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DRY ANAEROBIC DIGESTION OF SOLID ORGANIC WASTE IN A BIOCEL REACTOR AT PILOT-PLANT SCALE

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ABSTRACT

Dry anaerobic digestion of the source separated organic fraction of Municipal Solid Waste (Vegetable, Fruit Yard waste) was studied in pilot-plant-scale reactors (5 m^3, 450 m^3). The maximum loading rate that could be applied was 7 kg VS/(m^3.day) which is similar to the loading rate reported for experiments on laboratory scale. Per ton organic waste 70 m^3 (STP) biogas could be recovered. A reactor temperature at start-up of 20 °C which was gradually increased to 35 resulted in a prolonged digestion time, while a temperature of 43 °C at start-up with a gradual decrease to 30 °C gave a similar digestion time as start-up at 35 °C. Particle size reduction of the Vegetable, Fruit and Yard waste resulted in a longer solids retention time which was related to the reduced leachate recycle flow that could be applied. The optimum value for the inoculum factor I, i.e. the ratio of inoculum solids and the initial total solids at start-up, was 0.5 - 0.6. A solids retention time of 30 days was observed. At higher values of I longer retention times were observed due to a suboptimal leachate recycle flow rate. At lower values of the inoculum factor (0.40 or lower) the solids retention time was 50 days or longer due to the relatively long period of suboptimal conditions (low pH, high organic acid concentrations).

KEYWORDS

Municipal Solid Waste; source separation; Vegetable Fruit and Yard Waste; agricultural solid waste; dry anaerobic digestion; pilot plant; batch reactor; biogas; inoculum factor; temperature effects; compost; leachate recycle.

INTRODUCTION

So far, dry anaerobic digestion of the source separated organic fraction of MSW, the Vegetable Fruit and Yard waste (VFY) and of agricultural wastes in the BIOCEL process has been studied in laboratory-scale reactors with a maximum working volume of 78 l (Ten Brummeler et al., 1991a,b). The BIOCEL process is based on batch-wise digestion of solid organic waste materials, which are brought into the reactors as a static pile. Due to the batch-wise operation and the absence of mixing in a BIOCEL reactor a characteristic pattern is oberved: initially there is a build-up of volatile organic acids with a concomittant pH-drop, followed by a period of decreasing concentrations of volatile organic acids and an increasing pH. The shorter the initial "sour" period, the higher the mean degradation rate of the volatile solids. The maximum (batch) loading rates (averaged over the toal period of the digestion expressed as kg VS/m^3.day) which could be applied at 35 °C were in the same order as those reported for continuous dry digestion systems on pilot-plant scale (Ten Brummeler et al., 1991b). The potential of the process for practical application has to be assessed from results of relevant pilot-plant-scale experiments and full-scale systems. Preliminary experiments with a BIOCEL-reactor on pilot-plant scale (5 m^3) gave promising results (Koster et al., 1988).

The present study deals with several aspects of scale-up of the dry anaerobic digestion process in a BIOCEL reactor. Important process factors like leachate recycling, temperature regime and the optimum inoculum factor (ratio of inoculum solids and initial organic waste solids plus inoculum solids) were investigated. The objects of the present study were:

- the scale-up of the proces from 78 l to 5 and 450 m^3
- to determine the effect of leachate recycle and the minimum flow needed
- to assess the effect of several values of I (inoculum factor)
- to assess the effect several ways of heating the process.

MATERIALS AND METHODS

Apparatus

The experiments were carried out in two tank reactors made of stainless steel, which were 2.40 m in height and 1.75 m in diameter (Fig. 1). The working volume was 5 m^3. A perforated plate (holes of 1 cm) was placed 30 cm above the the reactor bottom to prevent clogging of the outlet during leachate recycle. Leachate was recycled to the top of the reactors with peristaltic pumps. The flow rate was monitored by registering the rounds of the pump with a magnetic counter. Leachate recycle was carried out intermittently, dependent on the amount of leachate that was collected in the leachate chamber. A level indicator which was placed 5 cm above the reactor bottom switched on the pump when the leachate level reached this height. One round of the pump corresponded to a certain volume of leachate.

