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Enhancing performance in anaerobic high-solids stratified bed digesters by straw bed implementation

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ABSTRACT

Anaerobic high-solids single-stage stratified bed digesters have been found to be simple and flexible design candidates for small-scale reactors located in medium- to low-technology environments. In the present study, wheat straw was used as the starter material for the stratified bed. Upon green mass feeding, the anaerobically stabilised straw bed functioned both as a biofilm support and as a particulate filter. It enabled a direct onset of 7 kg VS·m^{-3} batch loads, added twice a week, and it permitted a low but consistent bed permeability during feeding at an average superficial flow velocity of 1 m·d^{-1} to be achieved. Fed-batch tests with sugar beet tops in pilot- and laboratory-scale setups at an average loading rate of 2 kg VS·m^{-3}·d^{-1} resulted in average biogas production rates of 1.2–1.4 m^3·m^{-3}·d^{-1} and methane yields of 0.31–0.36 m^3·kg^{-1} VS. At the end of the laboratory-scale feeding trial, the 200 days old straw bed had compacted to 50 % of its initial volume, without any negative effects on performance being detectable.

Keywords: crop residues, straw bed priming, packing density, dry digestion, farm-scale, fixed bed, lignocellulosics, intermittent leachate recycle, foaming

INTRODUCTION

The search for alternative energy sources is an ongoing effort throughout the world. Developing countries are trying to reduce their dependence on imported fossil fuels (Kivaisi 1996), at the same time as various developed countries such as Sweden are trying to move away from use of hazardous and waste producing energy sources (Gustavsson et al. 1992). Renewable energy sources are often prioritised in efforts to mitigate the greenhouse effect and eventually achieve a completely sustainable energy supply.

Residual plant biomass from agriculture and forestry constitutes a major source of renewable energy. If it is digested under anaerobic conditions, the energy recovery will be highly sustainable, provided the methane produced is retained and is fully utilised, and the digestate produced is recycled back to the soil as fertiliser. Subtropical and tropical countries are the richest sources of residual plant biomass. India alone produces 1120 million tons of residual biomass a year in dry weight (Jagadish et al. 1997). A conservative estimate (50 % utilised, 0.1 m^3 CH$_4$·kg^{-1} TS) indicates this to correspond to a biogas potential of over 500 TWh/year. Even in countries with a temperate climate, significant supplies of residual plant biomass are available. Sweden, for example, when one considers

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the residual plant biomass agriculture could provide, has an unused biogas potential of 11 TWh/year, one that could be made available within a decade (Nordberg et al. 1998).

In conventional anaerobic slurry digestion, the plant biomass needs to be homogenised and diluted down to a pumpable slurry containing only about 3–8 % total solids (TS)(Gunaseelan 1997). This increases the handling costs of the end-product (Nordberg 1996, Dalemo et al. 1993). Also, since influent heating is the major energy input, the slurry digestion of lean, dry substrates such as straw would be too costly from a heating standpoint (Legrand and Jewell 1986). Process disturbances inherent in the high water content of the slurry, such as crust and foam formation, often occur as well, resulting in low maximum loading rates and poor decomposition (Chanakya et al. 1997). If one cold reduce the amounts of process water that needed to be added, this would help avoid the problems that dilution creates, including the process problems just referred to. The development of new reactor and process designs for the high-solids digestion of plant biomass could make it possible to utilise the large energy potential of the world's ample supply of plant biomass to a greater extent, even if only small-scale reactors were involved. Most of the processes available for high-solids digestion today concern the large-scale treatment of municipal solid waste, such as the single-stage technologies of the *BIOCEL* process (Ten Brummeler 2000) and of the *DRANCO* process (De Baere 2000; Six and De Baere 1992).

To succeed with high-solids digestion on a smaller scale than this, it is essential that the approach employed be as simple as possible, so as to minimise the investment needed and the operational costs. A hybrid approach, one that combines the advantages of single- and of two-stage digestion, in the form of a single-stage downflow fixed bed reactor in which the bed is made up of the plant biomass which is being fed into the system has been proposed (Chanakya et al. 1997; 1999). At the top, the plant material fed in most recently starts to hydrolyse and acidify. The solutes trickle down further into the bed, which becomes more and more methanogenic in character, since its material is closer and closer to being fully digested. A stratification thus develops, separating the different steps of the anaerobic process in terms of their depth within the biomass bed.

