Programme Area: Bioenergy

Project: Energy From Waste

Title: Appendix B - Anaerobic Design

Abstract:

This deliverable forms part of Deliverable 2.2 in Work Package 2 and provides information on the anaerobic digestion rig scale testing.

Context:

The Energy from Waste project was instrumental in identifying the potential near-term value of demonstrating integrated advanced thermal (gasification) systems for energy from waste at the community scale. Coupled with our analysis of the wider energy system, which identified gasification of wastes and biomass as a scenario-resilient technology, the ETI decided to commission the Waste Gasification Demonstration project. Phase 1 of the Waste Gasification project commissioned three companies to produce FEED Studies and business plans for a waste gasification with gas clean up to power plant. The ETI is taking forward one of these designs to the demonstration stage - investing in a 1.5MWe plant near Wednesbury. More information on the project is available on the ETI website. The ETI is publishing the outputs from the Energy from Waste projects as background to the Waste Gasification project. However, these reports were written in 2011 and shouldn't be interpreted as the latest view of the energy from waste sector. Readers are encouraged to review the more recent insight papers published by the ETI, available here: http://www.eti.co.uk/insights

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Batch anaerobic digestion assay for food waste and paper and card as well as their mixtures

1. Material and methods

1.1. Experimental design

The aim of the study was to determine the maximal methane production obtained from an almost complete anaerobic digestion of food waste and paper/card, as well as their mixtures to different ratios (**Table 1**).

The ratios applied for the mixtures as well as the methane yields were calculated relatively to the total Volatile Solids (VS) share of the substrate, which represents the organic fraction of a substrate (**Figure 1**). In order to determine this parameter, fresh substrate samples were taken, weighed and dried at 105°C for 24 hours, the dry residue was weighed, burned at 550°C for 8 hours and eventually the ash residue was weighed. The values obtained for the specific methane yields are not affected by differences in the water content of samples (affected by production paths, climate, and storage conditions), neither by differences in the ash content (affected by the share of minerals, contaminants, sand, and dust).

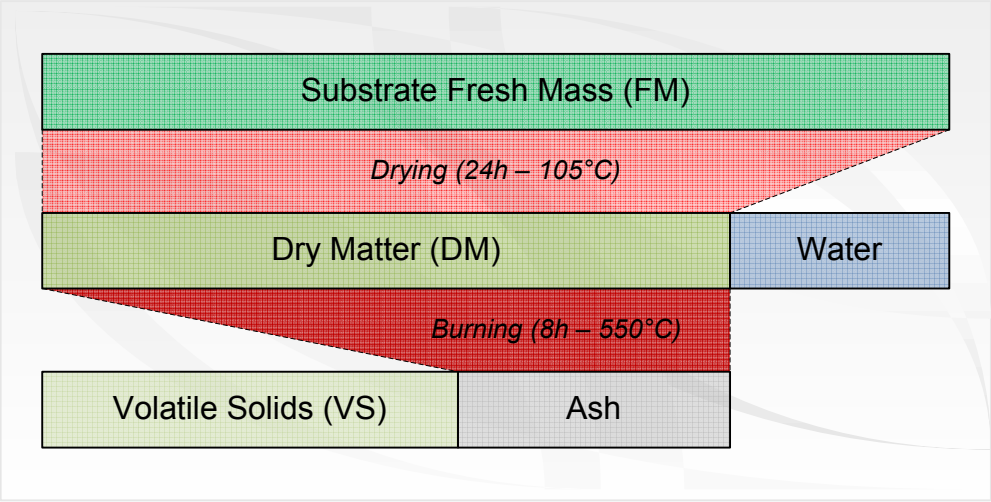

Figure 1. Definition of Volatile Solids (VS)

Volatile solids contents of food waste and paper and card were determined prior to the experiments, and the required amounts of substrates fresh mass added to the digesters were calculated accordingly.

Table 1. Experimental design for laboratory-scale anaerobic digestion assays.

Variant Nr.	Substrate 1	Share of substrate 1 (%VS)	Substrate 2	Share of substrate 2 (%VS)
1	Food waste	100	Paper and card	0
2	Food waste	75	Paper and card	25
3	Food waste	50	Paper and card	50
4	Food waste	25	Paper and card	75
5	Food waste	0	Paper and card	100

Laboratory-scale anaerobic digestion assays were performed as batch experiments. Food waste, paper and card as well as an inoculum were added successively at the beginning of the experiments, the digesters were subsequently closed. Mixing of the substrates occurred during the anaerobic digestion through the stirring of the digesters applied in the processes. Biogas production as well as methane concentrations of the digesters were monitored over a period of 35 days.

Batch assays are best suited to measure accurately the maximal methane production of substrates. However, they are inappropriate to evaluate the influence of substrate composition on the performance of semi-continuous digestion. The latter should be evaluated through semi-continuous experiments, which are usually more expensive, less precise, and more time-consuming (experimental period of several months).

One should keep in mind that batch assays were designed to evaluate the maximal methane yield of a substrate, provided that appropriate nutrient balance, process design and process control are implemented. Methane production in full-scale units might be lower (depending on the operating conditions).

The experimental designs used to carry out batch anaerobic digestion assays complied with the norms DIN 38414, part 8, as well as with the German norm VDI 4630. As a convention, gas volumes will be presented as Nm^3, i.e. m^3 of dry gas in normal conditions (temperature of 0°C, pressure of 1013.25 hPa). The equipments used for performing batch anaerobic digestion trials are described shortly in **Table 2**, and will be discussed further in the following parts of the report.

The batch digestion assays were performed using 3 different laboratory digestion processes, which will be described further in this document: the HBT process (Hohenheim Biogas Yield Test), 2L-digesters and pressure bottles. The experiments involving the HBT and the 2L-digesters were performed at the State Institute of Agricultural Engineering and Bioenergy in Hohenheim, Germany. The experiment with the pressure bottles was carried out at the Test and Research Institute PFI in Pirmasens, Germany. The chemical characterization of the substrates and of the digested effluents was carried out at the Agricultural Technology Centre LTZ of Augustenberg in Karlsruhe, Germany.

Particle size reduction was required to obtain homogenous samples while using small amounts of substrate for the assays. Food waste was passed through a laboratory mixer. Paper for the HBT experiment was finely shredded in a laboratory mill and paper for the 2L-digesters was coarsely shredded in a laboratory mixer.

Table 2. Characteristics of the laboratory equipments used for anaerobic digestion assays.

Process	Volume	Main characteristics	Monitored parameters	Determination method
HBT process	30 mL	Syringes	Gas volume CH_4-content	Scale Infrared sensor
2L-digesters	2 L	Eudiometer-type	Gas volume CH_4-content H_2S-content	Scale Infrared sensor Electrochemical sensor
Pressure bottles	2 L	Pressure bottles	Gas volume CH_4-content H_2S-content	Gas counter Infrared sensor Gas chromatography

1.2. HBT-process

The Hohenheim Biogas yield Test method (HBT) is a non-continuous (batch) digestion process involving a single feeding of the substrate at the start of the experiment. Each digester consisted of a calibrated glass syringe of 100 mL with a gas outlet. The syringe plug was sealed against the glass syringe by means of a non-biodegradable lubricant. A hermetic pipe was connected to the bored side of the syringe, and closed by means of a fastening clip. Through this pipe, the gas could be let out of the syringe for measurement of the methane content. 129 syringes were fitted inside a motorized rotating support. The rotation of the support ensured the thorough mixing of the substrate. The whole rotating unit was built inside a thermostat-regulated incubator, in which the digesters could be heated to the desired temperature.

As the anaerobic digestion occurred in a batch process, inoculating material was required as a source for bacteria, mineral nutrients and buffer. 30 mL of an inoculum mixture were added to each syringe, together with about 360 mg (VS) from the substrates. The zero variant was made of 3 replicates of inoculums without substrate, because the inoculums itself produced a small amount of gas.

After being filled with substrates and inoculum, the syringes were closed and incubated at 37°C for 35 days. The gas production was read on a calibrated scale on the side of each syringe. When the amount of gas in the syringes exceeded 20 mL, these were manually emptied into an infrared methane sensor, which recorded the methane content of biogas.

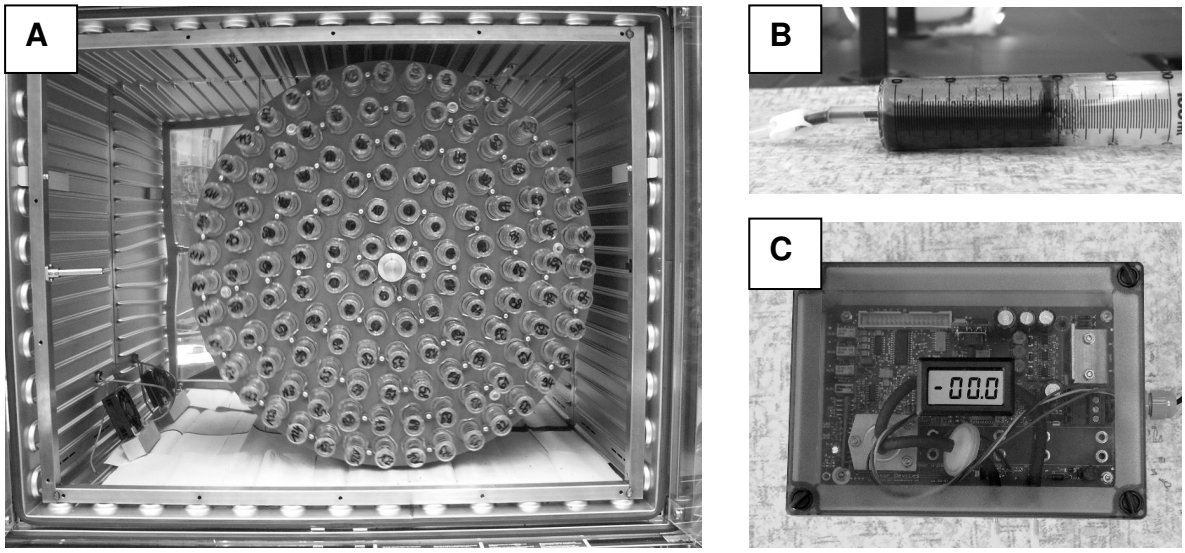

Figure 2. Pictures of the HBT-process. A. Incubator with rotating unit bearing syringes. B. Syringe containing biogas and substrate. C. Methane measurement device.

