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Postponing of the intracellular disintegration step improves efficiency of phytomass processing

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ABSTRACT

In the last two decades, subsidised purchase prices for electricity produced from biogas generated from purpose-grown crops has seen the construction of hundreds of biogas plants across Central Europe in response. The resulting intensive cultivation of monocultures has had a negative impact on the environment and has been a waste of taxpayers' money. In addition, this policy has made the processing of other biowaste uncompetitive, resulting in further public funds being spent on their disposal in landfill sites, thereby raising more environmental concerns.

Given that the conditions under which the subsidies are provided cannot be changed retroactively, proposals are being sought to increase the efficiency of biogas generation in order to reduce the volume of purpose-grown feedstock required, thereby mitigating the negative impacts on the environment and public funds alike.

A new proposal, as outlined in this article, sees the incorporation of a steam explosion device at a later stage of the fermentation process, rather than at the beginning (pre-treatment of feedstock) as conventional wisdom would have it. This proposed process change was applied on a commercial scale and techno-economically assessed. The process change generated significant savings in feedstock (29% reduction due to the intensification of the process parameters ceasing to be limited by the formation of inhibitors) whilst maintaining the same level of electricity production. As a result, the payback period was reduced by 9%, which is a good prerequisite for commercial expansion. However, this comes at a cost, namely in the form of a doubling of water demands. Intensive work is now being conducted to determine how this issue can be overcome.

1. Introduction

Central European countries initially welcomed the boom in biogas plants. Their hope was that they would bring economic benefits to marginalised areas and support the transition from fossil fuels (Tafdrup, 1994). It cannot be stated categorically that either of these assumptions have not been met to some degree (Mardoyan and Braun, 2015). However, after two decades of commercial experience with biogas, there is mounting evidence that the subsidy policy designed to support the generation of electricity from purpose—grown crops over that of electricity generated from biowaste has had a negative impact on the environment (Börjesson and Tufvesson, 2011). Within the context of this now controversial subsidy policy, maize (*Zea mays* L.) silage was determined to be the optimal solution from the economical point of view. The reasons for this are clear. Farmers were already familiar with the cultivation of maize and with the subsequent silage process, the feedstock is easy to store, and it provides good and stable yields of biogas at an affordable price (Amon et al., 2007). It was also initially assumed that the process of anaerobic digestion would also turn the silage into a valuable organic fertiliser (Chantigny et al., 2008). However, a decade later, Kolář, et al. (2008) confirmed the disappointing observations of farmers. They discovered that the ballast present in the solid fraction of the fermentation residues contains only negligible concentrations of nutrients and that it is only capable of extremely slow degradation and therefore cannot play the role of humified organic matter in soil. To make matters worse, subsequent research revealed that the agrochemical value of the liquid fraction is also negligible; the concentrations of nutrients are also low and present in organic forms that must firstly undergo mineralisation by soil biota before being acceptable to plants (Kolář et al., 2010). These findings are in line with Maroušek et al.

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(2017), who confirmed that the cost of applying the fermentation residues to the topsoil is economically unprofitable, in particular when taking into consideration the fertilisation effect and the economic and environmental advantages of processing the fermentation residues into charcoal (Maroušek et al., 2013) or biochar (Maroušek et al., 2015). Despite this, the application of fermentation residues into the topsoil remains common practice, which raises concerns about soil fertility (Oyedele and Aina, 2006). In light of the above, it would appear that under the current complex legislative framework and economic conditions, the technological efforts to increase biogas yields is the quickest way to reduce the intensity of maize cultivation. Various biological (Zhong et al., 2011), chemical (He et al., 2008), mechanical (Krátký and Jirout, 2011) or combined (Taherzadeh and Karimi, 2008) pretreatment techniques have also been examined for the processing of miscellaneous agricultural residues such as straw, husks, stalks and the like (Selig et al., 2010). However, such feedstock is excluded under the terms and conditions of the subsidy policy (Hašková, 2017). Established commercial practice for increasing biogas yields from maize silage is to subject the feedstock to intracellular disintegration, through the application of steam explosion technology, prior to the anaerobic fermentation phase (Maroušek, 2013). However, the fractions of the silage are easily biodegradable. As a result, they quickly turn into furan and hydroxymethylfurfural (among others), thereby inhibiting the subsequent fermentation process. It is for this reason that the process conditions for steam explosion (in particular the maximum temperature, operating pressure and hydraulic retention time) should be set at relatively conservative levels (0.2–0.6 MPa; 120–140 °C; 2–20 min (Liu et al., 2015)). On the basis of the above stated legal, environmental and economic issues, the following hypothesis was formulated.

Delaying the point at which intracellular disintegration (steam explosion) takes place enables the volume of feedstock to be reduced (while maintaining the same level of electricity production) and is financially beneficial.

It is assumed that the initial phase of anaerobic fermentation utilises the most easily biodegradable fractions of organic matter, and that the delayed steam explosion primarily supports the processing of the hardly biodegradable crystallic cellulose, which has fewer tendencies to form inhibitors under more intense process parameters. This therefore enables the application of more severe process parameters to achieve deeper intracellular disintegration and produce higher yields of biogas.

