Influence of gas residence time and air ratio on the air gasification of dried sewage sludge in a BFB

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Abstract

Because little information is available about sewage sludge gasification in a bubbling fluidised bed (BFB), further experiments are required in order to quantify the potential energy power of dried sewage sludge (DSS) as well as to evaluate the optimum conditions for its gasification. In this work, the influence of the bed height on the process was experimentally analysed using a laboratory-scale BFB reactor. The gasification tests were performed at different values of equivalence ratio (λ) and at two values of constant bed height (150 and 300 mm). Attention was focused on the effect of increasing bed height on the gas composition, average cold gas efficiency, and product distribution. Results obtained in this study show that a bed height increase improves the efficiency of the DSS gasification process. This fact could be explained because the high ash content of DSS represents an obstacle to the gas diffusion.

Keywords: Sewage sludge; Gasification; Fluidised bed; Tar content

1. Introduction

Sewage sludge is the residue produced by the treatment of domestic and industrial wastewaters. The rate of production in the European Union (EU) is forecast to increase to approximately 10^7 kg/year (dry basis) by 2005 [1]. Sewage sludge disposal has been the focus of much attention within the water industry in recent years, as some of the disposal routes, as sea dumping, land filling, composting, cropland application or incineration, have been banned or become subjected to greater constraints [2,3].

Gasification has attracted considerable interest from water utilities as an alternative technology with the advantages of destruction of pathogenic bacteria and volume reduction, and the additional benefits of energy recovery and lower-cost atmospheric emissions control [4,5]. The efficiency of the gasification process is better, in principle, because producer gas can be used directly in a power generation process. The only drawback to date for this technology is the high tar and dust content of the synthesis gas produced [6]. Tar is undesirable because of various phenomena involving condensation, formation of tar aerosols, and polymerization to form more complex structures, all leading to cause problems in process equipment as well as in engines and turbines used in application of producer gas [7]. However, the minimum allowable limit for tar is highly dependent on the kind of process and the end user application.

Because limited information is available about sewage sludge gasification in a bubbling fluidised bed reactor, the aim of this work is to investigate the effect of two important process variables (equivalence ratio and bed height) on several gasification parameters: gas yield and composition, average cold gas efficiency, and raw gas tar content. These data are required in order to quantify the potential energy power of dried sewage sludge (DSS) as well as to evaluate the optimum conditions for its gasification.

The use of a laboratory scale, atmospheric bubbling fluidized bed reactor to gasify dried sewage sludge with air (using sand as bed material), has been studied.

Results from a previous study [8], performed using the same experimental system, have already shown the possible influence of gas residence time on the quality of the product gas and particle conversion. In this sense, the lower heating value obtained (only 3–4 MJ/Nm^3 compared to typically 5 MJ/Nm^3 corresponding to gasification from wood) could be related to the fact that the high ash content of DSS represents an obstacle to the gas diffusion. As a consequence, the intrinsic kinetics of the particle conversion is lower than for low-ash fuels.

2. Experimental

2.1. Samples

The samples of dry sewage sludge (DSS) used in the study were obtained as a dried, granulate product from an urban wastewater treatment plant. The sludge was previously treated by anaerobic digestion and thermal drying. Proximate and ultimate analyses of the received sewage sludge are shown in Table 1. The lower heating value (LHV) has also been determined by means of a calorimeter IKA A-2000 (standard procedure: ISO-1928-89). The value obtained for LHV was 10.26 MJ/kg. The dried sewage sludge was crushed and sieved to provide a feed sample in the size range of 250–500 μm.

2.2. Laboratory scale BFB gasifier

Experiments were performed in a laboratory-scale plant operating at atmospheric pressure, continuously feeding sewage sludge and air, and with a continuous ash removal device. The plant is coupled to a gas cleaning system. Figure 1 shows a diagram of the system.

The reactor is made of refractory steel (AISI 310), with an inner diameter of 38.1 mm and a height of 800 mm. Biomass is fed through a sloping pipe (13.1 mm inner diameter), provided with an air jacket to avoid pyrolysis before entering the reactor. The bed height is kept constant at two values (150 or 300 mm, depending on experimental setup) by means of a concentric pipe which goes through the distributor plate, enabling the bed material to overflow and be collected in an ash hopper.