The lid of the reactor was placed in a water lock. The reactors were insulated with glass wool with a thickness of 10 cm. The reactor was placed on a plate of glass foam. The mean reactor temperature of 35 °C (± 2) was maintained by pumping hot water from a boiler through a metal coil, which was placed inside the reactor. The temperature was measured at three points in the reactor with detectors which were located at depths of 0.40, 0.75 and 1.25 m respectively. Gas production was measured with dry gas meters, which corrected the volume of the gas produced at a certain temperature to the volume of the gas at 15 °C. Before the gas meters a bypass was installed for gas sampling. Samples for analysis of organic acids and pH could be taken at three points of the reactors. The mixture of raw solid waste and inoculum (digested solids) was brought into the reactor with a conveyor-belt. For each experiment the weight of the raw solid waste and the weight of the inoculum was determined with a balance. After termination of an experiment the reactor was emptied with a crane.

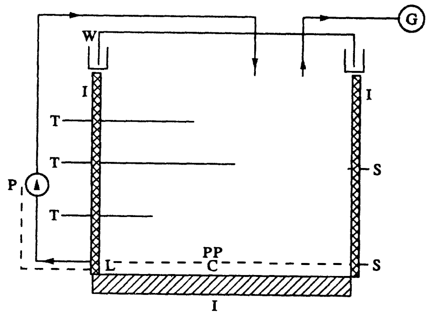

Fig. 1. Flow chart of the 5 m^3 BIOCEL reactor; C: leachate chamber; G: gasmeter; I: insulation;L: level indicator;P: peristaltic pump; PP: perforated plate; S: sample ports; T:temperature sensors; W: water lock.

Procedures

A series of digestion experiments was conducted at different values for the inoculum factor I, the ratio of digested solids to total amount of solids at the start of the experiment. The experiments were carried out during the period September 1987-September 1990. The VFY waste was obtained from a source separation of Municipal Solid Waste from the city of Apeldoorn, the Netherlands. Source separation means that the organic compounds are kept separately from the other MSW fractions by the households themselves. The mean total solids concentration of the VFY amounted to 36 % TS (w/w) and the volatile solids content amounted to 65 % of the total solids. The agricultural solid wastes were obtained from the North of Holland, and included waste grass, tulip bulbs amd skins, narcissus bulbs and Belgian endive roots. The mean total solids content of the agricultural wastes amounted 42 % and the volatile solids amounted 55 % of the total solids. The inoculum for each experiment was obtained from the former digestion experiment. The total solids of the digested VFY and the digested agricultural waste as well amounted to 42 % TS. After weighing, the fresh waste and the digested waste were roughly mixed and brought into the reactor (without further compression) using a conveyor belt. The initial density amounted to 280 kg total solids per m^3_r. Tap water was added when the initial total solids of the mixture exceeded 35 % w/w. At total solids concentrations exceeding 35 % TS, leachate recycle is not possible due to lack of free moving water.

Gas production and reactor temperature were measured 2-3 times a week. Samples of biogas and reactor contents were taken with the same frequency.

Analyses and Calculations

Samples of the biogas were analyzed for CH_4, CO_2 and H_2 using a gas chromatograph equipped with a TCD detector and with two parallel columns: a column of 1.5 m x 1/8", teflon packed Chromosorb 108, 60-80 mesh and a 1.2 m x 1/8" molecular sieve 5A, 60-80 mesh. The column split ratio was 1:1. Samples of 100 μl were taken from the reactors with a glass tight syringe. The volume of the biogas produced was measured by reading a dry gas meter three times a week. The gas volumes produced were recalculated to standard temperature and pressure (STP: 0 °C, 1 bar). The samples taken from of the reactors were analyzed for pH, total organic acids concentration, and ammonium-nitrogen as described elsewhere (Ten Brummeler et al., 1991a). Digestion was considered to be completed when the concentration of organic acids dropped below 1 g COD. The period required to reach this value is defined as the digestion time (DT) (Ten Brummeler et al., 1991a). To compare the experiments at different values of I, the solids retention time was calculated from DT according to the following. A BIOCEL reactor is therefore considered as a reactor with recirculation of the digested waste.

For a reactor with recirculation DT is defined according to equation (1):

$$DT = V/(Qw+R) \quad (1)$$

where V is the reactor volume, Qw the average amount of the solid waste fed to the reactor, and R is the amount of recirculated digested solid waste. For a BIOCEL reactor Qw (m^3/day) is the load of the reactor divided by the digestion time, R (m^3/day) is the average amount of the inoculum fed to the system per day divided by the digestion time.

