Anaerobic digestion of sewage and domestic waste. How small can it be?

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Abstract

Anaerobic digestion (AD) is a well-established technology, particularly suited to handle organic material. It is widely used at large scales as a renewable energy source as it produces biogas, while the remaining digestate is used as fertilizer. However, as energy and transportation prices rise, small-scale applications and decentralised local energy production will become more attractive. The aim of this work is to evaluate the sustainability of small-scale urban AD systems and investigate the scale down to which they remain techno-economically viable.

Data on small-scale domestic AD applications was gathered from literature and analysed to provide an overview of the current situation and identify gaps, potential correlations and trends. A steady-state mathematical model of the AD process was developed for scenario evaluation, based on feedstock analysis, mass balances and kinetics. Literature data from AD applications were simulated, and a sensitivity analysis was also carried out to study the effect of several model parameters on the process.

The data analysis confirmed the challenges of small-scale systems, as larger reactor volumes are required to treat more dilute feedstocks, such as sewage. The analysis showed that the clear majority of small AD systems are installed on farms and in rural areas, and conversely, very few small-scale applications treat municipal wastes or sewage, indicating a technical gap in these systems. Finally, the model can successfully predict the efficiency of AD systems based on feedstock characterisation and it will be used to evaluate the feasibility of such systems.

Keywords: Anaerobic digestion; Biogas; Decentralized treatment; Sewage; Small scale.

1. Introduction & Aim

Anaerobic digestion (AD) is commonly used to treat the organic matter from sewage sludge, manure-slurries, and food and agricultural wastes. It is widely used as a renewable energy source as it produces biogas, which is suitable for energy production (electricity, heat, gas). At the same time the nutrient-rich remaining digestate can be used as fertilizer, since it contains nearly all its major mineral elements (nitrogen, phosphorous and potassium). AD is also an important pillar of the European circular economy concept as it mitigates greenhouse gas emissions, it recycles nutrients, it prevents nitrogen leakage into groundwater, and it avoids the spread of harmful diseases through extended landfilling [1].

AD is traditionally conducted at large scale, e.g. at a wastewater treatment works or in a co-operative of farms, and hence transport to centralized facilities is required. However, as energy and transportation prices rise and the demand for local waste treatment increases, this framework may change and local fertilizer and energy production will become more attractive [2]. Besides the financial aspect, decentralized treatment also contributes to sanitation and provides local and social benefits. Implementing more localised AD also offers the opportunity to reduce additional loadings on existing sewer and wastewater treatment works due to new development.

Small-scale (household and community) AD systems are popular in several parts of the world, particularly in Asia, Africa and South America, where sewage and kitchen waste is co-digested with agricultural streams. According to Rajendran et.al [3] there are millions of household digesters around the world with most of them in China, followed by India. In most of these cases manure is the basic feedstock used to produce local energy, mainly for heating and cooking. However, in the industrialized world small-scale AD applications treating domestic derived wastes are rare. There are a lot of small-scale farm applications producing energy from manure and crops, but very few small-scale AD systems to treat municipal wastes. This is mainly due to the lower content of biodegradable organics in such feedstocks. Small scale domestic AD systems have mainly been used as projects by companies to test various substrates and technologies, and by small communities as pilot projects. In most of these cases AD is part of a bigger ecological and sanitation project.

Whilst a sustainable AD process has been achieved for large scale applications, this is connected to economies of scale, and thus the economic sustainability of smaller systems is in question. As AD systems become smaller in scale, several technical and economic limitations will arise. Garfi et.al [4] highlight that although the potential of this technology is well demonstrated, some barriers are identified such as the need for technical improvements, lack of social acceptance, and high investment costs. Hence, for smaller AD systems to be sustainable, the energy (biogas) and nutrient recovery must be optimized. This would allow the use of AD as a decentralised technology, which would move the treatment closer to source, reducing loadings on existing wastewater treatment plants. Examples could include the use of small-scale AD systems to treat waste from food and drink processing industries, from new housing developments, in villages, and for large office blocks, etc.

The capital investment costs, feedstock characteristics and methane production are the most important parameters, which will define the required size of the AD system. This work focuses on three types of domestic waste feedstocks: food waste, source separated waste, and sewage. Generation of different substrates varies per capita or per household, as does the composition (solids content, organic matter etc.), which determines the biogas production according to biodegradability. Thus the size of the AD reactor is strongly dependant on the type of feedstock treated. Based on literature [5, 6], in the UK, the average person produces 150 litres of wastewater per day of which 4.5 litres is black water. With regards to food waste an average value is 150 Kg per year.