The reactor is heated by an electrical furnace, with three independent heating zones (bed, freeboard, and cyclone). Biomass is fed by a variable speed screw feeder, and the air flow rate is set by means of a mass flow controller. About 33% of the gasification air is diverted to the screw feeder, thus helping the solid to enter the reactor, while the other 67% enters the reactor through the distributor plate. Bed pressure drop is registered along each experimental run in order to be aware of bed fluidization problems.

A small cyclone downstream the gasifier is used to remove entrained particles in producer gas, which are collected in a “char pot”. The gas leaving the cyclone is then cooled in two ice condensers, where most of the tar and water are collected. Tar and water are extracted with 2-propanol, and water is determined off-line using a Karl Fischer titration (tar is calculated by difference). Final cleaning of the gas is performed by a cotton filter. Part of the cleaned gas is diverted to a continuous CO/CO_2 infrared analyser, which is used to monitor the process.

The gas production is measured by a volumetric gas meter, taking into account gas temperature and pressure. The gas composition is determined by means of a micro gas chromatograph (Agilent 3000A) connected on-line to the process, giving the volume percentage of N_2, O_2, H_2, CO, CO_2, CH_4, C_2H_2, C_2H_4, C_2H_6, and H_2S. The time interval between two consecutive analyses is approximately 4 min.

2.3. Operating procedure

The reactor was fed with sewage sludge and sand (20% of the mass rate of DSS) in the size fraction of 250–500 µm (u_{mf} = 2.8 ± 0.1 cm s^{-1} at 850 ºC). Previously to each experimental run, the reactor was loaded with an initial quantity of sand (50 g for experiments performed at a bed height of 150 mm and 100 g for the rest of tests).

To calculate the amount of air needed for stoichiometric combustion of the residue, carbon, hydrogen, and sulphur content were considered. It was found that 3.31 × 10^{-3} Nm^3 of air per gram of residue were necessary for complete combustion. Thus, the air ratio used in a given experiment (λ) can be calculated as follows:

$$\lambda = \frac{Q_{air}}{Q_{sludge} \times 3.31} \times 100 \quad (1)$$

where Q_{air} is the air flow rate used in a given experiment (Nm^3/min), and Q_{sludge} corresponds to the mass flow rate of DSS (g/min). The value of Q_{air}, flowing at eight times the minimum fluidising velocity, was fixed at 3.75 × 10^{-3} Nm^3/min. In this way, the value of λ was changed adjusting the feed rate of solid.

Experiments were performed at three different values of λ (approximately 25%, 30%, and 35%), and at two bed heights (150 and 300 mm), giving a total of six different experimental conditions set-up. The average experiment length was 45 min.

Due to small variations in the solid feeding system, the experimental values of λ have varied a little from the ones calculated using (1).

Two replicates of each experimental condition were carried out in order to calculate the standard error associated with each response measured: average gas composition (dry basis), specific yield to gas obtained (y_{gas}), lower heating value of the product gas (LHV), average cold gas efficiency —defined as the ratio of the LHV of the produced gas to the LHV of the DSS fed (η), average percentage of carbon in the biomass recovered in the gas (y_{carbon}), and mass product distribution. Product distribution calculations were based on the biomass fed. In addition, and in order to validate an experimental run, the mass balance was also calculated based on the DSS weight plus the oxygen mass fed during the experiment, giving an experiment closure balance of nearly 100%.

3. Results and discussion

Analysis of Variance (ANOVA) has been used to study the influence of equivalence ratio, bed height, and their possible interaction on the results obtained. The statistical analysis was carried out using the Design-Expert® Version 6 Software from Stat-Ease, Inc. [9]. To consider significant a given effect (to reject the null hypothesis that changing the factor has no effect on the observed response), a confidence level of 95% for the F-distribution was selected.

3.1 Effect on the dry gas composition

The influence of air ratio and bed height on the gas composition can be calculated as empirical models for the different gas compounds. Although the equations obtained are only valid for the experimental range tested and the experimental installation used, they are useful to make a rough prediction of the relative influence of the factors studied (Table 2 shows the coefficients of the models obtained).