The solids retention time (SRT) for a reactor which is run with or without recirculation of digested solid waste is defined as:

$$SRT = V/Q_w \quad (2)$$

The solids retention time can be calculated from the DT and R by combining equation (1) and (2) to:

$$SRT = DT*(Q_w+R)/Q_w \quad (3)$$

The inoculum factor (I) can be defined as follows:

$$I = R/(Q_w + R) \quad (4)$$

The SRT can be calculated from DT and the inoculum factor I according to:

$$SRT = DT/(1-I) \quad (5)$$

RESULTS AND DISCUSSION

Effect of Scale-up and Leachate Recycle

To investigate the effect of scale-up (from 78 l to 5 m^3/450 m^3) and the effect of leachate recycle (0.3 m^3/(m^3.day)) two reactors were started up with an inoculum factor value I of 0.35. This first start-up was carried out with digested dewatered pig manure as methanogenic inoculum. The second and following series of experiments were carried out using digested waste as inoculum. In Fig. 2 the results are shown of the experiments concerning the efffect of leachate recycle. The reactor with leachate recycle showed a digestion time (DT) of 42 days, which corresponds to a solids retention time (SRT) of 63 days (Fig. 2). After 42 days the organic acids concentrations were lower than 1 g COD/l. Then 50 % of the potential methane yield was obtained, which means a yield of 35 m^3 (STP)/ton solid waste, or 70 m^3 (STP) biogas. The biogas production rate decreased significantly at this point, indicating that the hydrolysis of the organic compounds in the VFY waste became rate limiting. In fact the VFY has a high grade of stabilization at this stage.

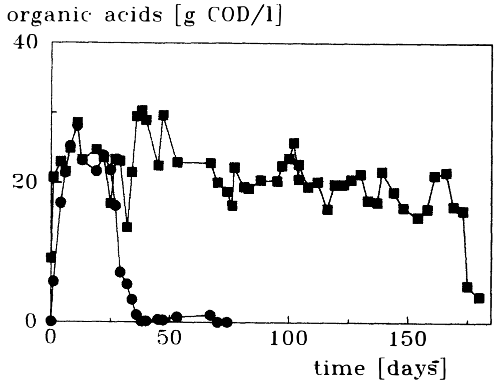

Fig. 2. Volatile Fatty Acids concentration in the dry anaerobic digestion of solid waste with and without leachate recycle (0.3 m^3/m^3_r.day); (●) with leachate recycle; (■) without leachate recycle.

The value of DT is quite similar to what has been reported for dry digestion of VFY in a 78 litre BIOCEL reactor (Ten Brummeler et al., 1991b). Apparently, as far as the volume is concerned, scaling-up does not affect the rate of the process, provided that leachate recycle is applied at a rate of 0.3 $m^3/(m^3$.day). Even after 180 days the reactor without leachate recycle did not show complete digestion. At that stage leachate recycle (0.3 $m^3/(m^3$.day)) was started in this reactor and resulted in complete digestion within 20 days additionally (Fig. 2). The effect of leachate recycle in a laboratory-scale reactor of 78 litres was much less pronounced (Ten Brummeler et al., 1991b).

Effect of the Inoculum Factor on the Solids Retention Time

As was reported elsewhere (Ten Brummeler et al., 1991a,b), the rate of the digestion process in a BIOCEL reactor is determined by the extent of imbalance between acid formation and methane (acid-consuming) formation. A higher amount of inoculum will result in a decreasing retention time (SRT) because the period of severe imbalance becomes shorter than at lower inoculum factors. Fig. 3 shows the effect of the inoculum factor (I) on DT. It is clear that a relation existed between I and DT. At I = 0.55 a retention time of 30 days, which corresponds to a mean VS (batch) loading rate of 7 (kg/m^3.d), is found.
The calculated SRT at I = 0.55 is in accordance with the SRT of 28 days which has been found in experiments at a 78 litre scale. From

Fig. 3 it also appears that for I = 0.77 and 0.9, a longer solids retention time is required, which amounts to 47 days and 60 days respectively. As the concentrations of the organic acids during the experiments with different values of I are considered (Fig. 4) the reason for a longer retention time is not clear, since significantly lower concentrations at I = 0.77 and 0.9 were detected than at I = 0.3 and I = 0.5. A likely reason might be the lower applicable initial rate of leachate recycle which at higher values of I. The increasing value of I affects the initial porosity negatively of the waste/inoculum mixture, because the digested solid waste has a higher density (kg solids/m^3) than the raw waste.