The basic aim of this work is to evaluate the sustainability of small-scale AD systems to treat domestic waste and investigate AD for more decentralized applications, whilst maintaining technical and economic viability. We study the optimisation of biogas production using modelling tools to investigate the effect of varying substrate composition and other operational parameters (hydraulic retention time, organic loading rate, solids content etc.) on the qualitative and quantitative properties of the produced biogas. The final objective is to characterise different feedstocks and explore their feasibility for use in small scale and decentralised AD systems.

2. Methodology

2.1 Small-scale AD database construction

Data regarding AD applications was gathered from literature and analysed to evaluate the current status of small-scale AD technology and feedstocks, to develop a better understanding of the sustainability of AD systems, and to explore any trends or correlations within the data. The database was constructed based on small-scale AD applications (< 1,000 m^3), and targeting the most common operational parameters which control the process, e.g. reactor type and volume (m^3), temperature (^oC), hydraulic retention time (HRT, d), organic loading rate (OLR, Kg COD $m^{-3}d^{-1}$), COD removal efficiency (%) and biogas yield (m^3 biogas Kg^{-1} VS added).

The data was sorted based on the scale of application (full scale, pilot, lab, feasibility studies), and the type of the feedstock treated and its composition. The targeted feedstocks were food waste, source separated waste (black water) and sewage. Farm and animal waste was also included as a reference point. Where needed, the literature data was reprocessed to standardise values and to fill in the gaps of information. As a result, a database of small-scale AD systems was built, based on size classifications used by the original authors. Table 1 shows the number of cases per feedstock type and per type of application found in the literature search.

Table 1 Small-scale AD applications from literature used for database construction.

Application	Feedstock type				Reactor size range (m^3)
	Source separation	Sewage	Food waste	Farm-animal	
Full scale	10	1	3	19	0.2 - 900
Pilot	1	4	3	42	0.125 - 25
Lab	8	1	-	5	0.005 - 1.22
Feasibility studies	-	2	-	-	200 - 700
Total	**19**	**8**	**6**	**66**	

2.2 Model development

A simple steady-state spreadsheet model of the AD process was developed to correlate gas production and substrate composition, to predict the influence of various parameters on the process, and to simulate the outcomes of literature cases. The data from literature cases were used as model inputs, and simulations were run by adjusting parameters such as kinetic constants or feedstock characteristics where these were missing from the data. Temperature, reactor volume, HRT, influent COD and inflow were taken from each literature case and the model calculated the methane yield, COD removal and OLR. The model predictions were then compared to the literature data. All of the literature cases (Table 1) were simulated, apart from those treating farm and animal waste, which were used as a reference and to help identify trends and correlations within the broader literature data.

An internal sensitivity analysis was carried out to investigate how the model responds to changes in important operational parameters and the feedstock characteristics. The effect of dry matter content, temperature, HRT, non-biodegradable COD fraction, VFA content and feedstock composition was evaluated on methane yield and COD removal efficiency. The model was based on COD fractions and mass balances, Monod kinetics and the Buswell equation for biogas prediction. It was built as follows.

2.2.1 Influent characteristics

The influent wet mass (Kg d^{-1}) was calculated with the feed flow rate (m^3 d^{-1}) and the feedstock specific gravity (Kg m^{-3}). Dry matter content (DM, %) was defined as percentage of wet mass, while the organic dry matter (ODM, %) was defined as a percentage of the dry matter. Organic dry matter was broken down into proteins, lipids, carbohydrates, volatile fatty acids (VFA), and lignin, which corresponds to the non-biodegradable part. Where this information was not explicit from the literature examples, these features were calculated by interpolation and mass balancing, based on “typical” values.

2.2.2 Operational parameters

The reactor volume (m^3) was set and the hydraulic retention time (d) was then calculated based on the given flow rate (m^3 d^{-1}), or the other way around according the information gathered. The organic loading rate (OLR - Kg VS m^{-3} d^{-1}) was calculated based on the influent ODM (Kg VS d^{-1}) and the reactor volume (m^3). The reactor temperature was also defined, as this was used to adjust the kinetic parameters.

2.2.3 COD fractionation and Monod kinetics

This aspect of the model followed the mass balance and kinetic methodology of Sötemann et.al [7]. In the system, apart from the influent COD (S_{ti}, Kg COD L^{-1}), a fraction of COD that is converted into biomass (E) was calculated based on the biomass formation yield (Y_{AD}, g COD $_{biomass}$ g^{-1} COD $_{substrate}$) and the endogenous respiration rate (b_{AD}, d^{-1}). These parameters were based on typical literature values, and the solids retention time (SRT; d). SRT is assumed to be 20% greater than the HRT, as if the bacteria are not retained long enough an effective culture may not develop.