The performance of such high-solids stratified bed reactors should depend to a considerable extent on the choice of the plant biomass to serve as the fixed bed. The optimal material at the bottom would be one acting both as a particulate filter and as a support for the biofilm forming microorganisms. After digestion for a period of time, this starting bed material would when function as a "primer" for the growing bed, composed of the more easily degradable plant biomass which is being fed into the reactor (here referred to henceforth as "green mass"). This primer material should be rigid in structure and have a low biodegradability in order to maximise the period of continuous operation of the reactor. A situation in which a part of the plant biomass has the dual function of serving as a biofilm support and as a particulate filter in such a stratified bed reactor has not been reported in the literature previously. Straw has been found to function well as a carrier material for biofilm processes in different anoxic and anaerobic applications involving liquid feeds (Andersson and Björnsson 2002, Soares et al. 1998, Guitonas et al. 1994, Avnimelech et al. 1993, Das et al. 1993). It has also been used for liquid manure filtration (Kaluzhnyi et al. 2000).

In the present study, the effects of using a wheat straw bed as a primer of this sort in a high-solids single-stage stratified bed reactor on both a laboratory and a pilot scale was investigated. Since a straw bed filter used for priming purposes was expected to become compacted under the joint pressure of the solids and the liquid, it was interesting to investigate the effects of the initial packing density of the straw. Other parameters that were studied were (a) the length of the startup period, (b) the bed structural stability and (c) the length of the working life of the bed, and also (d) the permeability of the bed .

MATERIAL AND METHODS
Reactor design: The laboratory-scale reactor was a water-jacketed Plexiglas column reactor (4.75 l, inner diameter 11 cm) in which the straw bed rested on a horizontal steel grid. The leachate was collected in a reservoir (0.2 l), and was recycled to the top of the reactor, where the green mass was also added. An external water-jacketed reservoir (1.0 l), as shown in Figure 1, was connected to it on day 167 of the last trial. The biogas was collected in gas-tight bags.

The two pilot-scale reactors were insulated steel-column reactors (390 l, inner diameter 50 cm) attached to insulated and thermostatted steel-bottom reservoirs (400 l). The straw bed rested on an inclined steel grid (Figure 1). The recycling from the reservoir to the top of the reactor was controlled by level indicators in the reservoir. The green mass was mixed with leachate taken from the reactor and pumped to the top of the column.

Experimental setup: The study was performed in one laboratory-scale system and in two other pilot-scale systems that were identical. The laboratory-scale trials, designated as L1, L2 and L3, were performed in series. In L2 and L3, two periods of green mass feeding were employed, whereas in L1 there was none. In the pilot-scale trials, designated as P1 and P2, the degree of straw bed compaction was checked in each of the reactors prior to feeding by means of the top hatch being opened. The first feeding was short, one batch load being used in P2 and two of them in P1. The second and final feeding period in P1 and P2, just as in L3, was the longest and most intense. The specific conditions involved are shown in table 1.

Reactor operation: In L1 and L2, the packed straw bed was inoculated with a mixed anaerobic culture from a municipal anaerobic digester, whereas in L3 it was inoculated by parts of the bed from L2 together with diluted leachate from it. During the first three weeks of the startup, the temperatures were kept at 28 and 25 °C for L1 and L3, respectively. During the week thereafter, the temperature was increased incrementally to 33 °C. The green mass, added twice a week, consisted of an undiluted mixture of fresh sugar beet leaves and ensiled ley crop (6:1 wet mass ratio, homogenised (1–3 mm), 9 % volatile solids (VS) content). In L3, a total of 2.35 l of leachate was withdrawn during the final feeding trial.

In the pilot-scale reactors, digested cow manure from a farm-scale digester working at ambient temperature was used as an inoculum. The green mass, added twice a week, consisted of roughly crushed ensiled beet tops (3–5 cm, 10–12 % VS) mixed with leachate withdrawn from the reactor. Further homogenisation took place in the pump. A total of 120

l of leachate was emptied from P1 on day 154, in order to prevent overflowing. The specific conditions involved are shown in table 1.