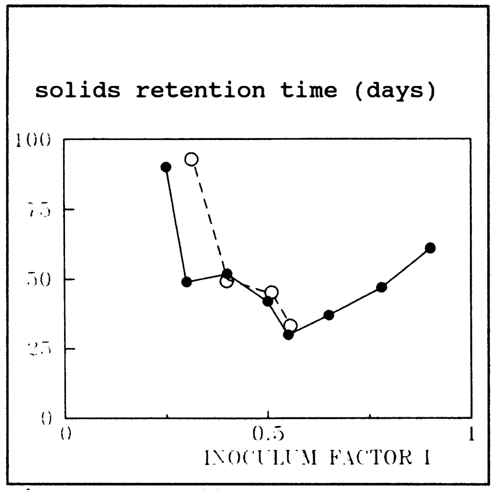

Fig. 3. The effect on the inoculum factor on the minimum Solids Retention Time in dry anaerobic digestion of solid waste in a BIOCEL reactor on pilot-plant scale; (●) VFY waste; (○) agricultural waste.

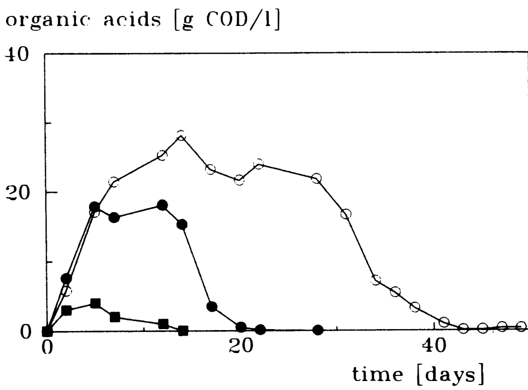

Fig. 4. Course of the organic acids concentrations at several values of I in the dry anaerobic digestion in a BIOCEL reactor; (○) I = 0.3; (●) I = 0.50; (■) I = 0.77.

To describe the influence of I on SRT we tried to develop a simple model. The following assumptions are made: the initial methanogenic activity of the inoculum is 0.02 (kg COD/kg.d); pH is higher than 6.5; the inoculum and solid waste are initially spatially separated in the reactor, and the methanogenic biomass and the VFY-waste/agricultural waste are completely mixed. In fact the reactor is subdivided into an acid-containing compartment and an acid-consuming methane-producing compartment. In this model the leachate transports the organic acids to the degrading organisms of the inoculum and stimulates colonization of the fresh waste with methanogens. The minimum flow that is needed for an optimal methane production rate can be calculated from the following equation :

$$Q = M/Cvfa \qquad (6)$$

where Q is the leachate recycle flow (m^3/day), M the total methanogenic capacity (kg COD/day) and Cvfy the concentration of Volatile Fatty Acids (kg COD/m^3). In Fig. 5 the minimum leachate recycling flow rate is shown as a function of I at 5, 15 and 25 g VFA-COD/l respectively. From Fig. 5 it can be concluded that indeed a higher flow rate of the leachate is needed with an increasing inoculum factor. At I = 0.77 the maximum organic acids concentration amounted to 7 kg COD/m^3, mainly acetic acid. The minimum leachate flow rate which is needed to prevent rate limitation amounts to 1.4 (m^3/m^3.d). The actual flow rate was 1.0 (m^3/m^3.d), which is below the minimum level to prevent rate limitation by a suboptimal substrate supply to the methanogenic biomass. The higher retention time which is found at I = 0.77 in comparison to the findings at I = 0.55 suggests that the suboptimal leachate flow rate is the main factor controlling the rate of the digestion process in the experiments described here. Although it was expected that at higher I values substrate inhibition of the methanogenic biomass should be of decreasing importance and should result in lower minimum SRT values, the minimum SRT increased. The rate limitation is also a result of the fact that the fresh and digested (inoculum) solids are just roughly manually mixed before start-up. Another way of mixing, for instance in a mixing drum, possibly could reduce the minimum leachate flow rate necessary. The initial spatial separation of inoculum and substrate (organic acids) in the reactor is unlikely when the inoculum and raw organic waste solids are mixed more intensively. However, for other reasons it is questionable if an inoculum factor of 0.77 is attractive. The BIOCEL concept is based on the application of rather plain technology and a minimum reactor handling (filling and drawing)(Ten Brummeler et al, 1986). Since application of an inoculum factor of 0.77 implies a digestion time of only 7-10 days, this means that a reactor has to be loaded once a week, and consequently processing of 1 ton of solid waste needs the handling intensity for 5.6 m^3 reactor. An inoculum factor of 0.5 needs handling for 2.57 m^3 reactor. Since an inoculum factor of 0.77-0.9 does not result in a lower solids retention time an inoculum factor of 0.5-0.6 is more attractive in practice.