1.3. Digesters of 2L

24 Erlenmeyer flasks (2 liters capacity each) were used for the experiment. These flasks were fitted with rubber stoppers on the top. Each rubber stopper had a gas outlet connected to a single 3.2 L transparent cylinder (gasometer) diving into a broader cylinder containing sealing liquid for gas collection.

The flasks were kept in a water bath containing water at 38°C. Cylindrical Magnetic bars of 6 cm length were placed in each flask. A 3-way valve was used to direct the flow of biogas from the digester either to the gasometer or to the measuring device during measurement steps.

About 20 g (VS) of each substrate or substrate mixture was added into 1.8 L of inoculum. The rubber stoppers were plugged tightly on the flasks, which were placed in the water bath. Gas production was recorded regularly on the scale on the side of the gasometers. When the amount of gas in each gasometer became higher than 800 mL, gas could be emptied into a measurement device comprising an infrared sensor to measure the methane content and an electrochemical sensor to determine the hydrogen sulfide content.

Figure 3. Picture of the apparatus with 2L-digesters.

1.4. Pressure bottles

25 g of fresh substrate were weighed and mixed together with 700 g of inoculum into glass bottles. For the mixture of food waste with paper and card, 12.5 g of food waste were mixed together with 12.5 g of paper and card. Subsequently, the volume was adjusted to 2 L with water. The pressure bottles were incubated at 40°C, and were shaken manually on a regular basis for homogenization. The determination of the biogas production was carried out in 3 replicates per variant. Pressure bottles were coupled to magnetic valves to release gas regularly into a gas counter and an infrared sensor measuring the methane content of the released gas. Another set of 3 replicates per variant was used to collect gas into gas bags and to measure the H_2S-content. The H_2S-content was measured by means of a gas chromatograph having a Pulse Flame Photometric Detector (PFPD).

2. Results

2.1. Characterization of the substrates

Paper and card was a very dry substrate, the dry matter content amounting to almost 100%, while food waste contained about two thirds of water. Paper and card contained slightly more minerals than food waste, as shown from the Volatile Solids content (**Table 3**).

Table 3. Dry matter and volatile solids contents of food waste and paper and card.

Substrate	Dry Matter content (% of Fresh Weight)	Volatile Solids content (% of Dry Weight)
Food waste	32.6	95.9
Paper and card	96.7	88.6

As expected, food waste contained a higher share of nitrogen than paper and card, but only a few was in the form of ammonia nitrogen (**Table 4**). The nitrogen contained in paper and card was most probably stored in the form of proteins. An approximation formula was used to estimate the share of proteins ($M_{Protein}$) in the samples from the masses of Kjedahl-nitrogen ($M_{Kjedahl\text{-}N}$) and ammonia-nitrogen ($M_{Ammonia\text{-}N}$):

$$M_{Protein} = \left(M_{Kjedahl-N} - M_{Ammonia-N}\right) \times 6.25$$

The nitrogen content of substrates intended to undergo anaerobic digestion should not be too high in order to avoid ammonia inhibition of the biological process. Usually, the limit is 4 g/L in the digestion medium, but adaptation processes are possible up to 8 g/L. According to the dry matter content of 32.6% of food waste, nitrogen concentration related to fresh mass would be higher than 4.5 g/L if food waste would be digested as sole substrate, i.e. nitrogen inhibition may occur.

Table 4. Nitrogen and sulphur contents of food waste and paper and card.

Parameter	Concentration in the dry mass (% w/w)	
	Food waste	Paper and card
Kjedahl Nitrogen	1.4	0.22
Ammonia Nitrogen	0.04	0.01
Estimated protein content	8.5	1.31
Sulphur content	0.24	0.11

The estimated protein content also gives an indirect indication about the sulphur content to be expected, since proteins generally contain a share of sulphur. High hydrogen sulphide concentrations in biogas are a typical issue related to protein-containing substrates. The sulphur content related to dry mass measured in food waste was more than twice the sulphur content of paper, showing that for a similar dry matter load, the anaerobic digestion of food waste should generate higher hydrogen sulphide concentrations in biogas as compared to paper and card.

The heavy metals contents of food waste and paper and card are shown in **Table 5**. Usually, slightly increased amounts of heavy metals should be found in the digested effluent after anaerobic digestion, so knowing the heavy metals content of substrates can be a way to anticipate issues related to the valorization of the digested effluent.

The mercury content in food waste was higher than the thresholds applied for compost quality in many European countries. Since the food waste investigated apparently contained a high share of seafood products, mercury accumulation might have occurred. Food waste comprising a lower share of seafood should have lower mercury contents. All other metals were within the acceptable range when compared to heavy metals regulations of the EU. The heavy metals contents of paper and card were sufficiently low.

Table 5. Heavy metals contents of food waste and paper and card.

Parameter	Concentration in the dry mass (mg/kg)		
	Food waste	Paper and card	Heavy metals limits of compost in EU
Pb	not detected	4.5	70 – 1000
Cd	0.010	0.061	0.7 – 10
Cr	5.3	3.4	70 – 200
Cu	not detected	36	70 – 600
Ni	8.9	1.2	20 – 200
Zn	1.5	24	210 – 4000
Hg	3.3	0.020	0.7 – 10
As	not detected	3.0	10 – 25

Source for the heavy metals limits of compost in Europe: W.F. Brinton, 2000. Compost quality, standard & guidelines: an international view, Final Report, Woods End Research Laboratory, Mt Vernon, ME, USA.

2.2. Characterization of the digested effluents

The macronutrients content of the digested effluents after 35 days of batch anaerobic digestion in the 2L-digesters are presented in **Table 6**. The pH of the effluents was in the range 8.5-8.6. The dry matter content of the digested residue of food waste is lower than for the inoculum alone and for paper and card. This might be due to a sampling error.

Batch anaerobic digestion assays were aimed at estimating the maximal methane production of the samples. Hence, high amounts of inoculums were used. According to the German norm VDI 4630, the organic matter contained in the inoculum should be twice the added organic matter of the samples in order to ensure optimal digestion. An appropriate interpretation of the results supposes that the concentrations of the digestates of food waste and paper and card should be compared to the concentrations of the digested inoculum. The addition of food waste increased the concentrations of nitrogen and sulphur, probably in relation to the high share of proteins. The concentrations of the different components in digested paper and card did not clearly differ from the digested inoculum.

Table 6. Dry matter and nutrients contents of digested inoculum, food waste and paper and card.

Parameter	Concentration in the dry mass (% w/w)		
	Inoculum	Food waste	Paper and card
Dry matter	3.80	2.90	3.80
Kjedahl-Nitrogen	11.1	19.3	10.8
Ammonia Nitrogen	6.9	13	7.6
Calcium (as CaO)	5.1	4.9	5.5
Potassium (as K_2O)	14	14	12
Magnesium (as MgO)	1.6	1.4	1.4
Phosphorus (as P_2O_5)	4.00	3.88	3.50
Sulphur (S)	0.56	0.65	0.56

2.3. Specific methane yield

Though it was initially planned to use the ratios 75-25, 50-50 and 25-75 related to the VS-mass for the mixtures of kitchen waste with paper, the small amounts required for feeding the digesters made an exact weighing difficult and thus created some deviation towards the target ratios. The initial velocities of methane production were higher for kitchen waste than for paper (**Figure 4**). The real ratios are specified on the legends of the graphs. The degradation of paper shows an initial 2-days lag-phase which is typical to the batch anaerobic digestion of cellulose. Although the final methane yield after a digestion time of 35 days for food waste was twice the methane yield of paper, the reaction kinetics for paper is only slightly lower, and both substrates were almost completely digested after 10 days. As expected, the mixture showed intermediate patterns corresponding to the weights of the ratios of kitchen waste and paper. The partial results of methane production velocities from the 2L pressure bottles up to 14 days of digestion seem to be in accordance with the results of the other experiments.