Analyses: Partial alkalinity (PA), total alkalinity (TA) and pH were determined either directly after sampling or within 24 hours following storage at 4 °C. In conjunction with the analysis, acidified leachate (pH < 2) was prepared and was frozen, for later use for the analysis of volatile fatty acids (VFAs). A 5 ml centrifuged volume of leachate was titrated down to pH 5.75 and 4.30 for determining PA and TA, respectively (Laboratory-scale: Andersson and Björnsson 2002. Pilot-scale: Schott TitroLine alpha; Schott-Geräte GmbH, Germany). Alkalinity was expressed as g $CaCO_3 \cdot kg^{-1}$. VFAs, VS and the biogas content were analysed according to Andersson and Björnsson (2002). In addition, on a pilot-scale, on-line measurement of CH_4 by use of the IR technique was performed during the feeding trial (GD10P 0-100 vol % CH_4 5 s source; Simrad Optronics, Norway). Gas volumes and flows were measured by volume displacement (Andersson and Björnsson 2002) and by differential pressure meters (Gallus 2000 G1,6 Actaris Technologies AB, Stockholm, Sweden) for the laboratory- and the pilot-scale setups, respectively.

Table 1: Summary of the experimental conditions

	Laboratory-scale			Pilot-scale	
Experimental designation	L1	L2 [a]	L3 [b]	P1	P2
Packing density, initial [$kg \cdot m^{-3}$]	140	100	93	62	34
Bed volume [liter]	3.5	3.3	2.7	205	281
Straw state	Fresh	Digested	Fresh/ digested	Fresh	Fresh
Trial period, total [d]	99	265	194	170	170
Trial period, startup [d]	99	22	55	52	71
Inoculum ratio [kg VS·kg^{-1} VS straw]	0.04	0.04	0.3	0.1	0.2
Wetting ratio, initial [kg inoculum·kg^{-1} straw]	4.5	4.5	5.4	32	42
Temperature [°C]	33	33	33	35	35

Notes. [a] Continued from L1 by reuse and repacking of the straw. [b] Digested straw not included in the calculation of packing density; the inoculum ratio calculation based on the total VS of the digested bed.

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Figure 1. The high-solids single-stage stratified bed reactor. Right: Pilot-scale reactor. Left: Laboratory-scale reactor with an external reservoir. Column reactor (1), metal grid (2), reservoir (3), recirculation pump (4), biogas outlet (5), biogas bypass (6), heating (7), feed inlet (8).
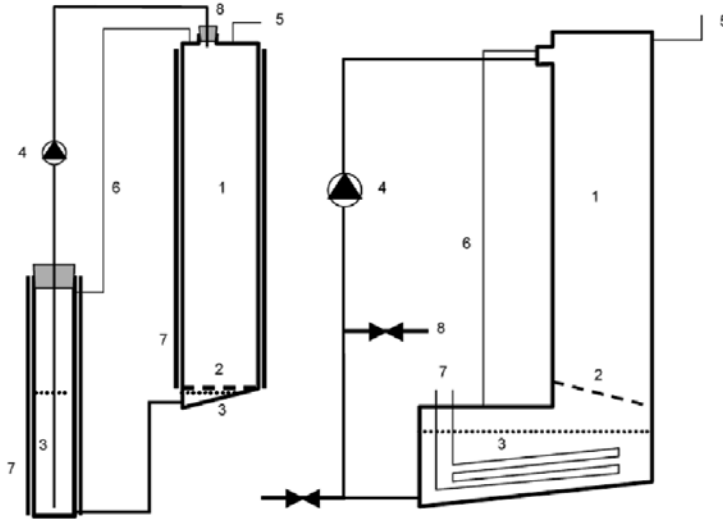
RESULTS

Process performance

Upon inoculation, easily degradable organic material in the straw bed was mobilised, resulting in elevated levels of VFAs and moderately high gas production rates (GPR). The startup period without feeding that followed allowed microbial and structural stabilisation to occur; the elevated levels of VFAs diminished significantly within three to four weeks in L3, P1 and P2. Full digestion of the easily degradable fraction, as indicated by the lowered GPRs, took up to eight weeks. In L3, feeding was initiated on day 55 at a background GPR of 0.15 $m^3 \cdot m^{-3} \cdot d^{-1}$, and had by then accumulated 0.18 m^3 methane·kg^{-1} VS straw (contribution from inoculum neglected).

