]; Blengini et al. [31]; Buratti et al. [32]; González-García et al. [33]). These studies indicate that biogas production from residual biomass is generally environmentally beneficial, but the modelling of biogas from energy crops somehow seems more complex, as it must consider carefully local conditions regarding crop cultivation and the supply chain [34]. The economic viability and optimisation of biogas production has also been investigated in a number of studies (e.g. Walla & Schneeberger [35]; Power & Murphy [36]; Gebrezgabher et al. [37]; Karellas et al. [38]; Stürmer et al. [39]; Brown et al. [40]; Delzeit & Kellner [41]; Møller & Martinsen [42]; Riva et al. [43]; Schievano et al. [44]), indicating that the profitability of biogas production is generally related to factors such as the plant size, the cost of feedstock, initial investment, costs for storage and transportation and biogas yield.

The integration of environmental and economic assessments was only attempted in a few cases. Most of these studies – e.g. Murphy et al. [45], Ayoub et al. [46], Ayoub et al. [47], Luo et al. [48], Santibanez-Aguilar et al. [49], Hennig & Gawor [50] –, however, focus on the use of dedicated energy crops and their conversion in complex and centralised biorefinery systems used for fuel production. Biogas production from residual materials is investigated, for example, in Yabe [51]. These studies nonetheless are static in nature, as the assessments are carried out at the scenario level. When looking at the co-digestion of residual biomass and energy crops, no studies were found to have attempted to optimise biogas production by dynamically modelling individual sub-parts of the biogas chain.

Therefore, the objective of the study presented herein is to develop a joint value-chain, energy and environmental model, to be used for optimising biogas chain production. This model is meant to provide advice to managers and decision makers in the form of a holistic evaluation of risks and benefits in producing biogas using sugar beet pulp silage (SB). This objective is achieved by 1) developing detailed economic, GHG emission, energy and mass models for the biogas chain, 2) integrating these models into a single framework capable of describing the relationships between economy, energy and emissions, while taking into consideration scaling effects, 3) applying the model to optimise the use of beet roots in manure co-digestion and 4) identifying the optimal scale of the biogas plant.

2. Materials and methods

2.1. The biogas production chain

As shown in Fig. 1, the biogas production chain assessed herein consists of five main process units, including:

- Raw material input: cultivation and harvesting stages
- Pre-treatment: washing, slicing and ensiling
- Transportation: transportation to the biogas plant and transportation to the farm
- Energy production: mixing tank, anaerobic digester, post-digestion plant and combined-heat-and-power (CHP) plant or gas upgrade for the gas transmission net
- Digestate process and fertiliser unit: after-storage and field stages

SB is first cultivated and then harvested between September and mid- or late November [52]. While harvesting, the root is separated from the beet top and left on the field. Beet roots carry a significant amount of soil, and so a cleaning step is thus required. Cleaning is normally performed at the farm level, but centralised cleaning can occur in some cases. The soil removed from the root is returned to the field. SB harvested in November are then stored in clamps covered with straw [52]. In February, the roots are chopped finely into beet pulp and moved into silos for 18 months (i.e. until September next year). Ensiling leads to the degradation of some organic pools, so that total solids (TS) and volatile solids (VS) contents change, while GHG are emitted. When needed, SB is collected and then mixed with pig slurry (PS) to a known ratio, and the mixture is then pumped into an AD reactor. PS is the main substrate, whereas SB is the co-substrate providing different benefits to the process: it contains abundant trace elements for microbial growth, it has a strong buffer capacity, thereby helping to maintain pH neutrality, and it is a good diluter for toxic compounds potentially contained in the manure. In the present study, the co-digestion of three mass-based ratios of PS and SB in the feedstock is analysed:

- PSSB-0: 100% PS, 0% SB
- PSSB-12.5: 87.5% PS, 12.5% SB
- PSSB-25: 75% PS, 25% SB

The additional use of SB (i.e. a 50/50 ratio) was attempted in preliminary tests; however, the AD operation was unstable with the accumulation of VFAs and a drop in pH level.

The main product of the digestion process is biogas (i.e. a mix of CO_2, CH_4 and other trace gases), which can be used for electricity and/or heat production, or fed to the natural gas grid. Depending on the final recipient and the energy conversion technology employed, biogas may need to be upgraded to remove most of its CO_2 and other trace compounds. The by-product of the digestion process is a type of slurry called "digestate," which is typically partly dewatered and further stabilised by means of aerobic composting. The finally cured digestate may be stored further until its final application to agricultural land as a fertiliser and soil amendment agent. The calculations herein considered a field-application scenario where digestate is applied in early spring, prior to seeding a spring cereal crop.

In the biogas production chain, the economy of scale can be a significant factor affecting the profitability of a project. In fact,