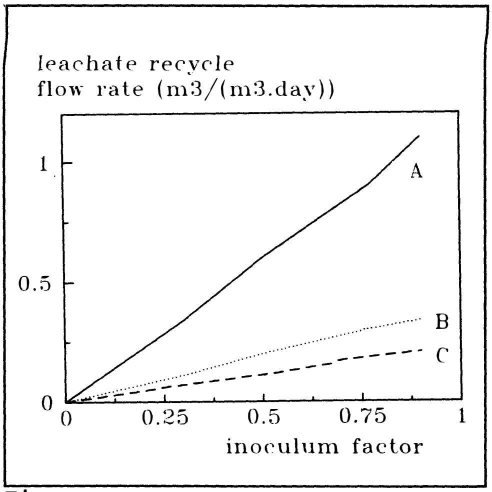

Fig. 5
Maximum applicable leachate flow rate in relation to the inoculum factor at several VFA concentrations; (A) 5 g COD/l; (B) 15 g COD/l;(C) 25 g COD/l.

The effect of the leachate flow rate was also observed in experiments conducted with VFY waste reduced in particle size with a shredder before the digestion. Particle size reduction was thought to be essential for a higher degradation rate of the volatile VFY-solids. Due to the reduced porosity of the solid waste, the maximum possible leachate flow rate was 0.5 ($m^3/m^3.d$) with an organic acid concentration of 15 g/l from day 0 to day 5. A solids retention time of 55 days was found at an inoculum factor of 0.5. The initial acid formation rate and the maximum methane yield of shredded VFY waste did not offer any significant differences with non-shredded VFY waste. Because of the negative effect on SRT the shredding of the VFY waste before the digestion was omitted.

Another factor that has an effect on the maximum leachate flow rate is the height of the reactor. In practice it is convenient to build compact reactors as high as possible to minimize the cost for ground area. As the porosity of the inoculum/raw solid waste mixture in the lower part of the reactor is reduced at increasing height of the digesting mass, the leachate flow rate might also be reduced below the optimum value. As the reactors of the present study were 2.3 m in height, the process was tested in a reactor with a height of 4.5 m, and a total volume of 450 m^3. The results that were achieved with this reactor were identical as compared to the smaller reactors. In the near future the results of the final scaling up of the process will be published in detail.

Influence of Temperature

In previous investigations we found that the optimum temperature for the dry anaerobic digestion process in the BIOCEL process in the mesophilic temperature range is 35-40°C (Ten Brummeler et al., 1991c). At temperatures beneath 30 °C the imbalance of the process by a higher acid formation than methane formation is inevitable. However, maintenance of the reactor temperature above 30 °C right from start-up might not be feasible, as the heating of solid waste mixture can be more difficult than heating a slurry because of the lower heat conductivity of the solid waste mixture in comparison to the slurry. In particular situations the temperature of the reactor input can be higher due to microbial activity by aerobic micro-organisms during storage before the waste is collected, especially in summer time. In winter time the raw waste generally is 20 °C or lower. Heating of the digesting mass after start-up might be problematic, due to limited input of heat to reactor with the leachate.

In order to assess different temperature regimes, three start-up experiments with an inoculum factor of 0.5 were carried out. One reactor was maintained at 35 °C (± 2), another reactor started at 43°C, i.e. the temperature of the waste after a 2 day storage period before reactor loading and the temperature was allowed to decrease to 30 °C. The third start-up of a reactor was carried out at a gradually increasing temperature, viz. from 20 °C to 35 °C at 1.5 °C increments daily.