The cumulative results of the final feeding trials for L3, P1 and P2 with respect to loading rate, gas production and methane yield are presented in figure 2 and in table 2. The feeding took place over an extended period of time, with intermittent recirculation and no removal of solids. Where applicable, all data are expressed in volume per column unit, so as to facilitate comparison of the pilot- and laboratory-scale results. The plotting of the specific methane yield is cumulative with respect to the total green mass added and the methane produced at each sample point. The plotted average of GPR (Av. GPR) is cumulative in character, since at each sample point the accumulated gas production is divided by the accumulated time. Real-time GPR values rose and fell as a result of the pulsed feeding schedule, the GPR ranging from 0.5 to 3.5 $m^3 \cdot m^{-3} \cdot d^{-1}$. At the end of the trial, the foaming in L3 reached up to the ceiling of the reactor, and in P1 emptying of the leachate was necessary to prevent overflowing. The VFAs trends for L3 and P1 are shown in figure 3.

The highest initial batch load of green mass sustained by the mass of the straw (Total VFAs peaking at 2.4 g/l) was 0.26 kg VS·kg^{-1} straw, or 6.6 kg VS·m^{-3} column volume, in P2.

Table 2. Summary of the experimental results of feeding over an extended period of time.

Trial designation	L3	P1	P2
Average loading rate [kg VS·m^{-3}·d^{-1}]	2.00	2.05	2.04
Average GPR [m^3·m^{-3}·d^{-1}]	1.38	1.31	1.22
Methane yield [m^3 CH$_4$·kg^{-1} VS]	0.36	0.33	0.31
Final day / Feeding time span [d]	191 / 39	157 / 34	157 / 34
Accum. green mass fed, initial / final [kg VS·m^{-3}]	37 / 116	13 / 82	7 / 75

Figure 2. Cumulative yields and gas production rates, and accumulated gas and VS in L3, P1 and P2 during the extended feeding trial.
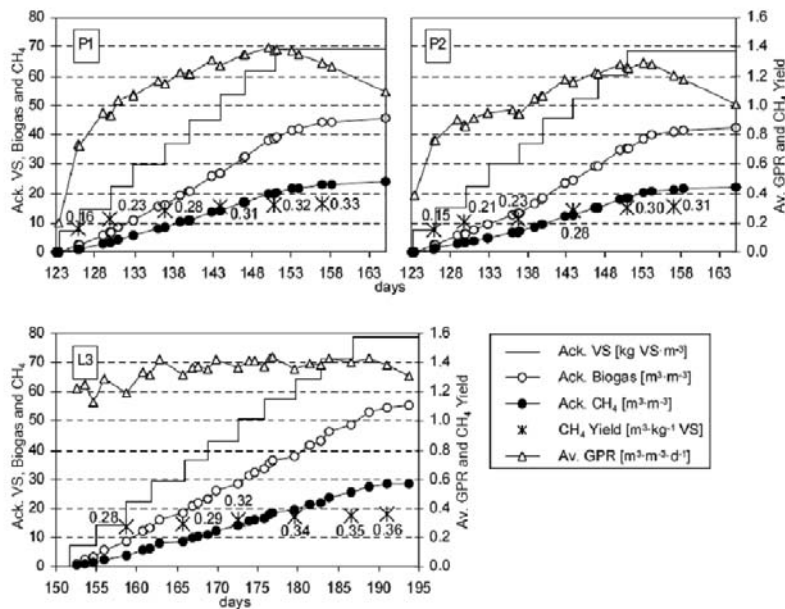

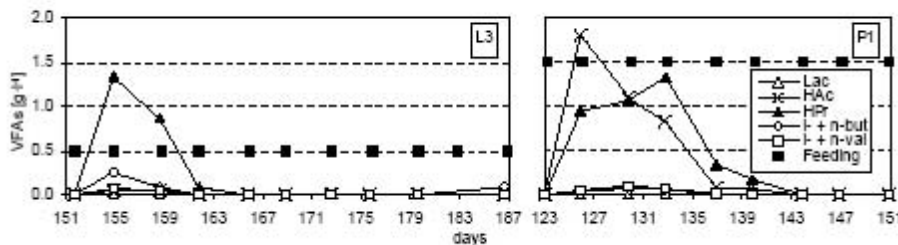Figure 3. VFAs trends in L3 and P1 during extended feeding. Sampling was done immediately before each batch feeding. Lactic acid (Lac), Acetic acid (HAc), Propionic acid (HPr), iso- and n-butyric acid (i- and n-but), iso- and n-valeric acid (i- and n-val).

