

Article

Co-Digestion of Cattle Slurry and Food Waste: Perspectives on Scale-Up

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Abstract: Anaerobic digesters fed with dairy cow slurry struggle to achieve economic viability, particularly when animals are housed seasonally, so additional feedstocks are usually required. This study applied experimentally derived data from the co-digestion of cow slurry (CS) and food waste (FW) to the UK dairy herd as a whole, and at average (AH) and large (LH) herd sizes of 160 and 770 animals, respectively. The experimental data confirmed stable operation at an organic loading rate (OLR) of 5 g VS L⁻¹ day⁻¹ at CS:FW ratios of 3:1 and 6:1 on a wet weight basis, and these parameters were considered for both AH and LH by herd size and country (Scotland, England, Wales, Northern Ireland) in order to provide energy production and policy observations. The results showed that these scenarios could provide between 959 to 23,867 GJ per year, and that a targeted policy intervention could affect slurry treatment from a significant number of animals in a relatively small number of large herds across the UK. For a more detailed analysis, better data are required on non-domestic FW arisings and FW transportation needs.

Keywords: anaerobic digestion; cow slurry; food waste; co-digestion; policy



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1. Introduction

Anaerobic digestion (AD) is widely recognised as one of the most effective methods for valorising organic waste, by converting diverse feedstocks into renewable biogas and nutrient-rich digestate [1]. Nevertheless, farm-scale AD systems, particularly those reliant solely on cow slurry (CS) as a feedstock, often face economic challenges due to the substrate's low biochemical methane potential (BMP) [2]. This limits their financial viability, especially in the absence of supplementary high-energy feedstocks. To make rural AD systems more viable, co-digestion with food waste (FW), which has a significantly higher BMP compared to animal slurry, offers a promising solution to improve biogas yields on-farm [3,4].

In the United Kingdom (UK), FW generation is estimated at approximately 116 kg per person per year [5], representing a substantial resource for AD. While urban and peri-urban biogas plants are designed to process large volumes of FW, transporting this feedstock over long distances from rural areas to centralised AD facilities is often economically and environmentally impractical. The relatively small quantities and dispersed geographical nature of FW arisings in rural areas and the associated high collection and transport costs further exacerbate the challenge. Instead, integrating FW into local farm-based AD systems aligns with the proximity principle, which emphasises treating waste near its

source. Local treatment of FW arisings cuts out the FW miles (or FW kilometres) incurred if these were transported to large, centralised AD plants. Thus, this approach not only supports the economic viability of rural digesters by supplementing CS with a high-energy density feedstock but also reduces transportation-related air pollution and greenhouse gas emissions.

Seasonal variability in slurry production presents additional challenges for rural AD operators, particularly those operating a combined heat and power (CHP) plant which needs consistent biogas production, and/or where the farm has relatively consistent energy use. During winter, when cows are typically housed in the UK and other northern European countries, slurry availability peaks; whereas summer months see a decline as cows graze on pasture and, in the case of dairy farms, only come indoors to be milked. The incorporation of commercial FW or even decontaminated source segregated FW into the digester feedstock mix could help to address these seasonal imbalances by more strongly underpinning the slurry-based biogas generation with co-substrate throughout the summer months [6,7].

Beyond energy generation, integrating FW into farm-based AD systems supports nutrient cycling, an essential component of sustainable farming. Without co-digestion, nutrients removed from the farm through the sale of agricultural products, such as milk, are often replenished with fossil-based fertilisers, contributing to greenhouse gas emissions [3,8]. By incorporating local FW, farmers can reduce reliance on synthetic fertilisers [3], enhancing the sustainability of their operations and contributing to circular economy principles. Importantly, the inclusion of FW as a feedstock can substitute for dedicated energy crops like maize, thereby mitigating concerns about land-use changes and the sustainability implications of energy crops, particularly those grown in monoculture systems [1].

In terms of AD process stability and effectiveness, co-digestion of animal slurry and FW is beneficial [9]. Although cattle slurry in general contains the macro nutrients required by the anaerobic microbial consortia, the carbon to nitrogen (C:N) ratio, with a reported average of 9:1 for dairy slurry [10], is below optimum and lower than the recommended minimum of 10:1, and the high lignocellulosic content makes the feedstock slowly degradable [11]. To address this, it is a widely used practice to add readily biodegradable, energy dense co-substrates such as FW or energy crops to slurry-based biogas plants [12,13]. Compared to mono-digestion, co-digestion also offers reciprocal benefits for FW treatment, as CS can act as a buffering agent, reducing the risk for volatile fatty acids (VFA) accumulation throughout the process, moderating total ammonia nitrogen (TAN) concentrations and providing trace elements critical for stable operation [14]. A major contributor to the buffering effect offered by cattle slurry is its high alkalinity, which prevents VFA-related inhibition by lowering the VFA/alkalinity ratio [15], supporting process stability especially with rapidly hydrolysable biomass such as FW.