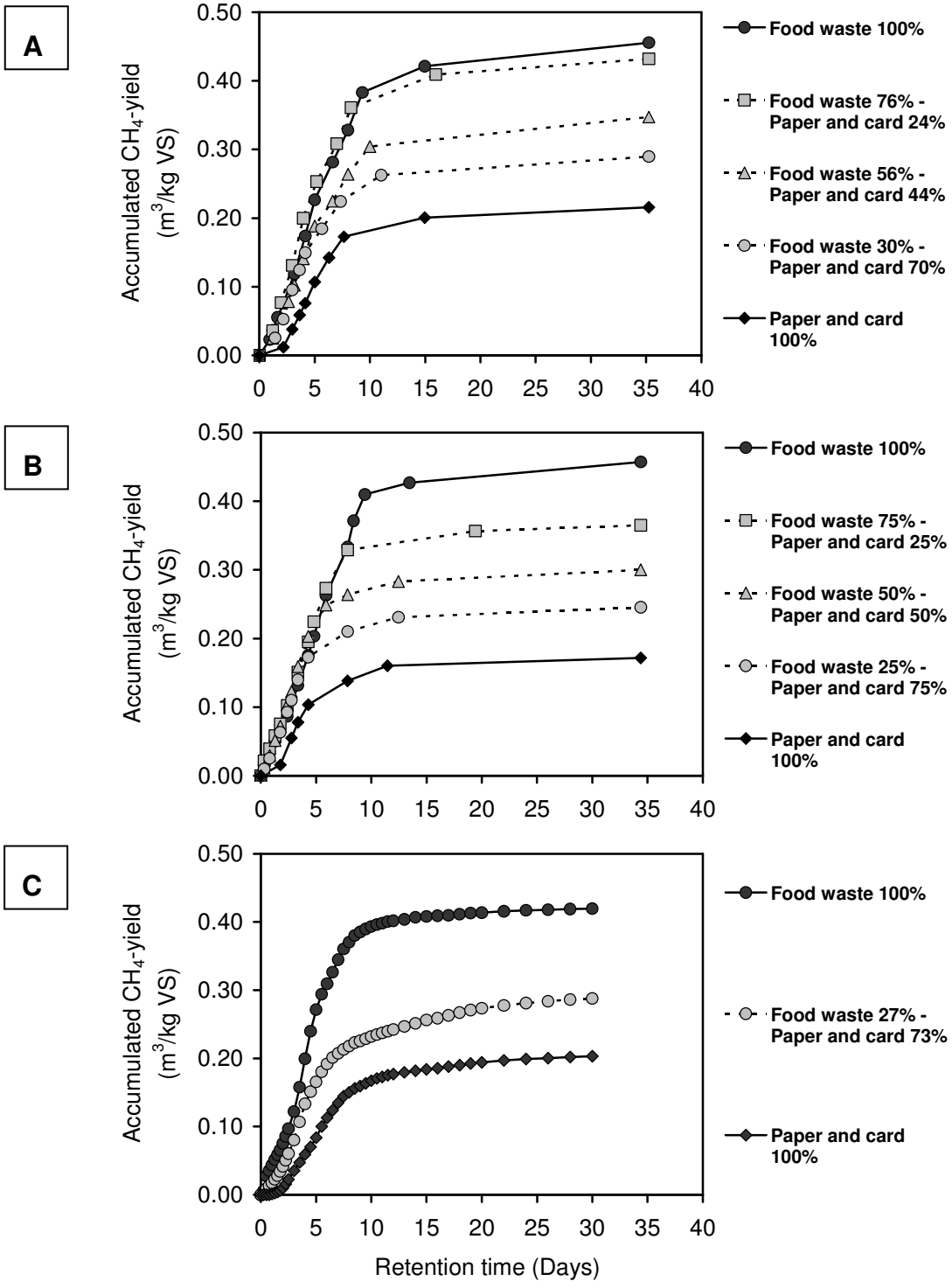

Figure 4. Time course of the specific methane yields of kitchen waste – paper mixtures. Average values. A. HBT digesters, n=3. B. Digesters of 2L, n=4. C. Pressure bottles, n=3.

2.4. H_2S content

Monitoring H_2S concentrations in biogas is a very important task because H_2S creates damage to engines and pipe works in full-scale biogas plants and is toxic for the operators. Most engine suppliers consider that the H_2S content should remain below the threshold of 200 ppm. Biogas having such concentration can be fed to the engines without further purification. However, some experts consider that the concentration should be as close to zero as technically possible to enhance the engine lifetime because the costs for early engine replacement are often underestimated.

In most biogas plants, H_2S is adsorbed on activated carbon columns. The costs for activated carbon replacement can be decreased by lowering the H_2S concentration of biogas. In agricultural biogas plants, H_2S concentration in gas can be reduced through biological desulphuration: an amount of air equivalent to about 3% of the generated biogas volume is injected in the gas phase at the top of the digesters. Woody structures serve as support for the bacteria which reduce H_2S into elemental sulphur. For technical reasons, the former approach is usually not suitable for waste treatment plants. H_2S can also be removed through gas washing using lime scrubbers, but the latter approach is only suitable to large biogas units and high H2S concentrations. H2S concentration is very difficult to measure. An attempt was made to measure H2S concentrations in the course of anaerobic digestion using an electrochemical sensor in the 2L-digesters. In the experiment involving the pressure bottles, H2S concentrations were measured out of sampled gas bags by means of gas chromatography. Although H2S is generally quite difficult to measure, at larger scales it is usually feasible because of the larger gas volume availability.

Figure 5 shows the H2S concentration measured in both experiments. We called "accumulated H2S-content" the concentration of H2S which would be found if all the gas were collected till the date of sampling. The latter is a better indicator than the immediate H_2S-content because it takes into account the fact that gas samples were taken into different gas volumes. The peak of H_2S concentration in the 2L-digesters occurred in the very beginning of the assay, at the first measurement, then H_2S gradually decreased along the retention time, as the substrates became more completely degraded. This means that biogas plants having short retention times or high loading rates (and therefore having only a partial degradation of the substrates) may endure higher H_2S concentrations than biogas plants operated at longer retention times or lower loading rates. Moreover, ensuring a constant feeding rate of the substrate instead of an intermediate feeding may limit H_2S peak concentrations. In practice, peak concentrations of H_2S mostly occur in the case of intermediate mixing, as a huge amount of H_2S degasses suddenly from the digestion medium when the mixing starts. The use of continuous mixing may solve this problem.The effect of mixing could not be investigated there. Interestingly, mixing paper and card together with

food waste in the 2L-digesters greatly reduced H_2S concentrations, and also removed peak H_2S concentrations, even at a low share of 25%.

This suggests that adding paper and card might be a good strategy to reduce H_2S-related problems in biogas plants treating biowaste. The H_2S content of food waste was about 400 ppmv after complete digestion. This value seems rather low since H_2S concentrations of several thousands ppmv might be expected from such substrates. Since H_2S usually originates from the degradation of proteins, the food waste sampled might have been poor in protein.

The results obtained with the pressure bottles are not consistent with the results of the 2L-digesters. We have discussed previously that food waste probably contains a much higher share of proteins than paper, and probably more sulphur. Thus, higher concentrations of H_2S should be found in food waste when compared to paper and card, while the opposite behavior has been noticed in the pressure bottles. We suppose that there should be an issue in the pressure bottles methodology related to H_2S measurement. The sulphur analysis of the samples confirmed this hypothesis, as more. Sulphur can be reduced by anaerobic bacteria to produce H_2S, and can be used indifferently in organic forms (e.g. proteins) and in mineral forms (e.g. sulfates). There should be a rather good correlation between the sulphur content of samples and the amount of H2S released through anaerobic digestion. The composition and contamination of the gas produced hence depends on which types of foods are digested, for example the meat/vegetable ratio. As food waste is, per definition, something that is not homogeneous and reproducible, for real world operation the exact instantaneous likely H_2S is not required to be known, but the important thing is to define the range of this fluctuation to dimension the gas cleaning system.

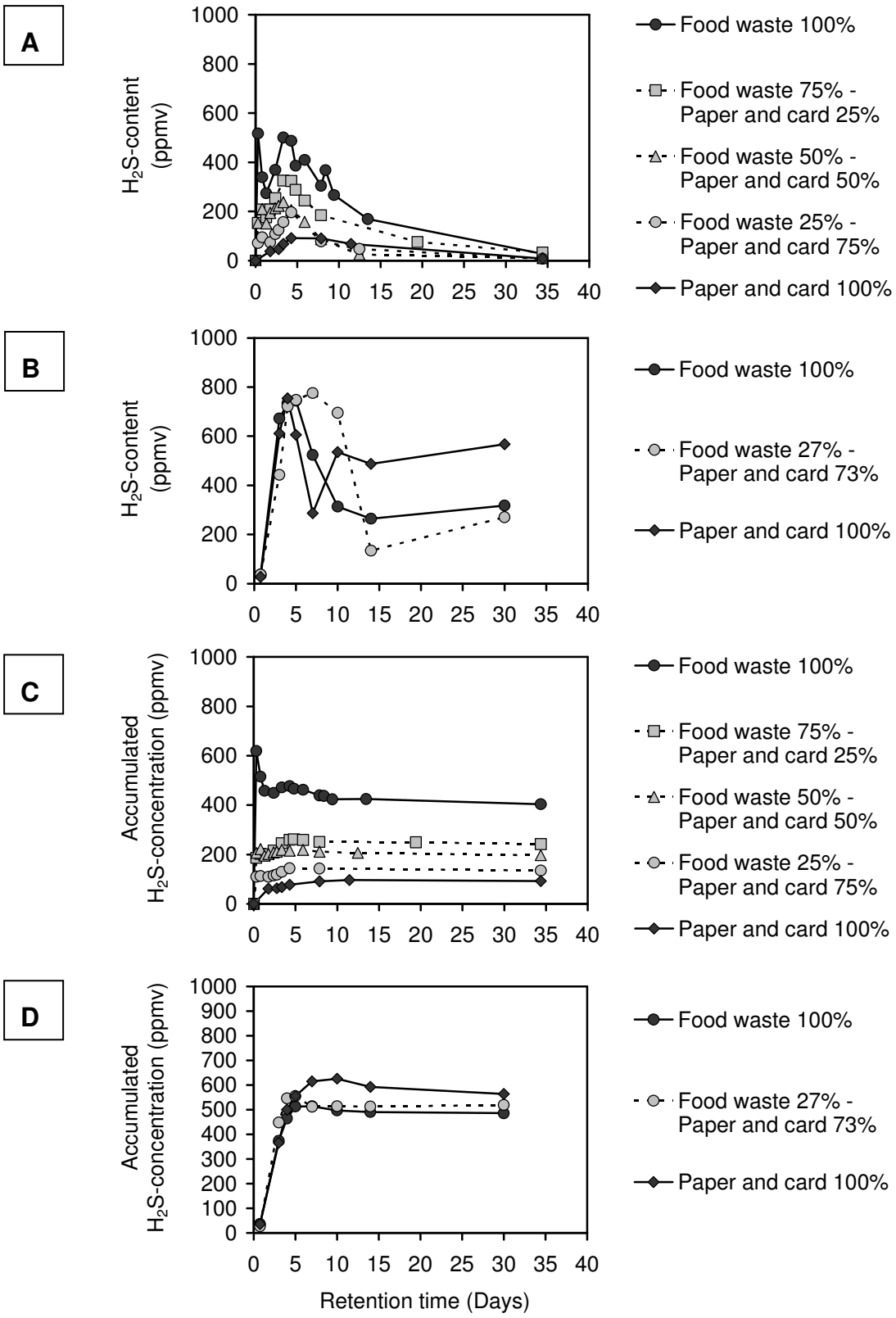

Figure 5. Time course of H_2S content of food waste – paper mixtures. Average values. *H_2S concentration in gas:* A. Digesters of 2L, n=4. B. Pressure bottles, n=3. *Accumulated H_2S content:* C. 2L-digesters, n=4. D. Pressure bottles, n=3.