The residual COD concentration (S_r, Kg COD L^{-1}) was calculated based on standard values of Monod kinetic constants: K_s (Kg COD L^{-1}), K_m (Kg COD Kg^{-1} biomass COD d^{-1}), b_{AD}, Y_{AD}, and the SRT. Assuming that 100% of the biodegradable COD fraction is degraded, which is over ambitious but at least provides the maximum potential, the biodegradable COD fraction removed (S_{br}, Kg COD L^{-1}) was calculated as $S_{br} = S_{bsi} + S_{bpi} - S_{r,}$ where S_{bsi} is the readily biodegradable soluble COD concentration and S_{bpi} the slowly biodegradable particulate COD concentration. The biomass COD concentration (Z_{AD}, Kg COD L^{-1}) was calculated as $Z_{AD} = S_{br} \times E$. Having defined biomass and residual concentrations the hydrolysis rate (r_h, Kg COD L^{-1} d^{-1}) was calculated as $r_h = (K_m \times S_{br} \times Z_{AD}) / (K_s + S_{br})$.

The total effluent COD concentration (S_{te}, Kg COD L^{-1}) was calculated as $S_{te} = S_{upi} + S_{usi} + S_r + Z_{AD}$, where S_{upi} and S_{usi} are the influent non-biodegradable particulate and soluble COD concentrations respectively. The produced methane concentration was calculated as $S_m = (1 - Y_{AD}) \times SRT \times r_h$, whilst the effluent COD concentration (S_e, Kg COD L^{-1}) was $S_e = S_m + S_{te}$ and the percentage COD removal efficiency: $COD_r = 1 – (S_{te} / S_{ti})$. In relation to gas production it was assumed that S_m includes the VFA COD concentration, which is completely converted into methane.

2.2.4 Stoichiometry and elemental balance

The organic dry matter of the waste is broken down into its major constituents (proteins, carbohydrates, lipids, VFA and the non-biodegradable part). The Buswell equation was used to calculate the composition (CH_4 and CO_2) of the produced biogas. The theoretical maximum CH_4 production (L d^{-1}) and methane yield were also calculated by based on the daily influent mass of ODM, as a reference point. Finally, the theoretical COD (g COD g $feedstock^{-1}$) was calculated based on the elemental composition of the ODM fractions. TOC was calculated based on the elemental composition of the ODM fractions and so was the COD/TOC ratio. The methane production values reported from the model are based on the substrate specific influent characteristics, the COD mass balances, and the temperature driven kinetics.

2.3 Model assumptions

The model uses typical literature values, and various assumptions were made, in order for to simulate AD processes treating different types of feedstock substrates. During the calculation of influent characteristics, the assumptions presented in Table 2 were made [8, 9, 10, 11, 12, 13 and 14]. Each feedstock has different total solids (TS) and organic volatile solids (VS) content, whilst the feedstock composition also varies. The values for these characteristics were based on literature data, so to increase robustness, several literature sources were compared, and in some instances average values were used to try and ensure uniformity. The sensitivity analysis allowed the influence of these values to be determined on the model predictions.

In addition to the parameters listed in Table 2, some constants used in the model were also fixed according to literature values – see Table 3. These parameters were fixed, unless relevant information was provided in the literature cases. In such cases the real data were used to replace the assumptions. In case of gaps in the literature data, simple mass balance calculations were used complete the data. Unless specified in the literature, a standard temperature of 35 ^{0}C was used, corresponding to mesophilic conditions.

Table 2 Characteristics and averaged assumed compositions for different substrates.

Parameter	Black water	Food waste	Sewage
Total Solids (TS, %)	0.74	20.00	0.10
Volatile Solids (VS as % of TS)	72.00	85.00	60.00
Specific gravity (tn.m^{-3})	1.01	1.20	1.05
Carbohydrates (% of VS)	27.81	41.07	45.00
Proteins (% of VS)	47.80	22.08	30.00
Lipids (% of VS)	6.08	20.28	6.69
VFA (% VS)	4.23	2.49	4.23
Non-biodegradable (% of VS)	14.08	14.08	14.08

Table 3 Constants and assumptions used according to literature data.