While the benefits of co-digestion of CS and FW are extensively documented in literature [12,13], there remain important knowledge gaps about the applicability of this solution in practice for dairy farms. This study explores the potential for integration of FW into farm-scale slurry-based AD systems using the Anaerobic Digestion Assessment Tool (ADAT) [16], for the UK context as a reference case. It focuses on dairy farming because dairy cattle are generally housed in barns where their slurry and urine is collected and stored, whereas beef cattle are typically housed on straw-based systems producing farmyard manure [17]. Dairy cattle on slurry-based systems are usually identified as milking cows > 2 years old. The paper examines UK dairy cattle numbers by country (Scotland, England, Wales, Northern Ireland) to establish their relative distribution, and to determine the number of cows in an average-sized herd (AH) and a large-sized herd (LH). Using data from the laboratory-scale trials of FW co-digestion with dairy CS, it evaluates energy production and greenhouse gas (GHG) reduction potential for seasonally housed

AH and LH cattle in three cases: where no FW is added and using the two experimental CS:FW ratios of 3:1 and 6:1 on a wet weight basis. This data were used to suggest some policy approaches which help to identify where the biggest positive environmental impacts could be made by implementing CS AD supplemented with FW.

2. Results and Discussion

2.1. Anaerobic Digestion Experiments

2.1.1. BMP Results

Cumulative net specific methane yields from the BMP assay are shown in Figure A1 (Appendix A.2), while BMP values and derived modelling coefficients are given in Table 1. BMP values for FW1 and FW2 were 0.459 and 0.470 L CH₄ g⁻¹ VS, respectively. These are typical of literature values for this material [18], and very close to the 0.456 and 0.471 L CH₄ g⁻¹ VS reported for previous samples from the same source-separated FW collection schemes [19,20]. The BMP value for the CS was much lower than for either FW, at 0.193 L CH₄ g⁻¹ VS. Low BMP values are typical of this feedstock, although a considerable range is reported in the literature. The value here is mid-range for those commonly reported, below those of 0.267 and 0.242 L CH₄ g⁻¹ VS found by Zhang et al. [21] and Labatut et al. [22], but higher than the 0.134 and 0.126–0.166 L CH₄ g⁻¹ VS reported by Cornell et al. [23] and Amon et al. [24], respectively.

Table 1. Measured BMP values and model coefficients.

Parameter	Unit	FW1	FW2	CS
Specific methane yield—replicate 1	L CH ₄ g ⁻¹ VS	0.463	0.478	0.187
Specific methane yield—replicate 2	L CH ₄ g ⁻¹ VS	0.455	0.462	0.200
BMP value (average of replicates)	L CH ₄ g ⁻¹ VS	0.459	0.470	0.193
BMP/TMP ^a	-	75.4%	75.3%	35.8%
BMP/ThCV ^b	-	81.6%	82.1%	35.1%
Modified Gompertz model (Equation (2))				
Ultimate methane yield M_m	L CH ₄ g ⁻¹ VS	0.460	0.475	0.210
Maximum methane production rate R_m	L CH ₄ g ⁻¹ VS day ⁻¹	0.214	0.203	0.027
Duration of lag phase λ	day	0.0	0.0	0.0
R ² value ^c	-	0.9734	0.9578	0.8172
Pseudo-parallel model (Equation (3))				
Ultimate methane yield M_m	L CH ₄ g ⁻¹ VS	0.460	0.475	0.210
Proportion of readily degradable material P	-	0.87	0.82	0.58
Readily degradable rate constant k_1	day ⁻¹	1.00	0.96	1.15
Less readily degradable rate constant k_2	day ⁻¹	0.10	0.07	0.05
Duration of lag phase λ	day	0.15	0.15	0.00
R ² value ^c	-	0.9981	0.9951	0.9959

^a Ratio between measured BMP and TMP from Table A1; ^b ratio between measured BMP and equivalent methane yield for ThCV from Table A1, based on the higher heating value (HHV) for methane of 39.84 MJ m⁻³ at STP;

^c coefficient of determination for experimental and predicted values (for average of duplicates).