2.5. Final values of the parameters after 35 days of digestion

The final values of the specific methane yield of paper and card after 35 days of digestion were about 20% higher in the HBT process compared to the 2L-digesters (Table 7). Paper which was brought into the HBT process was ground more finely (powder-like) than paper used for the 2L-digesters (only shredded). The higher extent of particle size reduction of paper for the HBT process might have brought higher methane yields. In an industrial plant, rough shredding of paper is likely to be carried out to increase the surface area; this is likely to be a compromise between the energy consumption and cost of shredding and the increase in biogas yield. This trade off is difficult to predict because to date no detailed essays have been done on this type of issues for this type of substrates, although it is estimate that the effect on the biogas production should not exceed 10 - 20%.

In 2L-digesters, biogas produced from fermentation of food waste had higher H2S contents than biogas originating from fermentation of paper, and the mixtures had intermediate values which correlated well with their ratios. In the pressure bottles, the results did not follow our expectations regarding the final H2S production from paper and card (593 ppm) and from the mixture (514 ppm), which were surprisingly higher than the corresponding value for food waste (491 ppm).

Methane contents from anaerobic digestion of food waste were higher than for paper, which is logical because food waste contains proteins and lipids whose digestion generates a biogas with higher methane content. Nevertheless, methane content of food waste was lower than expected regarding a protein and lipid-rich substrate.

As shown in **Figure 6**, the increase in final values of specific methane yields correlated well with the share of kitchen waste in the mixtures (r^2=0.979, r^2=0.992 and r^2=0.998 for HBT digesters, for 2L-digesters and for pressure bottles respectively). Departures from linearity were within the accuracy range of the assay. One can deduce that the digestion of the mixtures did not generate any synergetic or antagonistic effect on final methane yields. Such effects may appear in practice through an optimization of the nutrient and micronutrient balance (e.g. the C:N ratio), but they can not be proven in batch assays.

Table 7. Final values of CH_4 yield, CH_4 content and H_2S-content after 35 days of digestion for HBT process, 2L-digesters and pressure bottles (Average values ± Standard Deviation).

Variant	CH_4 yield (NL/kg VS) (Nm^3/t FM)			CH_4 content (%)			H_2S content (ppmv)		
	HBT	Digesters of 2L	Pressure bottles	HBT	Digesters of 2L	Pressure bottles	HBT	Digesters of 2L	Pressure bottles
Food waste 100%	456 ± 13 142 ± 4	457 ± 11 143 ± 3	419 ± 26 131 ± 8	56.7 ± 1.0	57.8 ± 1.1	59.1	-	403 ± 177	486 ± 3
Food waste - Paper HBT: 76% - 24% Digesters of 2L: 75%-25%	432 ± 20 159 ± 7	365 ± 6 135 ± 2	-	57.0 ± 0.4	55.7 ± 0.3	-	-	242 ± 159	-
Food waste - Paper HBT: 50% - 50% Digesters of 2L: 75% - 25%	347 ± 11 150 ± 5	300 ± 3 137 ± 2	-	55.0 ± 0.8	55.8 ± 0.5	-	-	197 ± 167	-
Food waste - Paper HBT: 25% - 75% Digesters of 2L: 30% - 70% Pressure bottles: 27% - 73%	290 ± 1 163 ± 1	245 ± 6 146 ± 3	288 ± 11 168 ± 6	54.2 ± 0.5	55.9 ± 0.3	56.9	-	135 ± 92	519 ± 3
Paper and card 100%	216 ± 1 185 ± 1	172 ± 9 147 ± 7	203 ± 9 174 ± 7	51.2 ± 0.3	52.6 ± 1.4	51.5	-	93 ± 55	563 ± 23

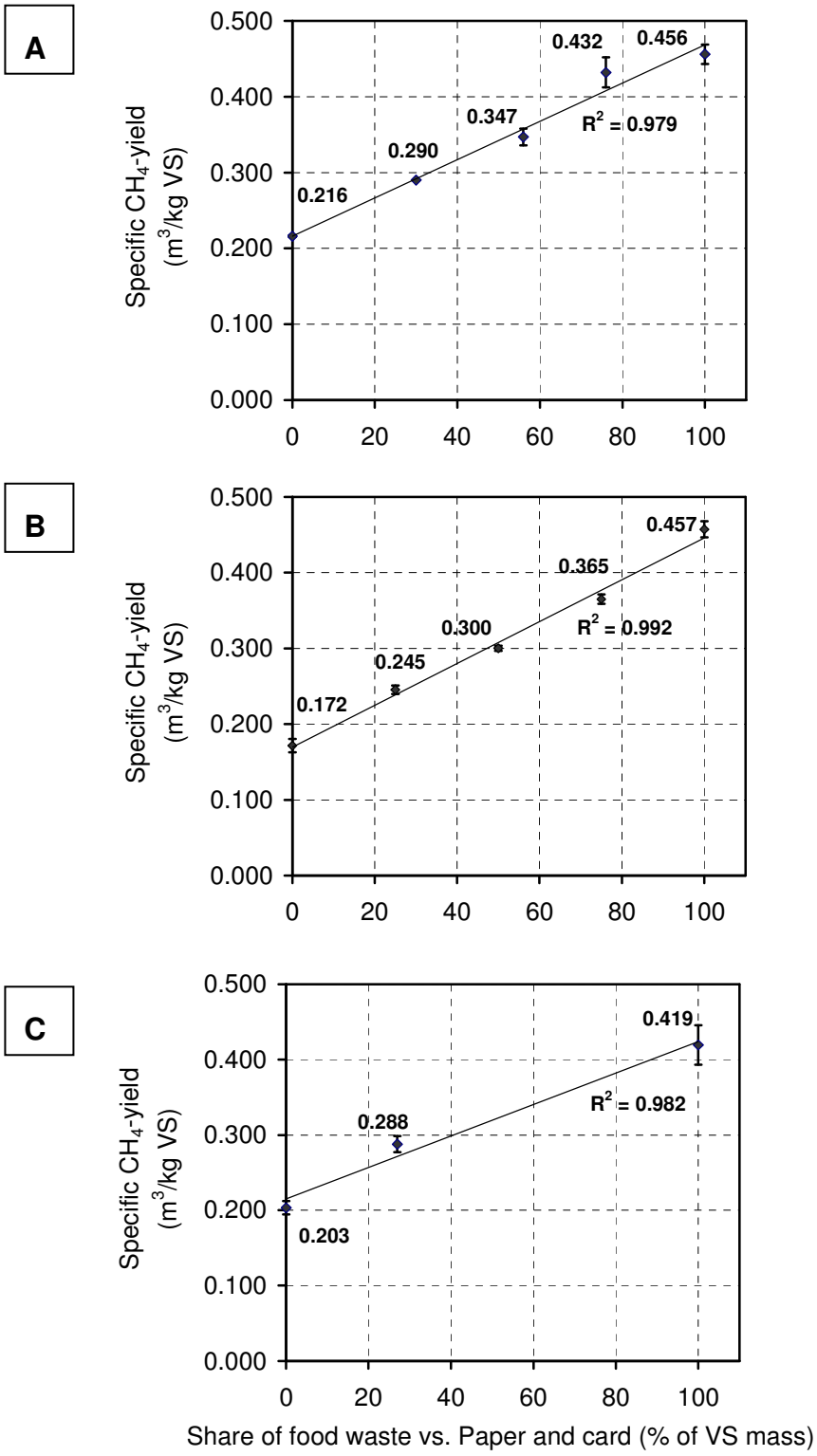

Figure 6. Correlation between final values of specific methane yields and share of kitchen waste in kitchen waste – paper mixture. Average values. Vertical arrows stand for SD. A. HBT digesters, n=3. B. Digesters of 2L, n=4, C. Pressure bottles, n=3.

3. Literature review

3.1. Theoretical methane yields

There is a high discrepancy in the methane yields of the individual ingredients contained in food waste (Cho et al., 1995). However, ultimate methane yields of food waste determined in the laboratory have on average a relatively narrow range of variation, comprised between 435 and 540 NL/kg VS (**Table 8**).

The value about 460 NL/kg VS assessed in the present experiment is good within this range, showing that the sample is representative of the food waste regarding its methane production. The methane yields are quite high when compared to other substrates, with the exception of lipid-rich substrates.

For a good evaluation of the specific methane yield in BMP assays, several conditions should be fulfilled, like a sufficiently low substrate to inoculum ratio, a sufficient inoculum activity, and the absence of inconsistencies in the measurement methods. Liu et al. (2009) varied the substrate/inoculum ratio and revealed a tremendous influence on the methane yields of food waste, which varied between 252 and 518 NL/kg VS at substrate/inoculum ratios of 5.0 and 1.6, respectively. El-Mahad and Zhang (2010) found a methane yield as low as 353 NL/kg VS after 30 days of digestion at 35°C, however, the methane production curve was still steadily rising by the end of the assay, showing that by that time the value for the ultimate methane yield was far from being reached.