Taking into account the experimental arrangements used in this study, only linear tendencies can be observed, if present. To compare the relative influence of the two factors analysed in this section, terms were coded in a –1 to +1 scale, being –1 the lowest level tested (λ = 24% and 150 mm of bed height) and +1 the highest level (35% for λ and 300 mm for bed height).

From analysing the evolution of the different gas components shown in Figure 2, it can be observed that H_2, CO, CH_4, C_2H_4, and C_2H_6 show the same trend. This indicates that the gas composition was affected by both λ and bed height. As the air ratio was increased, the concentration of those compounds decreased. On the other hand, an increase of the bed height was proven effective and the concentrations of the gas species mentioned above were increased. Nevertheless, the average nitrogen composition followed exactly the opposite trend, increasing as the air ratio was increased and decreasing as the bed height was increased.

From the statistical analysis of the data, it was observed that the influence of air ratio was more significant than the effect of bed height (for all variables reported in the experimental range tested).

Concerning the CO_2 composition, this gas component showed a rather odd behaviour, because CO_2 percentages don't seem to be affected either by the air ratio or the bed height but only for their interaction. The tendency of CO_2 concentration with λ was different depending on the bed height value: for a bed height of 150 mm, the CO_2 concentration tends to increase as λ increases, whereas it decreases when λ increases for a bed height of 300 mm. However, as can be deduced from coefficients reported in Table 2, the variation was not very important as the interaction coefficient was two orders of magnitude smaller than the constant one.

The composition of acetylene, a minor gas component with a concentration ranging from 0.12% to 0.15%, seems to be affected only by the bed height and not by λ. As happened for CO_2 composition, the variation observed was very small as the constant term of the empiric model was 20 times bigger than the one corresponding to bed height. This finding can be ascribed to the fact that the gas analysis was not precise enough to detect any trend for this lower level of C_2H_2 concentration.

Hydrogen sulphide was the only compound, apart from the observed CO_2 trend, that has been showed an interaction of air ratio and bed height. Although the H_2S percentage decreased as λ increased (in a more oxidizing atmosphere), the decrease was less important when the bed height was 300 mm, thus a longer gas residence time in the bed has been proven not to be effective to reduce the concentration of this undesirable compound.

Figure 2 displays the volume percentage of each gas analysed as well as the estimated means and their 95% confidence interval. The observed variations with λ of the percentages of H_2, CO, CH_4, N_2, C_2H_4, and C_2H_6 in the dry gas were in agreement with the ones experimentally observed in the fluidised bed gasification of sewage sludge [10], pine sawdust [11–13], and rice husk [14]. The height of a fluidised bed is not usually considered as an experimental factor in biomass gasification, as it is not likely to change noticeably when gasifying a low-ash fuel (as pine sawdust) or if ash is entrained with the produced gas and collected down stream the gasifier. However, when a high-ash biomass such as sewage sludge is gasified, a significant change of this parameter can be done, as was observed by Miccio et al. [10] during DSS gasification in a fluidised bed. As it has been explained in the Experimental Section, the fluidised bed used in this work was provided with a solid removal system which allows the bed height to be kept constant along an experimental run at any of the two bed heights used (150 and 300 mm). From the coefficients shown in Table 2 and Figure 2, it can be deduced that an increase of the residence time has been proven effective as the percentages of H_2, CO, CH_4, and C_2H_4 increased, and N_2 decreased, being these trends more important for H_2 and N_2. On the other hand, the increase of the gas-solid contact in the fluidised bed has not been beneficial from the formation of a non desired gas component (H_2S) point of view.

3.2 Effect on gas production and heating value, average cold gas efficiency, and yield of carbon to gas conversion

As it was shown for the dry gas composition, Table 3 displays the coefficients of the empirical linear models obtained from the data. It can be observed from Figure 3 that y_{gas} and y_{carbon} both have had the same behaviour, increasing their values as equivalence ratio and bed height were increased.

The effect of bed height for y_{gas}, although statistically significant, was very small.

Regarding the quality of the produced gas, the dry basis LHV was decreased as equivalence ratio increased. However, this expected effect can be compensated increasing the bed height.

In the experimental range tested, the air ratio seems to have a stronger influence than bed height for the parameters y_{gas}, y_{carbon}, and LHV. However, the average cold gas efficiency (η) has no dependence on the air ratio. This fact could be explained by the compensation effect caused by an increase of y_{gas} and an associated decrease of LHV. The average cold gas efficiency only depends on the bed height: the change from 150 to 300 mm enhanced this parameter almost by 10%.