2. Technological setup

The project was implemented at an existing biogas plant in Nedvědice (Czech Republic). This made it possible to conduct a cash flow analysis on a commercial scale. The conventional system at the plant (prior to adaptation) involves a steam explosion pretreatment unit, 3 anaerobic fermentors, and an end storage fermentor placed in sequence (acquisition costs EUR 2 million; according to CZK-EUR exchange rate on 1st January 2018). The main form of feedstock is a mixture of maize silage (90% in wet weight; SUBITO S260; very early hybrid) diluted (and inoculated) with fresh cow slurry (see analysis in Table 1) to obtain volatile solids (hereinafter referred to as VS) of approximately 12% (techno–economic optimum for mixers and pumps). The monthly running costs of EUR 16,000 mainly consist of the feedstock (EUR 15,000). The biogas plant operates at temperatures of 36–39 °C with an average hydraulic retention time of 7 weeks. This provides 1190 kW of electricity and 1050 kW of heat (monthly income of EUR 34,800 for the electricity produced; heat is not utilised). Under the new proposal, which incorporates own production (see Fig. 1; cost of acquisition EUR 300,000; life span of 20 years; electricity, heat and water demand covered by own production; other operating costs negligible), the feedstock described above is still fed (A) into the 1st fermentor (B; inoculation and bacterial hydrolysis), whilst most of the CH_4 is produced in the second fermentor (C; acidogenesis, acetogenesis and methanogenesis). However, instead of advancing to the other fermentors (G and H) in the system, the partially fermented organic biomass is dewatered (D) using a SEPCOM separator (WAMGROUP S.p.A., Italy). This removes (25 rpm; back pressure spring tension of 300 N) approximately 85% of the water content. Using a 400 L tailor–made mixer (200 rpm), the mechanically dewatered fermentation residues are dissolved (E) in fresh water (to obtain solids of 15%) and subsequently pre-heated to a temperature of 70 °C using the low–potential heat that is recovered from the JMS 416 (GE Jenbacher GmbH & Co OG, Germany) cogeneration unit (this turns the CH_4 present in the biogas into electricity). Using the high–pressure screw pump, the slurry obtained is pumped into the continuous TTP4 high–pressure reactor (F; Biomass Technology Ltd., Czech Republic) that operates under 1.45 MPa. After a hydraulic retention time of 5 min, the slurry is released (steam explosion) from the high–pressure reactor via an expansion tourniquet (single 0.3 l explosion performed in 0.1 s) and poured into the third anaerobic fermentor (G).

Table 1
Analyses of the processed biomass, where: A = maize silage; B = cow slurry; C = routine feedstock (mixture of A and B); D = steam exploded feedstock; E = steam explosion carried out after passing through the second fermentor without removal of the processing liquid; F = steam explosion carried out after passing through the second fermentor with replacement of the processing liquid with fresh water; I = VS (%); II = CH_4 production (L kg^{-1}); III = labile organic matter (sum of 1st and 2nd grade; %); IV = sum of inhibitors (mg kg^{-1}); V = sum of cellulose and hemicelluloses (%), (n = 5, $\alpha = 0.1$).

	I	II	III	IV	V
A	31.7 ± 1.1	258.3 ± 14.0	36.1 ± 1.4	0.0 ± 0.0	22.2 ± 1.4
B	3.2 ± 0.8	56.9 ± 7.5	1.8 ± 1.2	0.0 ± 0.0	6.0 ± 1.3
C	11.4 ± 0.8	308.4 ± 11.3	8.1 ± 1.4	0.0 ± 0.0	21.1 ± 0.9
D	11.3 ± 0.9	342.7 ± 15.9	14.8 ± 1.4	1004.8 ± 155.2	23.4 ± 1.3
E	11.4 ± 0.6	375.0 ± 14.6	13.9 ± 1.7	97.1 ± 44.3	22.5 ± 1.4
F	11.3 ± 2.8	396.4 ± 11.4	14.5 ± 1.3	105.7 ± 31.4	21.8 ± 0.8

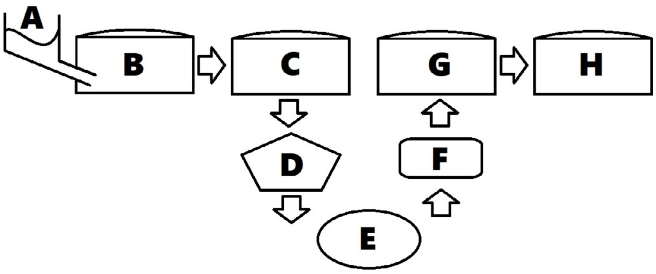

Fig. 1. Design of the upgraded technological setup, where: A = hopper with helix that pumps the feedstock under the water surface; B = input fermentor; C = second anaerobic fermentor; D = dewatering; E = addition of fresh water; F = steam explosion; G = anaerobic fermentor; H = finalisation of fermentation.

3. Analytical methods

Methane production (L kg^{-1}, hereinafter related to volatile solids and converted to 0 °C at 101.325 Pa) was calculated on the basis of the qualitative and quantitative analysis of the biogas using an AIR–LF biogas analyser (Aseko s.r.o., Czech Republic). The volatile solids (VS) were determined using an OV400 oven (Memmert