The experimental data showed a reasonable fit to the modified Gompertz equation. This equation is essentially a microbial growth model, however, and assumes uniform substrate degradability: whereas both FW and CS are complex feedstocks with more and less readily degradable components, which may limit this model's applicability. Values of R_m and λ , shown in Table 1, were obtained by optimisation and differed from those seen experimentally. Gas volumes in in this assay were recorded manually and, since apparent methane production rates will depend on the interval between readings, better agreement may be obtained with automatic data logging. In most cases, however, the maximum methane production rates observed were higher than calculated R_m values and

optimisation of fit did not pick up a small lag observed at the start of the run, reducing the usefulness of the derived parameter values.

As can be seen in Figure A1 and Table 1, the pseudo-parallel model gave a significantly better fit than the modified Gompertz equation, particularly for CS. According to this model, while there were differences in rate constants for each feedstock, the major difference was the proportion of readily degradable material in FW and CS. This is as expected since CS is an end-product of a highly effective ruminant digestive process, during which the substrate loses the majority of its readily degradable components [3]. This is further demonstrated in the ratios between BMP values and theoretical methane potential (TMP) and ThCV for the two feedstock types in Table A1. The best fit using the pseudo-parallel model for FW1 and FW2 was obtained with a lag of 0.15 days at the start of the assay, whereas no lag was needed for the CS samples. Some studies have obtained good results using the modified Gompertz model with similar substrates [25]. While the pseudo-parallel model requires additional parameters, it provided a better fit for these feedstocks and was therefore used in subsequent calculations.

2.1.2. Performance in Co-Digestion Trials

Trial 1

Gas production during Trial 1 is shown in Figure 1. During the first 37 days of operation on FW only at an OLR of $1 \text{ g VS L}^{-1} \text{ day}^{-1}$, values in all digesters were similar at around $0.45 \text{ L CH}_4 \text{ L}^{-1} \text{ day}^{-1}$. As the OLR increased, the VMP in all digesters receiving FW rose in proportion. In the CS controls, VMP fell when FW addition ended; this was as expected, due to the relatively low energy potential of CS. Once the target OLRs were established, VMP in the co-digesters was reasonably consistent, with average values over the last 7 weeks of operation of 0.99 , 1.30 , and $1.68 \text{ L CH}_4 \text{ L}^{-1} \text{ day}^{-1}$ at 3 , 4 and $5 \text{ g VS L}^{-1} \text{ day}^{-1}$, respectively (Table 2). The average VMP for the CS and FW controls in the same period was 0.30 and $1.39 \text{ L CH}_4 \text{ L}^{-1} \text{ day}^{-1}$, respectively.