These trends (showed in Figure 3) are in agreement with those reported by several authors for different biomass samples concerning the influence of the equivalence ratio [11–14].

3.3 Effect on the mass product distribution

Gas, char (and ash), tar, and water were obtained as products from the gasification of dry sewage sludge in the experimental plant used. After the experiment was finished, the mass balance and the product distribution were obtained for each experimental condition tested.

In light of the empirical coefficients showed in Table 4, tar and char production did not show any significant tendency with respect to both air ratio and bed height, thus the values corresponding to the intercepts (see Table 4) are nearly the same that the estimated means of the variables (interval sizes at a 95% confidence level). For this reason, Figure 4 only displays the gas and water productions.

Reported tar production value has ranged between 5.6% and 6.6% (percentage of DSS fed), whereas the solid obtained from the gasifier (char plus ash) has ranged from 42.0% to 45.9% of DSS fed (values near the ash content of the DSS samples used in this study, as shown in Table 1). A decrease of the tar content when λ is increased has been reported by the authors already cited in biomass gasification; this should be expected, and should have been observed here. Apart from the accuracy of the tar determination method, these unexpected results could be related to the fact that the experimental value of λ was set adjusting the solid flow rate (maintaining a constant air flow rate). Thus, a reduction of the DSS flow rate reduces the amount of ash, where catalytic metals are present and could promote the cracking of tar species [4,15] in the regions of the bed and freeboard, as has been reported by Miccio and co-workers [10]. Further experiments performed using DSS ashes as initial bed (for different values of λ) would be desirable in order to confirm this effect.

On the other hand, the percentage of gas obtained respect to DSS fed was increased with both λ and bed height, as it was observed for y_{gas}. In addition, water collected after the reactor system depended only on the bed height. The effect of the air ratio was negligible, although an increase of the water content for the higher values of λ could be expected. Less water was obtained at the higher bed height, indicating that water consuming reactions (as the water-gas shift and the steam reforming of char and hydrocarbons) could be kinetically controlled, and thus, higher conversions can be achieved as a consequence of the higher in-bed residence time.

As no trend has been observed in the tar and char productions, it is not possible to assert whether the gas-solid reactions (char reforming by steam that would lead to a smaller char production) or the gas phase reactions (hydrocarbons steam reforming that could imply a decrease in tar production), or maybe both of them, can play a major role when the gas residence time in the fluidised bed is increased. Nevertheless, it should be noticed that the high ash content of DSS represents an obstacle to gas diffusion; as a consequence, the intrinsic kinetics of the particle conversion could be lower than those for low-ash fuels. In conclusion, a longer gas residence time would be required for the complete conversion of fuel particles in the bed. In this sense, further experiments performed at high gas residence times would be desirable in future studies.

Finally, a rough estimate of the water-gas shift reaction evolution has been calculated from the data corresponding to dry gas composition, gas production, and water production. The percentages of deviation from the equilibrium value are shown in Figure 5. It can be observed that the deviation of the experimental ratio $[CO_2][H_2][CO]^{-1}[H_2O]^{-1}$ from the equilibrium was increased as the value of λ increased. On the other hand, and as could be expected, the increase of the bed height has lead to a ratio closer to equilibrium. However, it should be emphasised that the water-gas shift reaction is not the only reaction that occurs. In fact, the observed behaviour of the $[CO_2][H_2][CO]^{-1}[H_2O]^{-1}$ ratio has not followed the same trend as the CO concentration.

4. Conclusions

The influence of the bed height on the dried sewage sludge gasification process has been investigated as a function of the equivalence ratio value. Overall, the results obtained show that an increase of the bed height improves the efficiency of the DSS gasification process. This behaviour could be explained by the high ash content of DSS, which represents an obstacle to the gas diffusion. Consequently, the gas residence time plays an important role in the process studied. For this reason, further studies involving an analysis of the influence of the superficial gas velocity on the process would be interesting.

On the other hand, some unexpected results related to tar generation could be due to the catalytic effect of ashes present in the biomass feedstock. In this sense, further experiments performed using DSS ashes as initial bed (for all values of equivalence ratio) are needed in order to confirm this argument.