Parameter	Value	Source
COD/VS ratio	1.42	[15]
VFA/COD ratio	0.06	[15]
Non-biodegradable COD fraction (%)	20.00	[16,17]
Non-biodegradable soluble COD fraction (%)	5.00	[16,17]
Non-biodegradable particulate COD fraction (%)	15.00	[16,17]
Readily biodegradable soluble COD fraction (including VFA) (%)	20.00	[16,17]
Influent biodegradable particulate COD faction (%)	60.00	[16,17]
Typical elemental composition of lipids	$C_{51}H_{98}O_6$	[18, 19]
Typical elemental composition of proteins	$C_5H_7O_2N$	[18, 19]
Typical elemental composition of carbohydrates	$C_6H_{10}O_5$	[18, 19]
Typical elemental composition of VFA	$C_2H_4O_2$	[18, 19]
Typical elemental composition of lignin	$C_6H_{10}O_5$	[18, 19]
Biomass formation yield (g COD biomass.g^{-1} COD substrate)	0.113	[7]
Endogenous respiration rate (d^{-1})	0.041	7]
Solid retention time (d)	120% × HRT	-
Monod kinetics constant K_s (Kg COD L^{-1})	0.108	[7]
Monod kinetics constant K_m (Kg COD Kg^{-1} COD biomass d^{-1})	1.097	[7]
CH_4 COD (g.mole^{-1})	64.00	-
CH_4 gas volume at STP (l)	22.40	-

3. Results and discussion

The model was used to simulate the actual literature applications and evaluate the influence of operational parameters and substrate composition. The target substrates of sewage, source separated, and food waste were compared with other theoretical compositions and to the literature values. Finally, the model and literature analysis helped to evaluate the range of scale of small-scale AD to be used in decentralised systems.

3.1 Current small-scale AD situation

The evaluation of current published small AD studies showed that at the typical mesophilic (35°C) and thermophilic (55°C) AD temperatures there is high variability in terms of organic loading, OLR (Figure 1a). Average OLR values under thermophilic conditions were higher for mesophilic, which is in line with theoretical increased kinetic rates at higher temperatures. In the same way, at low temperatures the kinetics rates are reduced and as a result the loading rates were kept below 2 Kg COD m^{-3}d^{-1} to avoid overloading. Figure 1a also reveals that nearly all source separation and sewage applications were carried at lower temperatures, indicating that probably no additional (or parasitic) heating was employed. Thermophilic temperatures (> 45 ^{o}C) seem only to be employed for smaller reactor sizes.

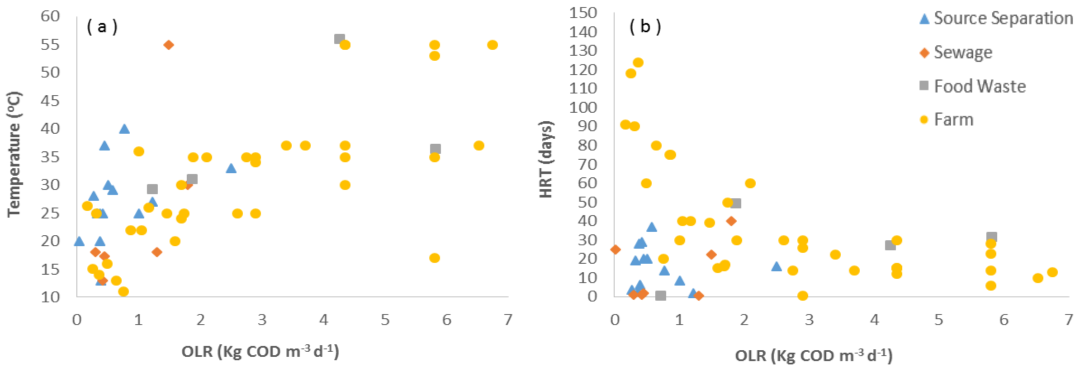

Fig. 1 Correlation of temperature (a) and HRT (b) with OLR for published small AD application data.

The OLR is not linearly dependent on HRT (Figure 1b) under thermophilic conditions, even with similar feedstocks, which is because various combinations of reactor size and feed flows were used in the evaluated cases. Figure 1b also reveals that higher loading rates are used at smaller retention times. This is consistent with the mass balance relationship which indicates that for the same or similar COD, lower loading rates should be applied for longer retention times. It is also clear that feedstocks such as source separated black waste and sewage, which are more difficult to break down than farm-derived feedstocks, employ lower values of OLR for the same HRT.

The literature data analysis revealed that farm applications tend to have much higher OLRs than systems treating municipal waste, but at the same time they show a lower COD removal efficiency (Figure 2). As that all substrates except food waste generate similar amounts of biogas, and lower removal rates are obtained for farm applications, the overall efficiency of such processes might be favourable for municipal waste treatment. However, Figure 2 also shows that applications treating sewage have a low OLR and lower HRT than for other substrates. This evidence confirms the challenge facing small-scale AD for sewage and domestic treatment, as these influents are more dilute than farm wastes, and hence larger reactor volumes are required.