Table 8. Comparison of substrate characteristics, methane yields and digestion conditions of food waste with other laboratory-scale biomethane potential assays from the literature.

Source	Dry matter (% FW)	Volatile Solids (% DM)	CH_4 yield (NL/kg VS)	Digestion period (days)	Digestion temperature (°C)
Cho et al., 1995	26	95	472	28	37
Heo et al., 2004	28	94	489	40	35
Zhang et al., 2007	26	87	435	28	50
Nayono, 2009	26	88	540	11	37
Liu et al., 2009	24	87	510*	25	50
Current work	**33**	**96**	**460**	**37**	**37**

* At a substrate to inoculum ratio of 4 or lower

Food waste does not represent the whole substrate flux treated in a typical biogas plant treating municipal solid waste (MSW). The organic fraction of municipal solid wastes (OFMSW) usually also contains garden waste, paper and contaminants. The share of contaminants depends on the type of collection applied. Unsorted or residual MSW undergoes a mechanical treatment to extract contaminants, inert materials and metals. The mechanically-sorted (MS) fraction of MSW may still contain about 20% of contaminants. Source-separated (SS) biowaste originate from private households, and is characterized with an undesirable fraction due to sorting errors. Separately collected (SC) biowaste is gathered from markets, canteens and restaurants, and has the highest degree of purity.

Separately collected biowaste has the highest methane yields (**Table 9**). Source-separated biowaste produces slightly lower methane yields and is more dilute. Methane yields of mechanically-sorted waste are much lower, depending on sorting quality. Mechanically-sorted waste from dry processes (screens, cyclones, sieves) is very dry.

Table 9. Substrate characteristics and ultimate methane yields of the organic fraction of municipal solid waste (OFMSW) depending on waste origin (Cecchi et al., 2003).

Waste category	Dry matter (% FW)	Volatile Solids (% DM)	CH_4 yield (NL/kg VS)
Mechanically-sorted (MS)	50-54	43-57	160 – 370
Source-separated (SS)	16-20	88-90	370 – 400
Separately collected (SC)	21-27	91-100	450 – 490

The ultimate methane yields of paper in laboratory assays are highly dependent on paper quality (**Table 10**). The differences are probably correlated to the share of lignin, which hampers biodegradation. Office paper contains a very tiny amount of lignin, while cardboard paper contains about 5% lignin and newspaper contains about 20% lignin (Owens and Chynoweth, 1993). Here again, the values are strongly dependent on the assay conditions. Lower yields were obtained by Eleazer et al. in a laboratory simulated landfill, amounting to 217, 152 and 74 NL/kg TS for office paper, cardboard paper and newspaper, respectively. The latter values confirm the decreasing order of digestibility of office paper, cardboard paper and newspaper.

No data could be found regarding practical yields of full-scale plants regarding paper because it is not profitable to attempt digesting paper waste as a sole substrate.

Table 10. Substrate characteristics and ultimate methane yields of paper and garden waste determined in a laboratory-scale biomethane potential assay (Owens and Chynoweth, 1993).

Assay conditions	Waste category	Waste type	Dry matter (% FW)	Volatile Solids (% DM)	CH_4 yield (NL/kg VS)
Substrates: clean material **Particle size reduction:** grinding **Digester size:** 275 mL **Incubation conditions:** 35°C, ≈ 80 days	Printing paper	Office paper	96.2	92.7	369 ± 14
		Cardboard paper	94.8	97.7	278 ± 12
		Newspaper unprinted	91.4	97.9	84 ± 3
		Newspaper printed	92.2	97.6	100 ± 3
		Magazine	97.1	78.1	203 ± 8
	Food packaging	Cellophane	93.7	99.4	349 ± 23
		Food board uncoated	95.8	98.6	343 ± 20
		Food board coated	96.2	93.3	334 ± 17
		Milk carton	96.1	99.4	318 ± 14
		Wax paper	94.6	98.4	341 ± 22
	Garden waste	Grass	37.0	88.1	209 ± 5
		Leaves	56.4	95.0	123 ± 5
		Branches	70.8	93.9	134 ± 6
		Mixed garden waste	50.4	92.0	143 ± 4
Substrates: hand-sorted residual MSW fractions **Particle size reduction:** shredding **Digester size:** 2L **Incubation conditions:** 35°C, 237 days	Paper	Office paper	97	74	340 ± 24
		Cardboard paper	87	77	217 ± 38
		Newspaper	86	68	58 ± 10
		Packaging	84	85	165 ± 112
	Others	Textiles	91	92	228 ± 118
		Diapers	38	78	204 ± 18
		Putrescibles	-	-	527 ± 54
		Residual MSW (whole fraction)	84	69	147 ± 41

3.2. Practical methane yields

In practice, biowaste composition is highly variable and undergoes seasonal variations. The share of garden waste decreases in the winter time, and may vary between 3 and 92% of the biowaste bin. Due to the higher production of garden waste, the amount of biowaste collected is about 35% higher in rural areas. Addition of a share of paper is beneficial to limit storage issues before biowaste collection, like infestation with flies and repulsive odours, and buffers against seasonal variations in waste amounts. Paper absorbs water and increases biowaste's dry matter content (Gellens et al., 1995).

In practice, at the Valorga biogas plant in Tilburg, Netherlands, the hydraulic retention time (HRT) of the reactor varied between 20 and 55 days. In the summer time, the plant received a higher biowaste input due to the increase of the amounts of garden waste, and the methane yields were the lowest. In the winter time, the feedstock contained a higher share of food waste, and the methane yields were higher. The lower specific methane yields in summer were due to both the lower biodegradability of garden waste as compared to food waste and to the lower hydraulic retention time from the comparatively higher amount of biowaste treated in this period (Fruteau et al., 1997).

The methane yields of biowaste digested in full-scale biogas plants undergo strong seasonal variations (**Table 11**). Methane yields depend strongly on local conditions: type of waste collection, share of paper and garden waste, share of sand and inert materials. Source-collected biowaste may have a totally different composition depending on local conditions. Biowaste feeding the Dranco biogas plants in Salzberg, Austria and Brecht, Belgium contained on average for the first 80% kitchen waste, and 20% garden waste, and for the second 15% kitchen waste, 75% garden waste and 10% paper waste (De Baere, 2000).

The values shown in Table 11 are higher than the values given by Kelleher (2007), who shows practical methane yields in the range 112-144 NL/kg FW for raw MSW, 80-90 NL/kg FW for digesters fed with food waste together with garden waste and 112-136 NL/kg FW for a food-waste/paper mixture. According to this latter author, adding a share of paper may be a good way of increasing the methane yields of the units.

Table 11. Comparison of substrate characteristics, methane yields and digestion conditions of full-scale biogas plants from Valorga (Saint-Joly et al., 2000), Dranco (Baeten and Verstraete, 1988; De Baere, 2000; Hartmann and Ahring, 2006) and Biocel (Hartmann and Ahring, 2006; Ten Brummeler, 2000).

Plant Type	Plant Location	Waste category	Dry matter (% FW)	Volatile Solids (% DM)	CH_4 yield (NL/kg VS)	Biogas yield (NL/kg FW)
Valorga	Amiens, France	Residual waste	55-65	50-70	205 (160-260)	145 (120-170)
	Tilburg, Netherlands	Biowaste	39-60	36-64	225 (160-320)	92 (60-140)
	Engelskirchen, Germany	Biowaste	33-44	52-75	280 (210-340)	126 (100-160)
Dranco	Salzberg, Austria	Biowaste	31	70	342*	135
	Brecht, Belgium	Biowaste	40	55	258*	103
	Bassum, Germany	Residual waste	57	51	278*	147
	Gent, Netherlands	Raw MSW	56	66	248*	168
Biocel	Lelystad, Netherlands	Biowaste	35	-	143*	-
Lab	**Current work**	**Food waste**	**33**	**96**	**460**	**250**

* Calculated assuming a CH_4-content in biogas of 55%

3.3. Substrate digestibility

Food waste is considered having a high digestibility and can be digested within short retention times. However, the rapid degradation of the easily degradable fraction of the waste into volatile fatty acids (VFA) as intermediate products of anaerobic digestion may cause process instability. Specific solutions include the digestion of food waste in a two-step process (the strong acidification phase taking place in the first reactor) or the co-digestion with slowly degradable substrates, which might be the ideal solution (Heo et al., 2004).

Food and yard waste have a C:N ratio below 20. The C:N ratio of mixed paper is more than 100. The optimal C:N ratio for anaerobic digestion is in the range 25-30 (Hartmann and Ahring, 2006).

The lower inhibition of ammonia makes mesophilic anaerobic digestion (temperature around 37°C) more suitable than thermophilic anaerobic digestion (temperature around 55°C) for the conversion of nitrogen-rich substrates, which usually contain a high share of proteins (Angelidaki and Ahring 1994; Sung and Liu 2003). Thus, for substrates having an excessive share of nitrogen, like food waste alone, mesophilic operation is recommended.

In this regard, adding a share of paper and card into a biogas plant operated with food waste can be beneficial to the stability of the digestion by reducing ammonia concentrations in the digester, increasing methane production rates and allowing the process to be shifted from mesophilic into more efficient thermophilic conditions (Hartmann and Ahring, 2006).

3.4. Effect of pretreatments on methane production

Pretreatments can be applied to increase the methane yield of lignin-rich paper substrates. The aim of these pretreatment is both to remove some lignin and to weaken cellulose-lignin associations (Xiao and Clarkson, 1997; Teghammar et al., 2010). Clarkson and Xiao (2000) claimed that methane production from newsprint could be improved through alkaline pretreatment with NaOH (5%), and that the pretreated newsprint could be efficiently neutralized with CO_2 through biogas scrubbing before anaerobic digestion.