Acknowledgement

The authors thank the Spanish Ministry of Education and Science (MEC) for providing frame support for this work (project CTQ2004-05528). J.J.M. acknowledges the postdoctoral grant received from the MEC and the European Social Found (ESF).

Nomenclature:

Nm^3	Cubic meter, normal conditions (0 ºC, 101 kPa)
Q_{air}	Air flow rate used in an experiment, Nm^3/min
Q_{sludge}	Mass flow rate of sewage sludge, g/min
u_{mf}	Minimum fluidisation gas velocity (gasifier bed conditions), cm/s
y_{carbon}	Average percentage of carbon in the biomass recovered in the gas, %
y_{gas}	Specific yield to gas obtained, Nm^3 of dry gas / kg of daf DSS fed

Greek Symbols:

η	Average cold gas efficiency based on LHV of gas and biomass, %
λ	Equivalence ratio, defined as the air-to-fuel ratio used in the reactor divided by the air-to-fuel ratio for the stoichiometric combustion, %

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Figure Captions

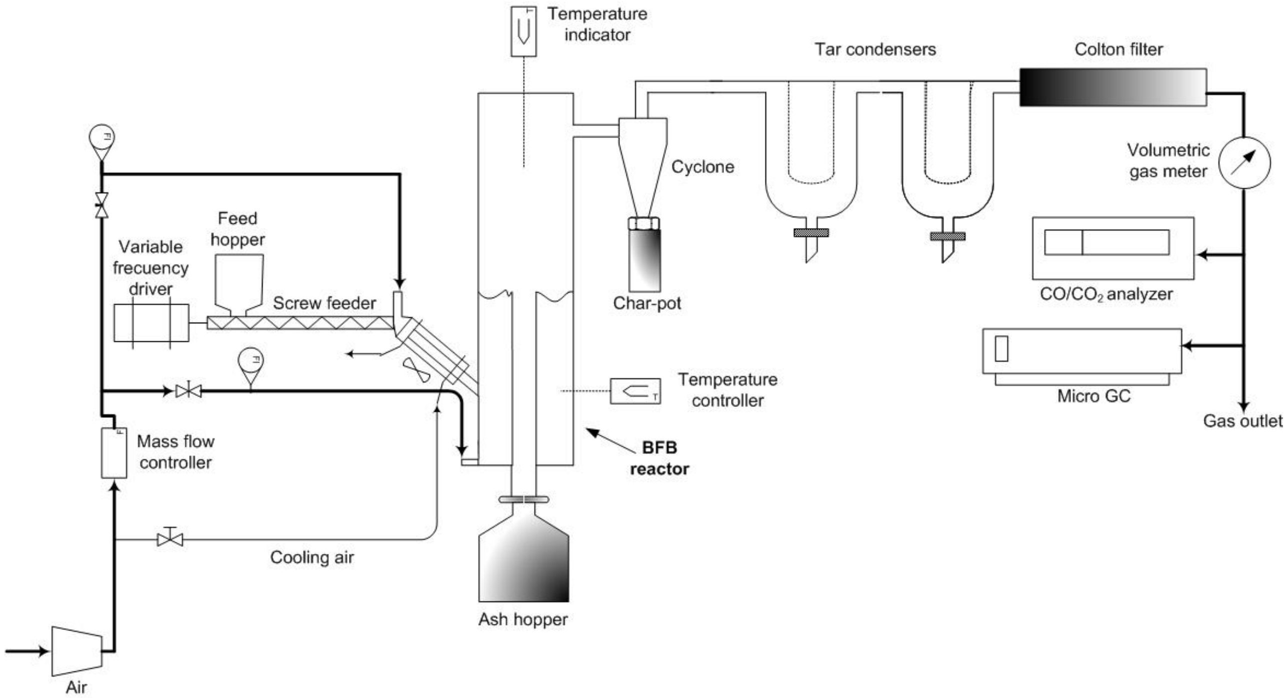
Fig. 1. Schematic diagram of the laboratory scale BFB gasifier.