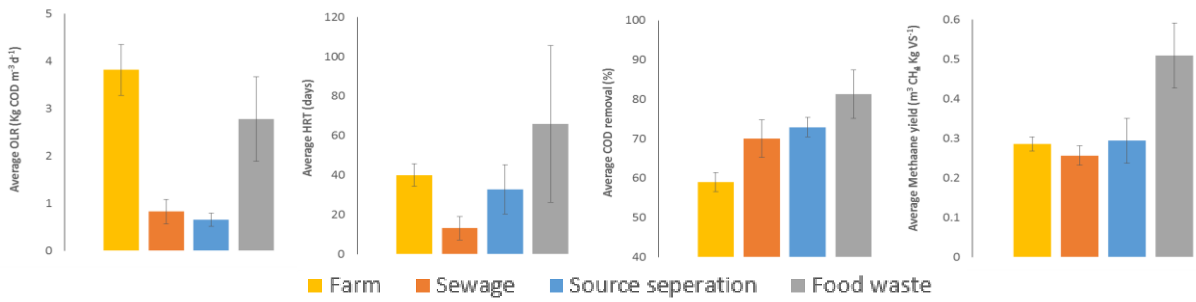

Fig. 2 Average literature values of four targeted parameters sorted by feedstock type – error bars represent the standard error of the sampled population of data.

Food waste is a substrate with high biodegradability and which could therefore be used to increase the influent biodegradability and methane potential during co-digestion of lower value feedstocks. The data analysis confirms that food waste achieved both the highest COD removal efficiencies and the highest biogas yields (Figure 2). Source separated waste applications also achieved high methane yields and COD removal. This is not surprising given the higher biodegradability, and thus biogas potential, of such feedstock types. According to the classification of reactor type (data not shown), up-flow anaerobic sludge bed (UASB) applications tend to have lower retention times, which is because of the higher degradation rate achieved by enhanced retention of the anaerobic biomass. However, UASB reactors cannot be applied to feedstocks with high solid content, such as municipal or food waste.

Analysis of the literature data also shows that there is more general variability for smaller scale reactors in terms of biogas yields achieved. It was noticed that at retention times longer than 30 days the COD removal efficiency is always higher than 60%, whereas at shorter HRTs there is more variability, with removals sometimes as low as 40%. Source separated wastes appear to lead to high removal efficiencies, and the highest COD removal efficiencies were achieved when the OLR was relatively low (below 2 Kg COD $m^{-3}d^{-1}$). The highest biogas yields (above 0.65 m^3 Kg^{-1} VS) correspond to relatively short HRTs (< 30 days) while the highest COD removal efficiencies and biogas yields were achieved in cases when OLR was relatively low.

The literature analysis shows that the rate of applications of small-scale AD systems is increasing, but that the significant majority of these applications are installed on farms and in rural areas to treat manure, kitchen waste and crop residues. There are very few small-scale applications that treat municipal wastes or sewage. This is likely to be due to the limitations that arise when reactor size is reduced, since it becomes much harder to maintain a low OLR, but also because of the economies of scale. 32 literature cases involved treatment of sewage, black water and food waste (Table 1). If we exclude the 9 lab scale cases, where the reactor volume is very small, the average reactor volume within the remaining 23 cases is 107.85 m^3. This suggests that AD can be sustainable at such sizes and supports the objective of our further research.

3.2 Influence of operational parameters on the AD process

A sensitivity analysis of the steady-state AD model was carried out to evaluate the effect of various operational parameters on the process, and to ensure that the model results are in line with theory. A baseline model substrate was used with a composition of 80% ODM, 55% carbohydrates, 30% proteins and 16.7% lipids by weight. The reactor volume was fixed at 1,000 m^3. The baseline DM content was 12%, the HRT was 25 d, and the operating temperature was 35 °C. These parameters were then varied independently, and the impacts of biomass yield, VFA/COD ratio, and the endogenous respiration rate were also investigated.

Figure 3 shows the influence effect of the dry matter content Figure 3a), HRT (Figure 3b) and temperature (Figure 3c) on the methane yield and COD removal efficiency. As expected, at higher temperatures, longer retention times and for feedstocks with higher solids content, both of these outcomes increase. Assuming the necessary methane yield for viable small-scale AD systems is 0.38 m^3 $KgVS^{-1}$, a minimum of 5% DM and an HRT of 10 days are required, while the temperature has little apparent influence on the outcome. The feedstock content in terms of carbohydrates, proteins and lipids is highly dependent on the type of influent being processed. Feedstock composition can be considered as an operational parameter, as pre-treatment methods may change the characteristics, for example, concentration techniques could be used for very dilute influents to increase the solids content prior to digestion. Deliberate blending of feeds may also be possible to improve feedstock characteristics.