TABLE 1 provides the minimum SRT's for the three temperature regimes. The start-up experiment at 43-30 °C gave similar results as the start-up experiment at 35 °C. In this experiment the DT amounted to 15 days. The temperature slowly decreased but remained higher than 30 °C during the digestion period. The reactor which was started up at 20 °C required a significantly longer retention time, due to the relatively high acid formation rate

TABLE 1 Influence of different temperature levels on the solids retention time during dry anaerobic digestion of solid organic waste on pilot-plant scale

Temperature (°C)	DT (days)
35	30
43..30	30
20..35	61

compared to the methane formation rate. This resulted in a longer period with high organic acids concentrations and low pH values, which again negatively affected the required solids retention time. These results imply that directly after start-up the temperature of the digesting mass should be in the optimum range of 35-43 °C, which can be roughly considered as the optimum temperature range. In this way a prolonged digestion time which is caused by a period of imbalance of the digestion process can be prevented.

CONCLUSION

Dry anaerobic digestion of Vegetable Fruit and Yard waste and of agricultural waste in a BIOCEL reactor at pilot-plant scale (5 m^3) proceeded at similar rates as was found in lab-scale reactors. The effect of leachate recycle on the rate of the digestion process was more obvious than in lab-scale reactors. The absence of leachate recycle (flow rate: 0.3 $m^3/(m^3.day)$ resulted in a digestion time of 180 days. Dependent on the grade of mixing of fresh substrate and the inoculum, leachate recycle is essential to a high rate digestion. Particle size reduction of the VFY waste resulted in a prolonged digestion time due to a strongly decreased maximum leachate recycle flow rate. The optimum flow rate of the leachate recycle depended on the inoculum factor and was in the range of 0.8 - 2.5 $m^3/(m^3.day)$. The optimum inoculum factor (I), i.e. the ratio of digested solids and total initial solids (inoculum solids plus VFY solids/agricultural waste solids), was in the range 0.5-0.6. A solids retention time of 30 days was observed, which is identical to results from lab-scale experiments. The maximum volatile solids loading rate amounted to 7-10 kg VS/(m^3.d). At an inoculum factor of 0.4 or lower, longer retention times and lower loading rates could be applied. At these values for I, the period during which suboptimal conditions (high organic acids, low pH values) are observed is too long to prevent strong inhibition of the methane formation. The suboptimal conditions are due to the higher grade of imbalance of acid formation and methane formation at low values of the inoculum factor.

The temperature at start-up should be above 30 °C. Start-up at 20 °C and gradually increasing to 35 °C resulted in a retention time a factor of two higher than start-up at 35 °C. If the organic solid waste had a temperature of 43 °C, which was observed in the summer period due to activity of aerobic micro-organisms during storage, further heating during the digestion was not necessary, and a similar solids retention time was found as with reactor start-up at 35°C in the winter period.

REFERENCES

Koster, I.W., Ten Brummeler, E. Zeevalkink, J.A. and Visser, R.O. (1988). Anaerobic digestion of the organic fraction of Municipal Solid Waste in the BIOCEL-process. In: ISWA 88 Proceedings, Andersen, L., and Moeller, J., (eds.), Academic Press, London, pp. 71-77.

Ten Brummeler, E., Koster, I.W., and Zeevalkink J.A., (1986). Biogas production from the organic fraction of Municipal Solid Waste by anaerobic digestion. In: Materials and Energy from Refuse. A. Buekens and M. Tels (eds.), KVIV, Antwerpen, Belgium, pp. 6.49-6.57.

Ten Brummeler, E. Horbach, H.C.J.M., and Koster, I.W.,(1991a). Dry anaerobic batch digestion of the organic fraction of Municipal Solid Waste, J. Chem. Technol. Biotechnol. 50, 191-209.

Ten Brummeler, E. Kip, P., Aarnink, M.M.J., Doekemeijer, E.C. and Koster, I.W., (1991b), Start up of dry anaerobic digestion of Vegetable, Fruit and Yard Waste in a BIOCEL-reactor, submitted for publication.

Ten Brummeler E. and Koster, I.W. (1991c). The influence of different levels of temperature and total solids concentration on dry anaerobic digestion, submitted for publication.