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Straw bed characteristics

The VFAs patterns for L1 and L3 during the startup, as shown in figure 4, indicate the effects of the initial packing density on the length of the microbial stabilisation period. L1, with its low flow permeability and high density packing, suffered from excessive VFAs formation (total VFAs peaking at 13 g/l on day 15), the methanogens of the process being clearly inhibited. Extensive buffering and reinoculation were needed to reverse the process failure, which began with a reactor clogging on day 5 (Svensson et al. 2001), the elevated levels of VFAs persisting until day 70. In L3, the startup proceeded without problems, the VFAs concentrations being close to zero by day 22. A neutral pH was maintained, whereas the PA decreased, the lowest value (1.5 g $CaCO_3 \cdot kg^{-1}$) coinciding with the peak of 4 g/l total VFAs on day 7. $NaHCO_3$ (equivalent to 0.22 g $CaCO_3 \cdot kg^{-1}$ of liquid inventory) was added as a precaution. The PA increased and stabilised at around 3 g $CaCO_3 \cdot kg^{-1}$ day 20.

The degree of straw bed compaction for the different trials is presented in table 3 together with the initial packing density, the straw age and the accumulated green mass, summarising the structural stability results for the bed. The relation of the volume of the compacted bed to its original volume is shown in percent. Early in the life of the straw bed, extensive compaction occurred only at a low packing density (P2, 53 %, 110 days). At extended age of the straw and with the accumulation of green mass, compaction occurred on all trials subjected to feeding. Compaction occurred both through slow progression and in the form of collapses. An abrupt halt in gas production followed the bed collapse in L2 at a straw age of 326 days, but gas production commenced again after dilution of the leachate. A final green mass batch load at a straw age of 352 days yielded 0.37 m^3 $CH_4 \cdot kg^{-1}$ VS within a week. Intermittent pumping, with the bed being flooded and drained at intervals, triggered bed compaction, as in P1 and L3. Nevertheless, this pumping schedule allowed the problems of excessive foaming upon feeding to be held under control, which extended the feeding period. The first L3 feeding trial (results not shown), fed in the same manner at an average loading rate of 2 kg $VS \cdot m^{-3} \cdot d^{-1}$ but with continuous recirculation, was terminated prematurely due to excessive foaming (Svensson et al., 2002).

Table 3: Summary of the experimental results for the structural stability of the bed.

|	Laboratory-scale						Pilot-scale	
Trial designation	L1	L2 [a]	L2 [a]	L3	L3 [b]	L3	P1 [b]	P2 [b]
δ_{straw}, initial [$kg \cdot m^{-3}$]	140	105	105	93	93	93	62	35
Compacted bed, % of original volume	100	80	31	98	86	46	83	53
Accum. green mass fed [kg $VS \cdot m^{-3}$]	0	18	59	37	37	116	13	7
Straw age [d]	99	274	326	138	141	194	110	110

Notes. [a] L2 bed after the first and after the final abrupt compactation, respectively. [b] Intermittent pumping employed. Intermittent pumping initialised in L3 on day 140.

Upon feeding, the permeability of the bed decreased on all of the trials, but the lower rate of flow was consistent, no complete blockages occurring at any time during feeding. In the laboratory-scale setup, the recirculation during feeding was typically sustained at settings of average superficial flow velocities ranging from 1 to 2 $m \cdot d^{-1}$. Even after severe compaction (down to 20 %, during the last days of the trial), such as in L2, the bed permitted a flow of

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1 m·d^{-1}. At a time 30 days after feeding had ceased in L3, the bed permeability was found to have decreased, recirculation being sustained at a setting of 0.5 m·d^{-1}. In the pilot-scale setup, the recirculation was governed by the permeability of the bed at the time, daily averages just before feeding ranging typically from 0.5 to 1.5 m·d^{-1}, whereas directly after feeding they were often higher, typically 1–2 m·d^{-1}.