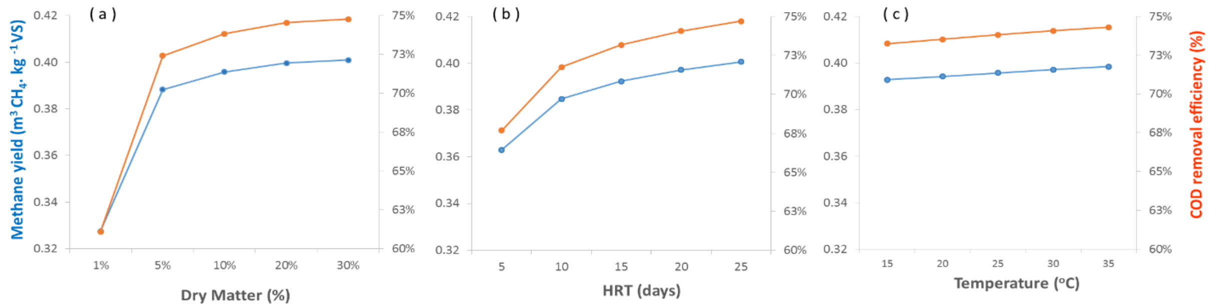

Fig. 3 The effect of dry matter content (%), HRT (d) and temperature (° C) on methane yield (m^3 Kg^{-1} VS) and COD removal (%). Results from model sensitivity analysis.

3.3 Influence of feedstock composition

Typical literature values with regard to protein, lipid and carbohydrate content were used to represent food waste, sewage and source separated waste (Table 1). Figure 4 shows how the varying composition of the feedstock affects the methane yield. The indices 1 to 8 on the x axis relate to random composition variations, whereas BW, FW and SW represent black water, food waste and sewage respectively. Food waste, which has the highest lipid content of the three feedstock types, unsurprisingly has the highest biogas yield. Various other combinations were modelling, to calculate methane production and COD removal (Figure 4). This shows a positive correlation between the percentage of lipids in the feedstock and the methane yield, i.e. the more the lipids present in the feedstock the more methane is produced. This is unsurprising as lipids are understood to lead to high methane yields. Similarly, as increasing percentage of carbohydrates in the substrate leads to reduced methane production. From Figure 4 it is obvious that small variations in composition can have strong impacts on the methane produced, and this supports the notion that blending feedstocks could be an important strategy with regard to the successful development of small-scale AD systems.

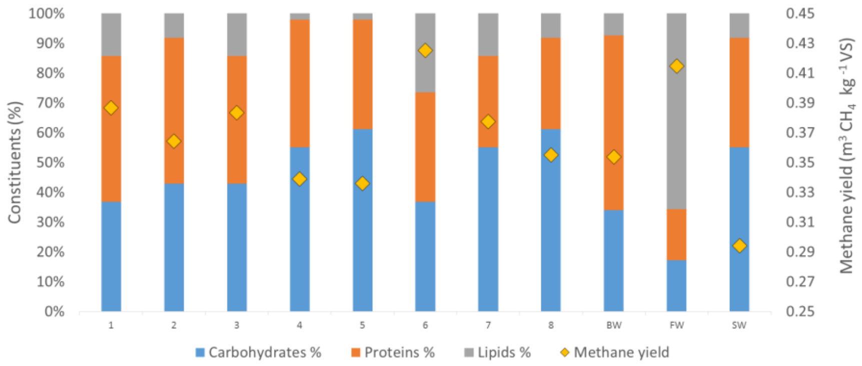

Fig. 4 The effect of feedstock composition on methane yield

3.4 Simulation of literature cases

A steady-state AD model was used to simulate different literature cases. The model was used to evaluate methane production and yield, COD removal efficiency, and other performance parameters, for three different type of feedstocks: food waste, source separated waste (black water) and sewage.

Figure 5 shows real data values compared to the model predictions when evaluating the various literature cases. Figure 5a shows the relationship between OLR and COD removal, whilst Figure 5b shows the correlation between OLR and operating temperature. Even though the fit is not perfect, the model can be said to succesfully reproduces the outcomes and that are found in the literature. It should be remembered that the model assumes steady-state operation and a number of assumed or estimated parameters – it is therefore performing well across the wide range of literature data under these circumstances and can be said to be robust.