Fig. 2. Average gas composition (dry basis) versus λ: H_2 (a), N_2 (b), CO (c), CH_4 (d), CO_2 (e), C_2H_2 (f), C_2H_4 (g), C_2H_6 (h), and H_2S (i) (square: bed height of 150 mm; circle: bed height of 300 mm; triangle: estimated mean for the gas composition at the experimental interval ends).

Fig. 3. y_{gas} (a), dry gas LHV (b), average cold gas efficiency (c), and y_{carbon} (d) as a function of the equivalence ratio value (square: bed height of 150 mm; circle: bed height of 300 mm; triangle: estimated mean for the gas composition at the experimental interval ends).

Fig. 4. Evolution of the mass production of gas (a) and water (b) as a function of λ (square: bed height of 150 mm; circle: bed height of 300 mm; triangle: estimated mean for the gas composition at the experimental interval ends).

Fig. 5. Percentage of deviation from the water-gas shift reaction equilibrium as a function of λ (square: bed height of 150 mm; circle: bed height of 300 mm; triangle: estimated mean for the gas composition at the experimental interval ends).


Temperature indicator
Tar condensers
Colton filter
Cyclone
Volumetric gas meter
Feed hopper
Variable frecuency driver
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Char-pot
CO/CO2 analyzer
Temperature controller
Micro GC
Gas outlet
Mass flow controller
BFB reactor
Cooling air
Ash hopper
Air