Xiao and Clarkson (1997) tested successfully the acid pretreatment of newsprint. The samples were treated with 35% acetic acid and 2% nitric acid at 100°C for 30 min and 80% of the lignin was removed. The methane yields could be increased from about 100 NL/kg VS to about 270 NL/kg VS, but remained below the methane yield of about 360 NL/kg VS from raw office paper. It was hypothesized that office paper still had lower lignin content than pretreated newsprint. The acids solution could be reused several times after separation from the pretreated samples through centrifugation. Nitric acid used in the pretreatment may be replaced, to some extent, with cheaper hydrochloric acid.

Steam explosion of paper tube residual following a reaction of 10 min with 2% H_2O_2 and 2% NaOH at 220°C yielded 493 NL/kg VS, against 238 NL/kg VS for untreated samples. Steam explosion after a reaction time of 10 min with 2% NaOH at 190°C yielded 403 NL/kg VS. Reaction without steam explosion with 2% NaOH during 30 min yielded only to a slightly increased yield to 269 NmL/kg VS. Other pretreatments without steam explosion had inhibitory effects. Steam explosion performed without chemicals addition had either no effect or inhibitory effects. It was hypothesized that steam explosion produced lower concentrations of phenolics, which were supposed to have inhibitory effects on anaerobic digestion. Chemicals addition increased the efficiency of steam explosion. Pretreated samples had to be neutralized with ammonium hydroxide and phosphoric acid prior to anaerobic digestion (Teghammar et al., 2010).

The anaerobic degradability of newspaper waste was increased through wet oxidation, which is defined as the oxidation of an organic material with gaseous oxygen in water. Wet oxidation was carried out through heating at 170, 190 or 210°C for 1h together with air scrubbing. For the treatment at 190°C, a conversion rate of 59% of TCOD into CH_4 was claimed. Assuming a COD conversion rate into CH_4 of 0.35 L/g, this may correspond to 207 L/kg VS, while the ultimate methane yield for untreated newspaper is about 100 NL/kg VS.

Liu et al. investigated hand-sorted MSW composed of 40% paper and card, 56% food and yard waste and 4% contaminants in batch anaerobic digestion at 55°C. After a primary digestion lasting for 35 days, they carried out a steam explosion of the digested MSW, followed by a secondary digestion. Steam explosion was performed at 240°C for 5 min without addition of chemicals. A control variant was operated without steam explosion. The biogas yield after the primary digestion was of 320 Nm^3/t TS. The biogas yield increased to 520 and 450 Nm^3/t TS after the secondary digestion with and without preceding steam explosion step. Thus biogas yields increased of 38 and 29% for secondary digestion with and without pretreatment, respectively, against the biogas yields reached after the primary digestion. In other terms, the effect of steam explosion alone was only a 13%-increase of the biogas production.

Lopez Torres and Espinosa Llorens (2007) tested lime addition at 2.8g $Ca(OH)_2$/100g TS for 6h on OFMSW diluted to 8% TS and found an increase of the methane yield of 173% over the untreated control. However, the methane yield of the pretreated sample of 150 Nm^3/t VS. The authors claimed that pretreatment with $Ca(OH)_2$ was economically profitable and a cheaper alternative to pretreatment with NaOH.

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4. Model for mass balance and biodegradability rate

A model was developed according to the dry matter content of the feedstock as well as the amount of biogas produced through anaerobic digestion. The amount of biogas released was considered equivalent to the mass reduction between the feedstock and the digested effluent. The models allowed calculating the decrease of the dry matter content between feedstock and effluent. An element-specific mass balance on sulphur was also attempted. Nitrogen and other minerals contained in the substrate are not released in the biogas, thus they will be conserved in the liquid phase. The nitrogen flux into biogas is negligible. Ammonia nitrogen concentration in biogas is very low (less than 200 ppm) and hardly measurable, as NH_3 gas directly condenses in presence of small amounts of water and easily adsorbs on materials.

4.1. Assessment of biodegradability rate according to biogas release

Knowing the Volatile Solids content of substrates, the rate of biodegradability can generally be estimated by mass balance according to the amount of biogas released. In the following, we will show that this method has some limitations.

Assuming that biogas components are perfect gases and have a molar volume of 22.4 L/mol, and knowing the molar mass of each biogas component, the weight of dry gas released per gram of volatile solids from the substrate can be calculated (**Table 12**). In these calculations, specific methane yields of 0.460 and 0.200 L/g VS were assumed for food waste and paper and card, respectively. Biogas yields were calculated after the methane contents.

Table 12. Calculation of the biodegradability rates after biogas amounts and composition.

Substrate	Gas component	Concentration in biogas (% v/v)	Volume (L/g VS)	Weight (g/g VS)
Food waste	Biogas	100	**0.807**	**1.01**
	CH_4	57	0.46	0.33
	CO_2	43	0.35	0.68
	H_2S	0,04	0.00032	0.00049
Paper and card	Biogas	100	**0.392**	**0.52**
	CH_4	51	0.20	0.14
	CO_2	49	0.19	0.38
	H_2S	0,01	0.00004	0.00006

The amount of biogas released is about 1.01 g/g VS for food waste and 0.52 g/g VS for food waste. Assuming mass conservation between substrate and biogas, this would mean that food waste and paper and card have biodegradability rates of 101% and 52%, respectively. The biodegradability rate of food waste being superior to 100% is probably due to water conversion into biogas, according to the extended Buswell equation (from the German norm VDI 4630, 2006):

$$C_aH_bO_cN_dS_e + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4} + \frac{e}{2}\right)H_2O \rightarrow \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4}\right)CH_4 + \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8} + \frac{e}{4}\right)CO_2 + dNH_3 + eH_2S$$

The elements N and S probably have a low impact on water absorption due to their low solubility. However, the increase of the share of hydrogen for highly reduced substrates (e.g. lipids) leads to more H_2O been absorbed. As an example, the anaerobic digestion of glucose ($C_6H_{12}O_6$) does not generate water, but the conversion of 1 mol of palmitic acid ($C_{16}H_{32}O_2$) into biogas consumes 7 mol H_2O to produce 11.5 mol CH_4 and 4.5 mol CO_2, i.e. the water consumption accounts for 44% of the amount of biogas released, on a molar basis, or 33% by weight.

In order to correct the biodegradability rate, the determination of the organic share of C, H and O would be required. However, in most cases, the bias may only be a problem while considering the biodegradation rate of lipid-rich substrates. To the author's opinion, the biodegradation rate of paper and card was unbiased, and the real biodegradation rate of food waste might be around 90%, meaning that about 10% of the weight of biogas produced is actually due to water consumption.

4.2. Simplified EIFER-model to assess effluent composition

The concentration of substances in the non-degraded effluent can be calculated according to a mass balance. In a first step, a simplified model will be implemented, neglecting water incorporation into biogas.

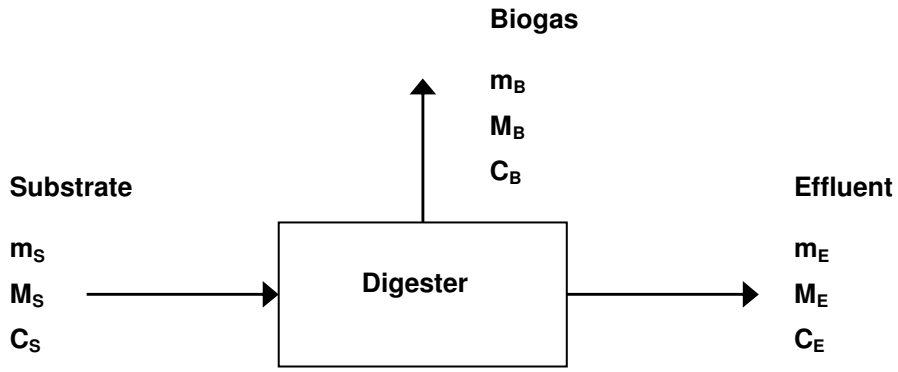

Figure 7. Simplified EIFER-Model for mass balance model for the calculation of effluent composition, simplified model.

Following variables were defined for the substrate (S), the biogas (B) and the digested effluent (E):

m weight of the compound considered (g)

M weight of the flux of diluted compound (g)

C weight fraction of the compound to the total weight of the flux (g/g)

The symbols m and M are dummy variables which disappear during the calculation steps.