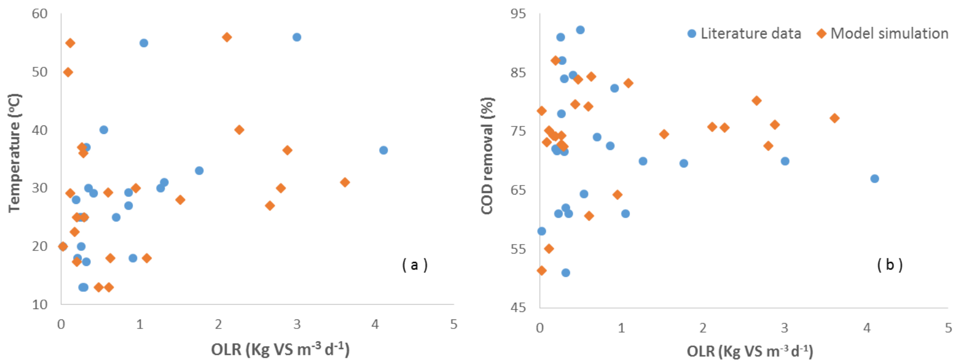

Fig. 5 Literature data vs model simulation results: All feedstock types

Figure 6a shows literature data from applications treating food waste and the corresponding modelling results, whilst Figure 6b shows results from analysis of applications treating sewage respectively. In both cases model fit is satisfactory compared to data values, given the steady-state assumption, and allowing for reasonable adjustment of model parameters in relation to published values from literature.

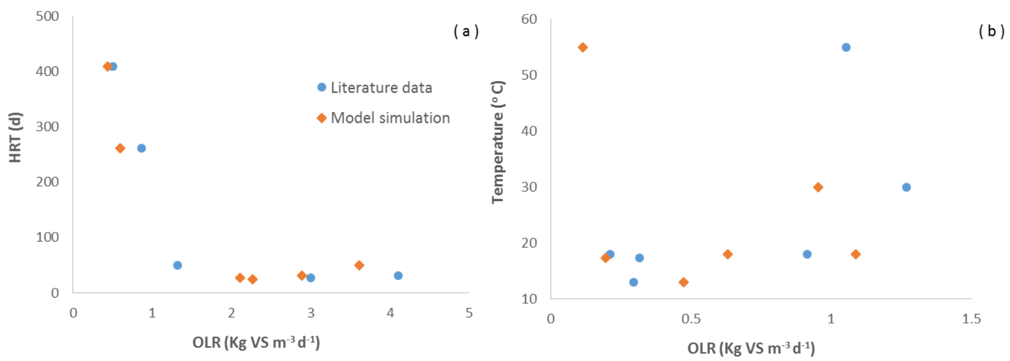

Fig. 6 Literature data vs model simulation results: Specific feedstocks

Finally, Figure 7 shows a correlation between the organic loading rate and the methane yield for different feedstocks, and compares model predictions to literature data. It is clear that the simulation results follow the same trend as the literature data, as at higher OLR the methane yield is higher. Figure 7 also confirms that food waste has the highest methane yield followed by source separated waste. With regards to sewage, there is high variability.

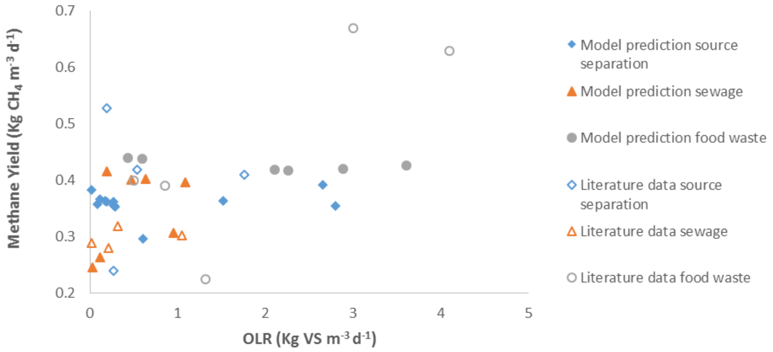

Fig. 7 OLR vs methane yield: Literature data compared to modelling results: sorted by feedstock type

4. Conclusions

The literature shows that the rate of application of small-scale AD systems is increasing, but that the majority of these applications (68%) are systems installed either on farms or in rural areas to treat manure, kitchen waste and crop residues. There are very few small-scale applications that treat municipal wastes or sewage, reinforcing the need to develop new approaches to tackling such challenges. The literature analysis also confirms the challenge of small-scale AD for sewage waste, by confirming that larger reactor volumes are used for more dilute influents.

The steady-state AD model allowed good prediction of methane production and COD removal for different feedstocks, even thought it was built with a number of assumptions and some fixed parameters. This suggests that the model is robust across the range of literature data analysed, and is a good basis for further work. The sensitivity analysis which explored changing operational parameters gave early indications of the limits within which small AD might work. Based on an assumed methane yield of 0.38 m^3 kg^{-1} VS, a minimum 5% DM content and an HRT of 10 days are required. Although a higher HRT would increase COD removal, larger volumes will be required to maintain a low OLR in order to stabilise operation. The literature analysis shows that there is inconsistent treatment of the results of AD trials in relation to feedstock characterisation and overall performance analysis. The steady-state modelling presented here indicates that reliable methods of AD performance analysis can be achieved with varying feedstocks, and demonstrates the benefit of a standardised treatment of trials data.