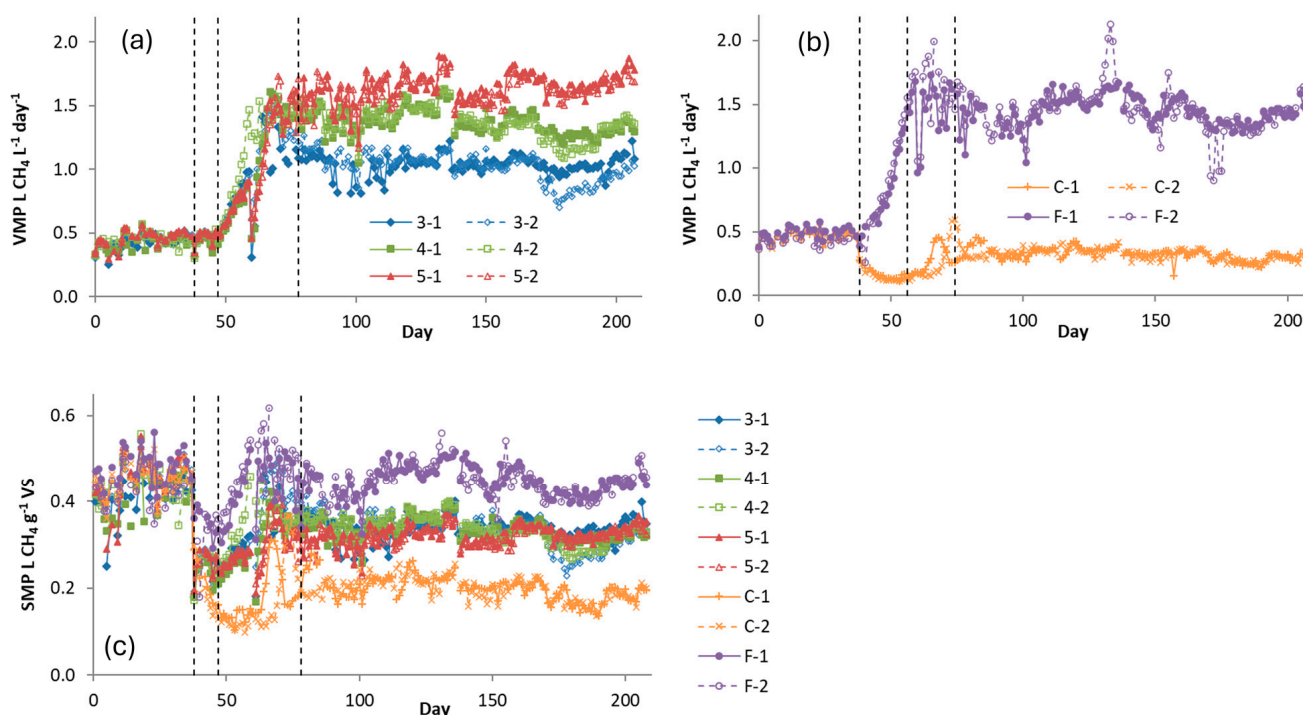


Figure 1. Trial 1 results for (a) VMP in co-digesters, (b) VMP in controls, (c) SMP in co-digesters and controls. Vertical dotted lines indicate changes in feeding regime on days 38, 47 and 78 for (a,c), and days 38, 56 and 74 for (b), as described in Section 2.2.

Table 2. Average values and range for digestion parameters in Trial 1 in last 7 weeks of operation.

Parameter	Unit	Co-Digestion			Control	
					CS	FW
Digester		3-1 and 3-2	4-1 and 4-2	5-1 and 5-2	C-1 and C-2	F-1 and F-2
VBP	L L ⁻¹ day ⁻¹	1.64 ± 0.09	2.14 ± 0.03	2.76 ± 0.04	0.48 ± 0.00	2.38 ± 0.05
VMP	L CH ₄ L ⁻¹ day ⁻¹	0.99 ± 0.05	1.30 ± 0.02	1.68 ± 0.02	0.30 ± 0.00	1.39 ± 0.02
SMP	L CH ₄ g ⁻¹ VS	0.322 ± 0.017	0.318 ± 0.005	0.329 ± 0.004	0.184 ± 0.001	0.435 ± 0.000
CH ₄ content	% v/v	60.5 ± 0.0	60.9 ± 0.2	60.1 ± 0.2	62.7 ± 0.1	58.3 ± 0.0
Digestate TS	% WW	6.49 ± 0.04	6.75 ± 0.02	6.95 ± 0.05	5.66 ± 0.05	7.40 ± 0.00
Digestate VS	% WW	4.47 ± 0.02	4.68 ± 0.02	4.84 ± 0.01	3.64 ± 0.04	5.76 ± 0.01
VS destruction	% VS	57.8 ± 0.2	59.3 ± 0.5	59.6 ± 0.2	37.8 ± 2.3	90.3 ± 0.0
pH	–	7.77 ± 0.01	7.69 ± 0.01	7.66 ± 0.00	7.78 ± 0.00	7.90 ± 0.02
TA	g CaCO ₃ kg ⁻¹ WW	16.5 ± 0.0	15.5 ± 0.3	14.8 ± 0.1	13.5 ± 0.1	20.0 ± 0.2
PA	g CaCO ₃ kg ⁻¹ WW	12.1 ± 0.0	11.3 ± 0.3	10.9 ± 0.2	10.1 ± 0.1	15.2 ± 0.2
IA	g CaCO ₃ kg ⁻¹ WW	3.9 ± 0.0	3.7 ± 0.0	3.4 ± 0.0	3.1 ± 0.0	4.2 ± 0.0
IA/PA ratio		0.32 ± 0.00	0.32 ± 0.01	0.31 ± 0.01	0.31 ± 0.00	0.28 ± 0.01
TAN	g N kg ⁻¹ WW	2.46 ± 0.01	2.30 ± 0.01	2.28 ± 0.02	2.01 ± 0.00	4.03 ± 0.07
Total VFA	g L ⁻¹	0.16 ± 0.03	0.12 ± 0.01	0.16 ± 0.01	0.04 ± 0.01	0.19 ± 0.01