The composition of the effluent will be calculated by setting a constant for biogas biodegradation rate (g biogas/g substrate), which will be defined as follows:

(1) $$R = \frac{m_B}{m_S}$$

The mass balances on each flux can be expressed as follows:

(2) $$M_S = M_B + M_E \;;\quad m_S = m_B + m_E$$

(3) $$M_S = \frac{C_S}{m_S} \;;\quad M_B = \frac{C_B}{m_B} \;;\quad M_B = \frac{C_E}{m_E}$$

Starting from (2):

(4) $$M_S = M_B + M_E \quad \rightarrow \quad M_E = M_S - M_B \quad \rightarrow \quad \frac{m_E}{C_E} = \frac{m_S}{C_S} - \frac{m_B}{C_B}$$

(5) $$C_E = \frac{m_E}{\frac{m_S}{C_S} - \frac{m_B}{C_B}} \quad \rightarrow \quad m_E = m_S - m_B \quad \rightarrow \quad C_E = \frac{m_S - m_B}{\frac{m_S}{C_S} - \frac{m_B}{C_B}}$$

Knowing $R = \frac{m_B}{m_S}$; we replace $m_B = R \cdot m_S$:

(6) $$C_E = \frac{m_S - m_B}{\frac{m_S}{C_S} - \frac{m_B}{C_B}} \quad \rightarrow \quad C_E = \frac{m_S - R \cdot m_S}{\frac{m_S}{C_S} - \frac{R \cdot m_S}{C_B}}$$

Eliminating m_S leads to the final equation, which allows calculating the concentrations of the effluent:

(7) $$C_E = \frac{1 - R}{\frac{1}{C_S} - \frac{R}{C_B}}$$

Input parameters:

R Biodegradation rate (g biogas/g substrate)

C_S weight fraction of the substrate to the total weight of the substrate flux (g/g)

C_B weight fraction of biogas to the total weight of the biogas flux (g/g)

4.3. Extended EIFER-model to account for water reaction into biogas

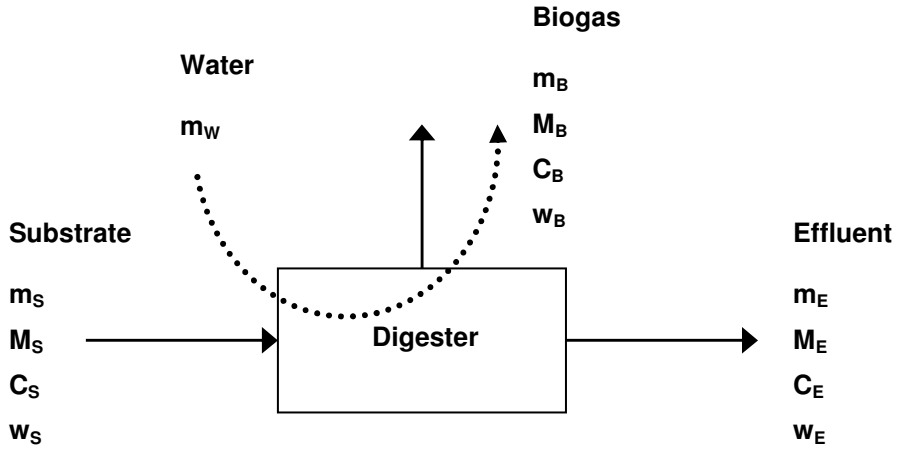

Figure 8. EIFER-Model for mass balance model for the calculation of effluent composition, model with water incorporation into biogas.

An additional share of water m_W reacts together with the substrate to produce biogas:

(8) $$m_S + m_W = m_B + m_E$$

Defining w_S, w_B and w_E as the weights of water in the fluxes of substrate, biogas and effluent, respectively, and considering m_W as the weight of water incorporated into biogas:

(9) $$w_S = w_B + w_E + m_W$$

However, the reaction of water to generate biogas does not affect the mass balance of the fluxes, since there is no leak in the system:

(3, 4) $$M_S = M_B + M_E \;; \quad M_S = \frac{C_S}{m_S} \;; \quad M_B = \frac{C_B}{m_B} \;; \quad M_B = \frac{C_E}{m_E} \;; \quad \frac{m_E}{C_E} = \frac{m_S}{C_S} - \frac{m_B}{C_B}$$

Therefore, the previous equation (5) remains true:

(5) $$C_E = \frac{m_E}{\frac{m_S}{C_S} - \frac{m_B}{C_B}}$$

However, the term m_E is now different:

(8) $$m_S + m_W = m_B + m_E \rightarrow \quad m_E = m_S - m_B + m_W$$

Replacing into (5) leads to:

(10) $$C_E = \frac{m_E}{\frac{m_S}{C_S} - \frac{m_B}{C_B}} = \frac{m_S - m_B + m_W}{\frac{m_S}{C_S} - \frac{m_B}{C_B}}$$

The biodegradation rate R has been previously defined as the

(1) $$R = \frac{m_B}{m_S} \quad \rightarrow \quad m_B = R \cdot m_S$$

Let us define the water incorporation rate K as the share of water incorporated into biogas:

(11) $$K = \frac{m_W}{m_B} \quad \rightarrow \quad m_W = K \cdot m_B$$

Replacing into (10) leads to:

(12) $$C_E = \frac{m_S - m_B + m_W}{\frac{m_S}{C_S} - \frac{m_B}{C_B}} = \frac{m_S - m_B + K \cdot m_B}{\frac{m_S}{C_S} - \frac{m_B}{C_B}} = \frac{m_S - R \cdot m_S + K \cdot R \cdot m_S}{\frac{m_S}{C_S} - \frac{R \cdot m_S}{C_B}}$$

Eliminating m_S leads to the extended model accounting for water conversion into biogas:

(13) $$C_E = \frac{1 + R \cdot (K - 1)}{\frac{1}{C_S} - \frac{R}{C_B}}$$

However, R being no more the real biodegradation rate, we have to calculate a corrected biodegradation rate RK accounting for the fact that water incorporation into biogas does not correspond to substrate degradation:

(14) $$m_W = K \cdot m_B \,;\; m_B = R \cdot m_S \quad \rightarrow \quad R_K = \frac{m_B - m_W}{m_S} = \frac{m_B - K \cdot m_B}{m_S} = \frac{R \cdot m_S - K \cdot R \cdot m_S}{m_S}$$

Eliminating m_S leads to the corrected biodegradation rate:

(15) $$R_K = R \cdot (1 - K)$$

Replacing RK in CE leads to a very interesting equation, which allows us to calculate R_K and eventually the value for the water incorporation rate K:

(16) $$C_E = \frac{1 - R_K}{\frac{1}{C_S} - \frac{R}{C_B}} \quad \rightarrow \quad R_K = 1 - C_E \left(\frac{1}{C_S} - \frac{R}{C_B} \right)$$

4.4. Calculation of effluent concentrations

Unfortunately, the effluent concentration C_E is not known, so that we are not able to calculate the value for the rate of water incorporation into biogas K. The parameters R, K, C_S and C_B will be set to calculate C_E.

(13) $$C_E = \frac{1 + R \cdot (K - 1)}{\frac{1}{C_S} - \frac{R}{C_B}}$$

The mass balance will be carried out on basis of the volatile solids, dry solids and sulphur. In order to perform this calculation, the input parameters for the EIFER-model have to be calculated according to **Table 13**. The meaning of the variables used in the formulas is explained in **Table 14**. Regarding the water content in fresh biogas $T_{W\text{-}FB}$, a value of 2% was taken, which should be expected in a mesophilic digestion system. At higher temperatures, in a thermophilic system, the water content of biogas can reach about 6%.

Table 13. Calculation of the parameters for the EIFER-model.

Parameter	Product concerned with the balance		
	Total solids	**Volatile Solids**	**Sulphur**
R	$R_{TS} = R_{VS} \cdot \frac{T_{VS}}{100}$	R_{VS} previously determined	$R_{Sulfur} = \frac{m_{Sulphur-Biogas}}{\frac{T_{Sulphur-TS}}{100} \cdot \frac{100}{T_{VS}}}$
C_S	$C_{S-TS} = \frac{T_{TS}}{100}$	$C_{S-VS} = \frac{T_{TS}}{100} \cdot \frac{T_{VS}}{100}$	$C_{S-Sulfur} = \frac{T_{Sulphur-TS}}{100} \cdot \frac{T_{TS}}{100}$
C_B	Volume share of water in the dry biogas: $T_{W-DB} = \frac{T_{W-FB}}{100 - T_{W-FB}}$ Weight of water in the biogas per g VS from the substrate: $w_W = T_{W-DB} \cdot \frac{V_{Biogas}}{22.4} \cdot 18$ Mass fraction of water in the wet biogas: $C_W = \frac{w_w}{R_{VS} + w_w}$ Mass fraction of dry biogas in the wet biogas: $C_B = 1 - C_W$		
K	$K = 0$ for paper and card $K = 0.1$ for food waste		

Table 14. Input parameters for calculating the constants of the EIFER-model.

Input Parameter	Definition	Value		Calculated Parameters
		Food waste	Paper and card	
T_{TS}	Total Solids content of substrate (% FW)	32.6	95.9	$C_{S\text{-}TS}$, $C_{S\text{-}Sulphur}$
T_{VS}	Volatile Solids content of substrate (% TS)	96.7	88.6	R_{VS}, R_{TS}, $C_{S\text{-}VS}$
R_{VS}	Biodegradation rate (g biogas/g VS)	1.01	0.52	R_{VS}, R_{TS}
V_{Biogas}	Volume of dry biogas generated per g VS from the substrate (L/g VS)	0.807	0.392	C_B
$m_{Suflur\text{-}Biogas}$	Weight of sulphur in biogas per g VS from the substrate consumed (g/g substrate VS)	0.00049	0.00006	$R_{Sulphur}$
$T_{Sulphur\text{-}TS}$	Sulphur content in substrate dry mass (% TS)	0.24	0.11	$R_{Sulphur}$, $C_{S\text{-}Sulphur}$
T_{TS}	Total Solids content of substrate (% FW)	32.6	95.9	$C_{S\text{-}TS}$, $C_{S\text{-}Sulphur}$
$T_{W\text{-}FB}$	Water content in the fresh biogas (% v/v)	2	2	C_B

The calculation of the input parameters allows running the EIFER-model. Results are specified in **Table 15**. For food waste, the mass fractions of TS and VS are much higher in the substrate (C_S) than in the effluent (C_E). The concentration of TS and VS related to fresh weight is reduced through the digestion process to 5.8 and 4.2%, respectively, while the effluent of paper and card is incredibly dry, with TS and VS content off 93.6 and 73.8%, respectively. Since the anaerobic digestion is only affordable at total solids contents below 40%, the digestion of this substrate would only be technically feasible with phase separation of the effluent and water recirculation.