Future work aims to identify at what reduced scales urban AD systems they can remain financially viable. This will include gathering more data and use of more advanced process modelling tools to simulate small-scale AD reactor performance. Lab scale experiments utilising blended pre-treated feedstocks will validate the modelling analysis and to help guide process optimization. Life cycle assessment and cost benefit analysis tools will be used to evaluate the economic and through life potential of the most promising small-scale AD systems.

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References

1. Anon, (2017). Contribution of anaerobic digestion to the European Circular Economy. [online] Available at: http://european-biogas.eu/wp-content/uploads/2015/11/2015-11-13_EBA-position-on-Circular-economy.pdf [Accessed 19 November 2016]
2. Gell, K.: Review of small scale, community biogas in the industrialized world. Wageningen University, Netherlands: Community Composting Network (2008)
3. Rajendran, K., Aslanzadeh, S. and Taherzadeh, M.J.: Household biogas digesters—A review. Energies, 5(8), pp.2911-2942 (2012)
4. Garfí, M., Martí-Herrero, J., Garwood, A. and Ferrer, I.: Household anaerobic digesters for biogas production in Latin America: A review. Renewable and Sustainable Energy Reviews, 60, pp.599-614 (2016)
5. Wte-ltd.co.uk. (2017). Wastewater Produced In The Home. [online] Available at: http://www.wte-ltd.co.uk/wastewater-amounts-in-the-home.html [Accessed 18 February 2017]
6. Rose, C., Parker, A., Jefferson, B. and Cartmell, E.: The characterization of faeces and urine: a review of the literature to inform advanced treatment technology. Critical reviews in environmental science and technology, 45(17), pp.1827-1879. (2015)
7. Sötemann, S.W., Ristow, N.E., Wentzel, M.C. and Ekama, G.A.: A steady state model for anaerobic digestion of sewage sludges. Water SA, 31(4), pp.511-528 (2005)
8. Georgiadis, I.: Biogas production from black water, kitchen refuse and farm waste: lab assessment and practical application at MCF Yatta, Kenya (Master's thesis, Norwegian University of Life Sciences, Ås) (2013)
9. Hertel, S., Navarro, P., Deegener, S. and Körner, I.: Biogas and nutrients from blackwater, lawn cuttings and grease trap residues-experiments for Hamburg's Jenfelder Au district. Energy, Sustainability and Society, 5(1), p.29 (2015)
10. Jönsson, H., Baky, A., Jeppsson, U., Hellström, D. and Kärrman, E.: Composition of urine, feaces, greywater and biowaste for utilisation in the URWARE model. Urban Water Report (2005)
11. Nielfa, A., Cano, R., Pérez, A. and Fdez-Polanco, M.: Co-digestion of municipal sewage sludge and solid waste: Modelling of carbohydrate, lipid and protein content influence. Waste Management & Research, 33(3), pp.241-249 (2015)
12. Poggio, D., Walker, M., Nimmo, W., Ma, L. and Pourkashanian, M.: Modelling the anaerobic digestion of solid organic waste–Substrate characterisation method for ADM1 using a combined biochemical and kinetic parameter estimation approach. Waste Management, 53, pp.40-54 (2016)
13. Tervahauta, T., Hoang, T., Hernández, L., Zeeman, G. and Buisman, C.: Prospects of source-separation-based sanitation concepts: a model-based study. Water, 5(3), pp.1006-1035. (2013)
14. Zaher, U., Chen, S., Chenlin, L., Yu, L. and Ewing, T.: Producing Energy and Fertilizer from Organic Municipal Solid Waste: Enhancing Hydrolysis and Bacterial Populations and Mixing and Thermodynamic Modeling of New Solid Waste Treatment Technology. Ecology Publication, (09-07), p.064. (2009)
15. Henze, M. Mark C. M. van Loosdrecht, George A. Ekama and Brdjanovic, D.: Biological Wastewater Treatment - Principles, Modelling and Design. IWA Publishing, UK (2008)
16. Płuciennik-Koropczuk, E., Sadecka, Z. and Myszograj, S.: COD fractions in raw and mechanically treated wastewater. Civil and Environmental Engineering Reports (2013)
17. Szaja, A., Aguilar, J.A. and Łagód, G.: Estimation of Chemical Oxygen Demand Fractions of Municipal Wastewater by Respirometric Method–Case Study. Rocznik Ochrona Środowiska, 17(cz. 1), pp.289-299. (2015)
18. Yao, Y.: Use of carbohydrate, protein and fat to characterise wastewater in terms of its major elemental constituents and energy (2014)
19. Møller, H.B., Sommer, S.G. and Ahring, B.K.: Methane productivity of manure, straw and solid fractions of manure. Biomass and bioenergy, 26(5), pp.485-495 (2004)