Figure 1

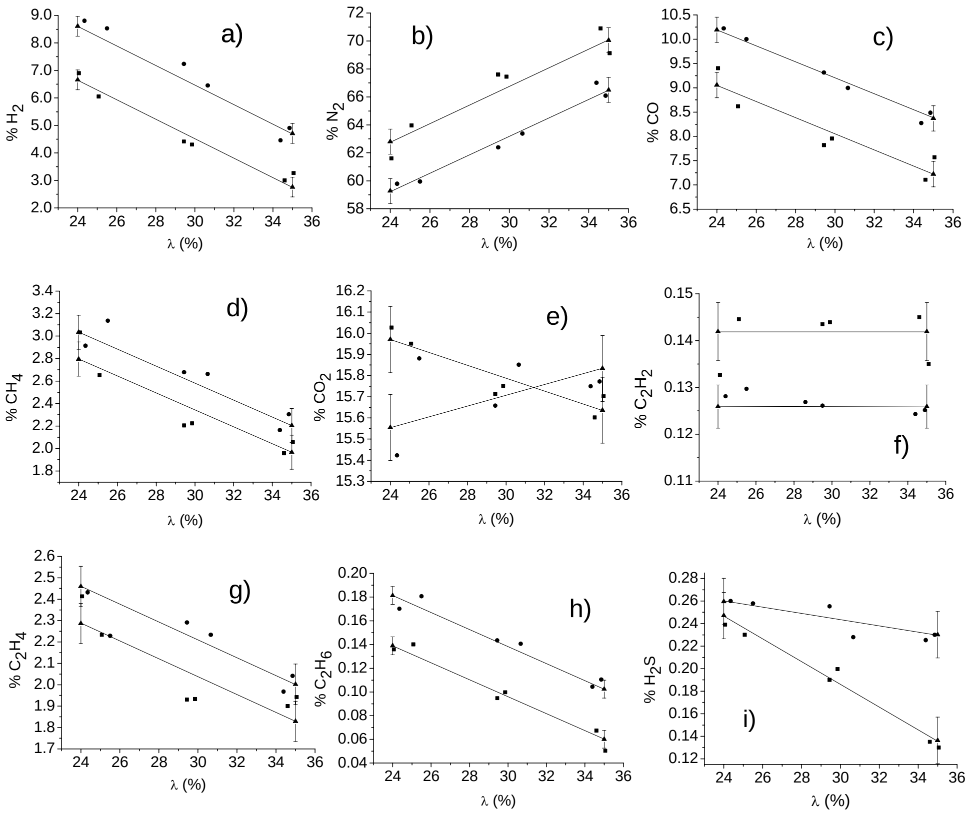


Figure 2

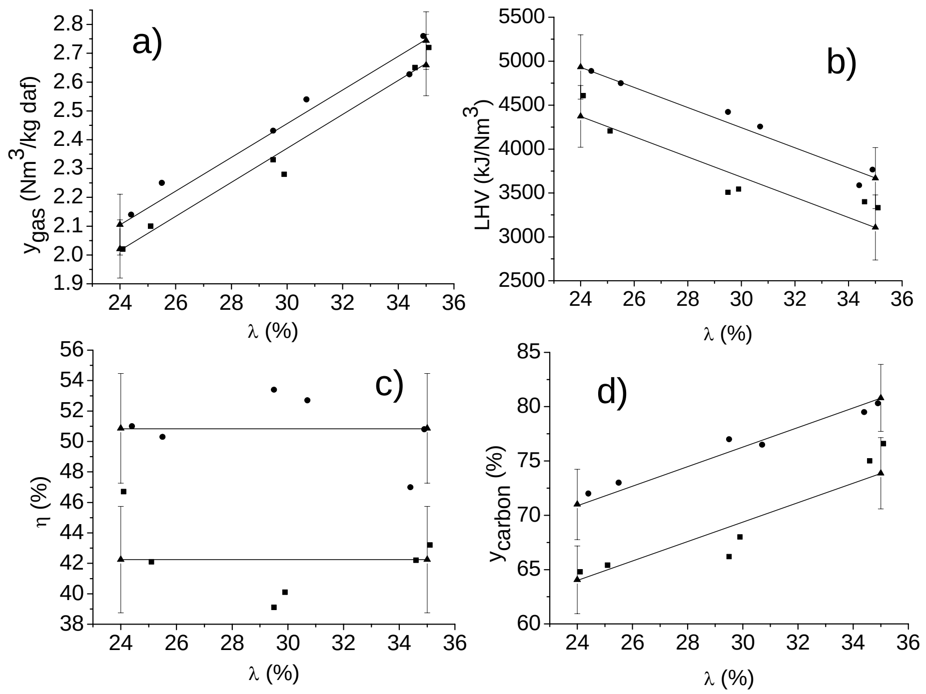


Figure 3

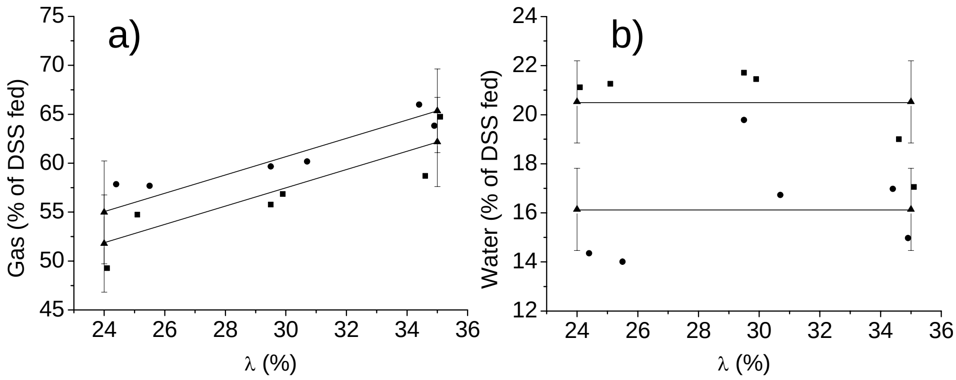
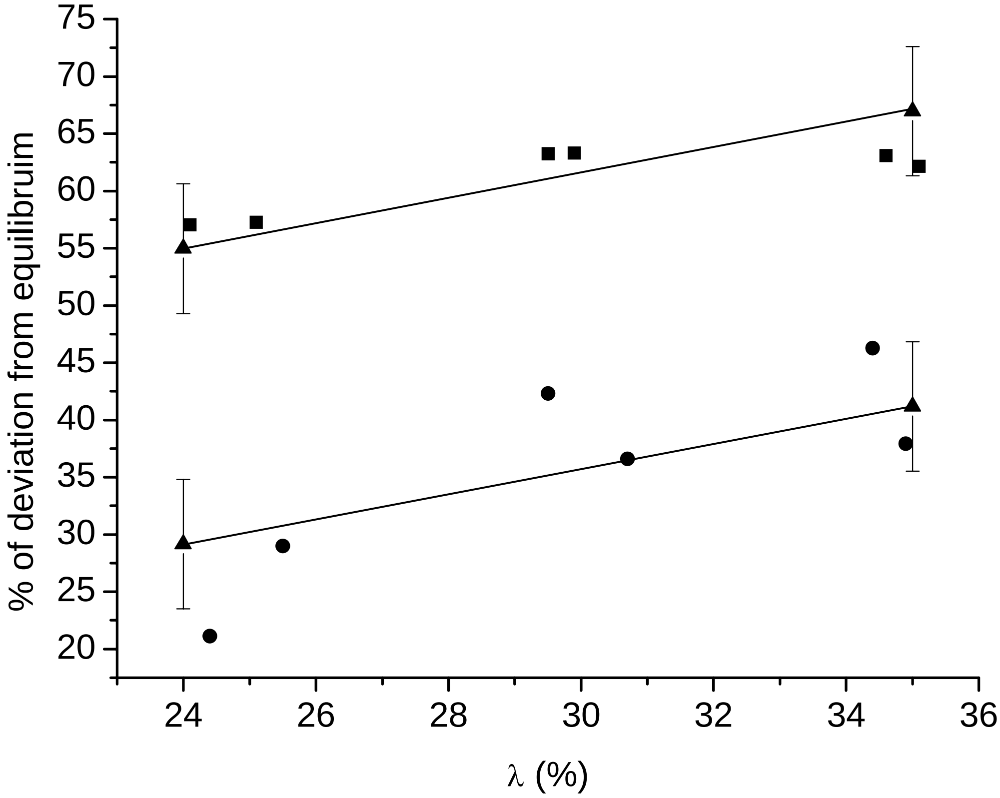