Biogas methane content ranged from around 58% for the FW-only digesters to 63% for the CS controls, with the co-digesters all around 61%. For FW this was close to the value predicted by the Buswell equation (Table A1); but for CS the experimental methane content was much higher. This poorer agreement may be due to differences in composition between the more readily degradable fractions of CS and its overall empirical formula. SMP in the CS and FW controls averaged 0.184 and 0.435 L CH₄ g⁻¹ VS, respectively, over the last 70 days of operation. The SMP in the co-digesters showed little variation with either OLR or HRT, at average values of 0.322, 0.318, and 0.329 L CH₄ g⁻¹ VS for OLR of 3, 4, and 5 g VS L⁻¹ day⁻¹, respectively. As expected, VMP and SMP values for the co-digesters were much higher than for CS alone, reflecting the contribution from the FW component. The VMP for co-digestion at OLR 5 g VS L⁻¹ day⁻¹ was higher than for FW alone (Table 2).

Average values for digestion stability parameters are shown in Table 2, with graphical results presented in Appendix A.2. In general, stable operation was achieved in all cases, although by the end of the trial, TAN concentrations in the FW digesters were close to the point at which changes in methanogenic population and dominant metabolic pathway are expected with this feedstock [26]. In the co-digesters, a slight increase in VS and a decrease in TAN concentrations was observed with increasing OLR (Table 2). TKN was measured at the end of the run and was close to 4.4 g N kg⁻¹ WW in all co-digesters. When taken together, these results indicate a slight increase in microbial biomass at the higher OLR.

Trial 2

At the start of Trial 2, when the co-digesters were receiving FW only at an OLR of 2 g VS L⁻¹ day⁻¹, VMP stabilised at around 1.6 L CH₄ L⁻¹ day⁻¹. When the feed was changed to CS and FW from day 62, VMP initially fell, then began to rise in response to the increases in OLR from day 76 and stabilised soon after the target OLR were achieved (Figure 2). Duplicate co-digesters showed similar behaviour, although there was a small divergence in VMP at 3 g VS L⁻¹ day during the final 50 days. Average VMP values for the last 7 weeks of operation were 0.70, 0.86, and 1.04 L CH₄ L⁻¹ day⁻¹ at 3, 4 and 5 g VS L⁻¹ day⁻¹, respectively. SMP in the co-digesters showed a slight decline with increasing OLR and reducing HRT, with average values in the last 7 weeks of 0.242, 0.223 and 0.216 L CH₄ g⁻¹ VS at 3, 4, and 5 g VS L⁻¹ day⁻¹, respectively.