Sulphur contents in the fresh weight were slightly higher paper and card than for food waste, however we have shown previously that biogas originating from food waste has a higher H_2S content. According to the model, sulphur contents in the substrate and in the effluent were almost similar, meaning that a high share of sulphur compounds were not converted into biogas.

Table 15. Input and output parameters entered in the EIFER-model.

Parameter type	Parameter	Food waste			Paper and card		
		TS	VS	Sulphur	TS	VS	Sulphur
Input	R	0.98	1.01	0.197	0.46	0.52	0.048
	K	0.1	0.1	0.1	0	0	0
	C_S	0.326	0.315	0.00078	0.959	0.850	0.00105
	C_B	0.99	0.99	0.99	0.99	0.99	0.99
Output	R_K	0.88	0.91	0.18	0.46	0.52	0.05
	C_E	0.058	0.042	0.00064	0.936	0.738	0.00100

In order to confirm that it has been appropriate to account for water incorporation into biogas, the parameter K (mass fraction of water integrated to biogas) was varied for food waste, while keeping all other values to the above-mentioned constants. As shown in **Figure 9**, water conversion into biogas even at a low share has a tremendous influence on both conversion rate and effluent dry matter content.

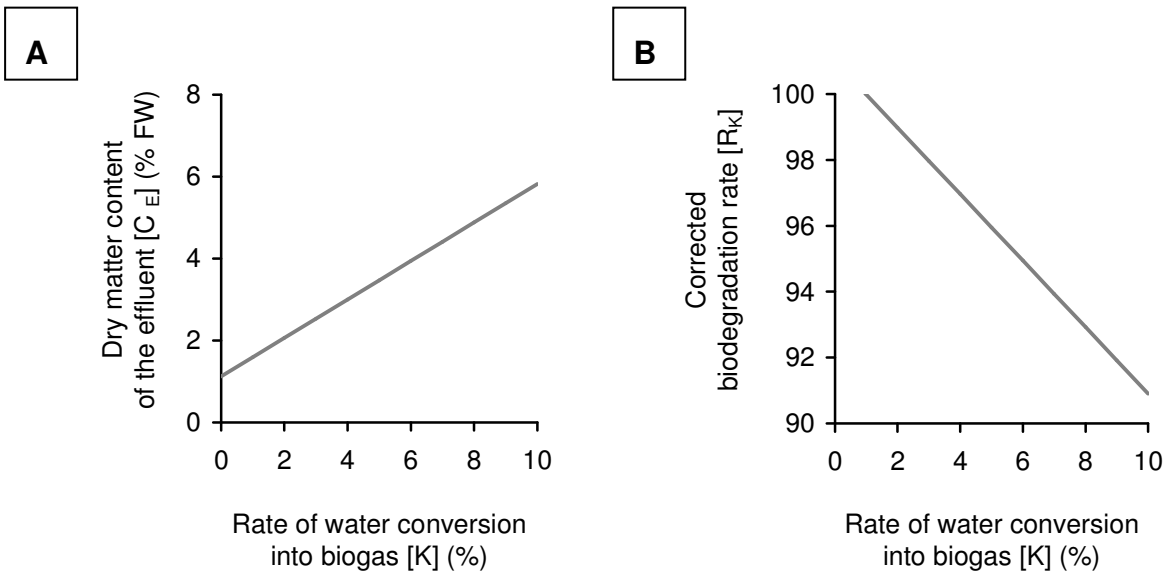

Figure 9. Influence of water conversion rate into biogas (K) on outputs of the EIFER-model. A. Dry matter content of the effluent (C_E). B. Corrected biodegradation rate (R_K).

The previous results have shown that the effluent of the mono-digestion of paper as a sole substrate has a too high dry matter content for anaerobic digestion to be easily feasible.

The EIFER-Model was implemented to find effect of the share of food waste in a mixture with paper and card on the dry matter content of the digester. The mixtures parameters were assessed through weighted averages of the values for food waste and paper and card. The graph below shows that a food waste content of a least 50% in weight is necessary to keep the dry matter content below 40%. One may conclude that it may be necessary to keep the share of paper waste at a relatively low level (e.g. in the range 0-20%) in order to maintain sufficiently low solids contents for the anaerobic digestion process.

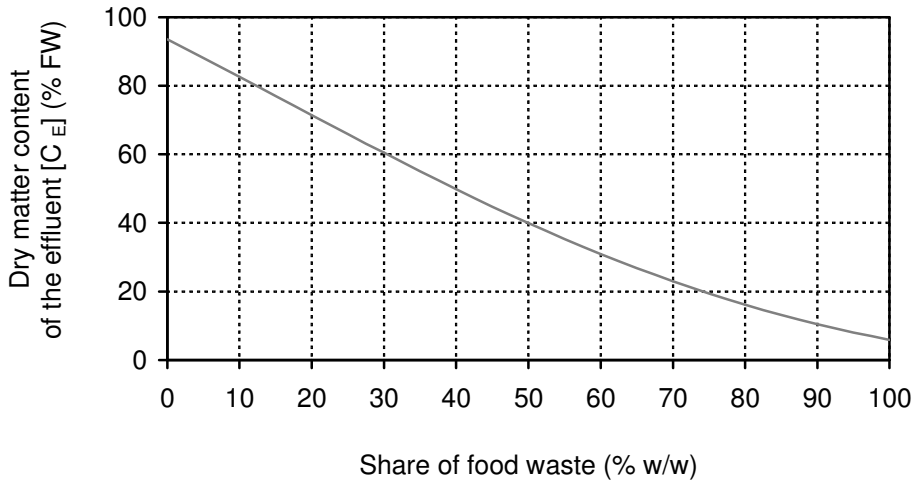

Figure 10. Influence of the share of food waste in a substrate mixture containing food waste and paper and card o the dry matter content of the effluent (C_E) assessed through the EIFER models.

5. Conclusion

Food waste was found to have a high methane yield of about 460 Nm^3/t (VS) while paper and card had much lower specific methane yields about 200 Nm^3/t (VS). The ultimate methane yields of finely shredded paper (powder-like) increased to 216 Nm^3/t (VS) as compared to 172 Nm^3/t (VS) for coarsely shredded paper. This corresponds to a 20% increase. The mixtures of food waste together with paper and card were showing intermediate behaviors. Food waste and paper and card had dry matter contents of 32.6% and 96.7%, respectively, and organic matter contents related to fresh weight of 96.7% and 88.6%, respectively (**Table 3).** Considering these values, the methane yields related to the Fresh Matter (FM) should be about 145 Nm^3/t (FM) for food waste and about 170 Nm^3/t (FM) for paper and card. One may assume that practical methane yields are usually about 20% lower than the maximal yields

measured in the laboratory. However, in some particular cases of good operation, fine particle size and long retention time, maximal yields may also be attained in practice.

Adding a share of paper and card to biogas plants operated with food waste might be a good strategy to deal with issues related to high H_2S concentrations. This has however to be proved with samples having a greater H_2S production. H_2S concentrations in the gas originating from the anaerobic digestion of food waste were rather low. Using a high share of paper and card might create stirring issues and floating layers in practice due to the physical resistance and lower density of paper. Mixing paper and card together with food waste may improve the extent and stability of digestion but does not necessarily affect the residence time to be applied. The optimization of feedstock composition is not intended to reduce the size of the reactor vessel. Moreover, as shown by the EIFER-model, paper and card, due to its high dry matter content and low digestibility, enhances the solids content of the digester, and may be added only at a low share to avoid process-related issues.

Nutrient balance and process stability could also be potentially improved through the implementation of substrate mixtures, provided that paper has been finely shredded before fermentation.

The 3rd experiment with pressure bottles and H_2S determination through gas chromatography did not confirm the H_2S production from paper and card and from the mixture. However, the sulphur analysis has shown that food waste has, on a dry weight basis, a higher share of sulphur, presumably leading to higher H_2S concentrations in biogas. However, the EIFER-model has shown that the conversion rate of sulphur into H_2S was low, and that much sulphur may remain in the effluent. Because of the difference in sulphur digestibility between substrates, it might not be accurate to estimate H_2S release alone after sulphur concentration in the substrate.

The EIFER-model has shown that for lipid-rich substrates the water uptake in biogas should be estimated in order to avoid drawing wrong conclusions regarding both the digestibility rate and the effluent concentration. The model appears to be a powerful tool to predict the digestion behavior of substrates, although correction factors should be applied to account for the difference between hypotheses made from laboratory results and reality of full-scale biogas plants. Moreover, the model needs to be validated.

6. Appendix

Table 16. Nitrogen and sulphur contents of the substrates (**related to fresh mass**).

Parameter	Concentration in the fresh mass (% w/w)	
	Food waste	Paper and card
Kjedahl Nitrogen	0.5	0.21
Ammonia Nitrogen	0.01	0.01
Estimated protein content	2.8	1.27
Sulphur content	0.078	0.105

Table 17. Heavy metals contents of the substrates (**related to fresh mass**).

Parameter	Concentration in the fresh mass (mg/kg)	
	Food waste	Paper and card
Pb	not detected	4.4
Cd	0.003	0.059
Cr	1.7	3.3
Cu	not detected	35
Ni	2.9	1.2
Zn	0.5	23
Hg	1.1	0.019
As	not detected	2.9

Table 18. Nutrient contents of digested inoculum, food waste and paper and card (related to fresh mass)

Parameter	Concentration in the fresh mass (% w/w)		
	Inoculum	Food waste	Paper and card
Kjedahl-Nitrogen	0.4	0.6	0.4
Ammonia Nitrogen	0.3	0.4	0.3
Calcium (as CaO)	0.2	0.1	0.2
Potassium (as K_2O)	0.5	0.4	0.5
Magnesium (as MgO)	0.06	0.04	0.05
Phosphorus (as P_2O_5)	0.15	0.11	0.13
Sulphur (S)	0.02	0.02	0.02