Figure 4. VFAs trends in L1 and L3 during startup.
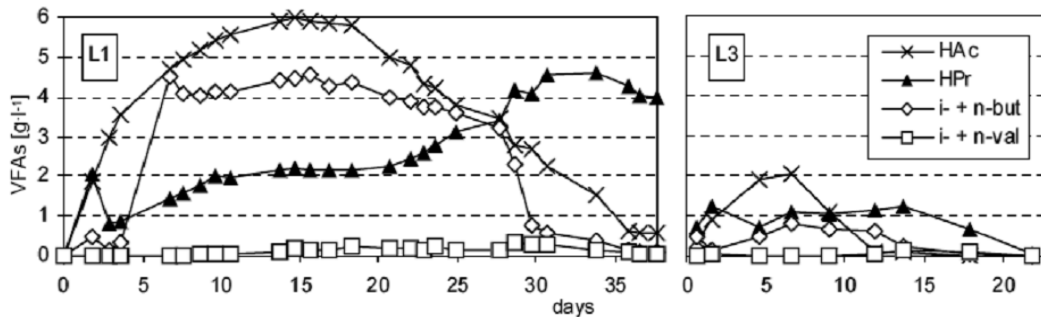
DISCUSSION

The study demonstrates that the performance of a stratified biomass bed can be improved by using straw as starter material as compared with the use of less rigid plant biomass starter materials (Chanakya et al. 1997). It was shown that if the initial packing density is kept within 60–100 kg·m^{-3}, the straw can function both as a biofilm support and as a particulate filter. After a startup period, it can sustain a direct onset of green mass feeding, in the present study 7 kg·m^{-3} being added twice a week (average loading rate 2 kg VS·m^{-3}·d^{-1}). Also, the permeability of the straw is low but consistent, without any clogging tendencies being evident. A straw filtering technique of this sort can thus contribute to the broader use and acceptance of high-solids single-stage stratified bed digesters, which can be regarded as promising candidates for localised energy and fertiliser production in medium- to low-technology environments such as farm-scale anaerobic digestion (Anonymous 2003, Andersson and Björnsson 2002, Björnsson et al. 2001) or household digestion in certain rural parts of India (Chanakya et al. 1997; 1999).

The microorganisms retained in the straw bed adapted quickly to the pulsed feeding schedule, that was started rather abruptly. This is shown by the reactors having overcome the elevated levels of VFAs within two weeks (figure 3), and by the methane yields of the green mass approaching the final yields within about three weeks (figure 2). The final yields (table 2) compare favourably with the values of 0.30–0.38 m^3 CH$_4$·kg^{-1} VS for fresh and ensiled sugar beet leaves in mesophilic batch trials that have been reported (Gunaseelan 1997). The stable GPR background levels that preceded the final feeding trials were 0.05 m^3·m^{-3}·d^{-1}. Neglecting this background contribution to the final yield results in an overestimation of no more than 5 %. The performance of P2 being worse can probably be attributed to its period without recirculation, and to its lower initial bed mass, rather than to differences in packing density.

Extended straw age and severe bed compaction were found to not jeopardise the overall performance of the reactor. A straw bed nearly 200 days old and compacted down to 50 % functioned well, despite the feeding regime being intensive. The less intensive feeding trial found in L2 suggests that a working life of a straw bed in excess of 300 days might be possible.

The straw bed filtering secured a moderate and consistent recirculation flow during feeding, which ensured a high level of mass transfer. As reported previously, the recirculation of either untreated leachate (TenBrummeler et al. 1991, Barlaz et al. 1992, Mata-Alvarez et al. 1986) or methanogenically stabilised leachate (Libanio et al. 2003, Xu et al. 2003, Chugh et al. 1998, Chynoweth et al. 1992) accelerates the degradation and reduces the problems in connection with stagnant zones.

The study strongly suggests that the use of straw as a starter material, as a "primer" for the biomass bed, speeds up and secures the feeding escalation phase. One can ask nevertheless to what extent the time required by the initial startup period of the straw bed reduces the benefits thus achieved. Further studies are needed to examine the utility of straw bed priming more closely. In the present investigation, the biomass bed increased in size with each feeding, making it impossible for steady state conditions to be achieved, since the methanogenically active volume grew over time. Continuous operation, upheld by digested biomass being withdrawn from the bottom of the column, would greatly benefit the economy of the process by minimising the time spent on unproductive reactor startups and terminations. Future work could be directed at developing a continuous process for the removal of solids, and for taking a closer look at the spatial stratification of hydrolytic and methanogenic activity.

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