a)
Gas (% of DSS fed)
75
70
65
60
55
50
45
24
26
28
30
32
34
36
λ (%)
b)
Water (% of DSS fed)
24
22
20
18
16
14
12
24
26
28
30
32
34
36
λ (%)

Figure 4



75
70
65
60
55
50
45
40
35
30
25
20
% of deviation from equilibruim
24
26
28
30
32
34
36
λ (%)

Figure 5

Table 1

Analysis of dried sewage sludge samples

Proximate	Analytical standard	% by weight
Moisture	ISO-589-1981	8.92
Ash	ISO-1171-1976	42.12
Volatiles	ISO-5623-1974	42.30
Fixed Carbon	By difference	6.66

Ultimate (organic fraction)	Analytical instrument	% by weight (daf)
Carbon	Carlo Erba 1108	55.33
Hydrogen	Carlo Erba 1108	6.70
Nitrogen	Carlo Erba 1108	8.15
Sulphur	Carlo Erba 1108	1.75
Oxygen	By difference	28.07

Table 2

Lineal empirical models for dry gas composition (coded factors)

	Intercept	λ	Bed height	Interaction
H_2	5.70±0.31	–1.95±0.46	0.99±0.32	*
N_2	64.66±0.62	3.62±0.91	–1.75±0.63	*
CO	8.71±0.18	–0.92±0.27	0.58±0.19	*
CH_4	2.50±0.11	–0.41±0.16	0.12±0.11	*
CO_2	15.75±0.09	*	*	0.15±0.13
C_2H_4	2.15±0.07	0.23±0.10	0.09±0.07	*
C_2H_6	0.12±0.01	–0.04±0.01	0.02±0.01	*
C_2H_2	0.13±0.01	*	–0.03±0.01	*
H_2S	0.22±0.01	0.03±0.02	0.03±0.01	0.02±0.02

* not significant

Table 3

Lineal empirical models for y_{gas} (Nm^3/kg of daf DSS), dry gas LHV (kJ/Nm^3), η (%), and y_{carbon} (%) (coded factors).

	Intercept	λ	Bed height	Interaction
y_{gas}	2.38±0.04	0.32±0.05	0.04±0.03	*
LHV	4020±120	–630±180	280±130	*
η	46.6±1.8	*	4.3±1.8	*
y_{carbon}	72.8±1.2	5.3±1.5	3.0±1.1	*

* not significant

Table 4

Lineal empirical models for the product distribution, expressed as percentage of DSS fed (coded factors).

	Intercept	λ	Bed height	Interaction
Gas	58.6±1.5	5.2±2.2	1.6±1.5	*
Tar	6.2±0.6	*	*	*
Char	43.3±2.3	*	*	*
Water	18.3±1.4	*	2.2±1.4	*

* not significant