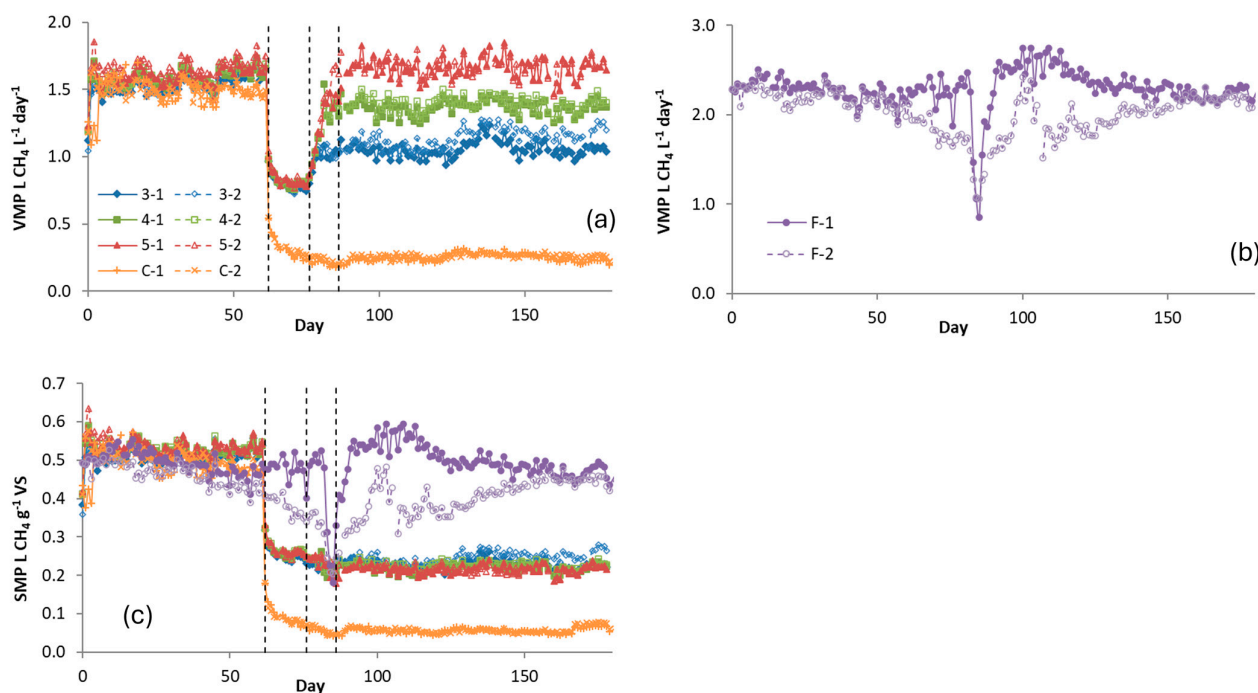


Figure 2. Trial 2 results for (a) VMP in co-digesters and CS control, (b) VMP in FW control; (c) SMP in co-digesters and controls. Vertical dotted lines indicate changes in feeding regime on days 62, 76 and 86, as described in Section 2.2. Note the different y-axis scale in (a,b).

Despite the higher OLR on the CS-only controls in Trial 2, both VMP and SMP in these digesters were considerably lower than in Trial 1. While some of this could be attributed to shorter HRT, the biogas methane content was also lower at 56.6%, indicating a probable change in feedstock composition e.g., with a more carbohydrate-rich degradable fraction [27]. From day 167, OLR in the CS digesters was reduced to from 3 to 2 g VS L⁻¹ day⁻¹, with a corresponding increase in HRT to 28 days. This resulted in a small rise in apparent SMP for the remainder of this trial as the change began to take effect (Figure 1c), but no significant change in methane content. Average VMP and SMP over the last 7 weeks of operation were 0.15 L CH₄ L⁻¹ day⁻¹ and 0.058 L CH₄ g⁻¹ VS, respectively, corresponding to a significant reduction in gas production potential compared to Trial 1. Although the cattle slurry properties had changed, this did not interfere with the stable operation of the co-digesters or CS-only controls. The average values for digestion stability parameters over the last 70 days of operation are shown in Table 2, with values through the experimental period shown graphically in Appendix A.2.

As noted in Section 3, the FW-only controls were not restarted with fresh inoculum at the beginning of Trial 2 but continued in operation at the same OLR as in Trial 1. By the start of Trial 2, these digesters had been running for 544 days without trace element supplementation, apart from the initial dose given to all digesters on day 46. Signs of continuing VFA accumulation appeared in both digesters from around day 375 and total VFA had reached 5–6 g L⁻¹ by the start of Trial 2, with TAN concentrations around 5 g N L⁻¹. VFA continued to accumulate at an increasing rate, reaching 11.7 and 15.8 g L⁻¹ in the two FW control digester by day 55 of Trial 2. On day 56, both digesters were given a one-off dose of Co, Ni and Se at 10 times the normal supplementation, followed by two weekly doses at a normal rate based on the amount of digestate removed.

Although the FW controls were duplicates, TE addition had different effects in each. One digester showed continuing stable gas production, with a small peak in VBP and SMP around day 106 linked to reduction in the accumulated VFA. TAN and alkalinity

concentrations remained high at around $6 \text{ g N kg}^{-1} \text{ WW}$ and $30 \text{ g CaCO}_3 \text{ kg}^{-1} \text{ WW}$ respectively. In the second digester, VBP and SMP fell, while the VFA concentration rose above 20 g L^{-1} and foaming was observed. An attempt to recover performance by removal of foam on day 96 was only partially successful, and ten days later foam blocked the gas outlet, leading to pressure build-up and minor loss of digestate. After this incident, however, the digester appeared to recover, with VMP and SMP gradually increasing to match those in the duplicate reactor by the end of Trial 2 (Figure 2). Operating parameters are presented graphically in the Appendix A.3.

2.1.3. Discussion of Experimental Results

As expected, the co-digestion of CS and FW gave significant improvements in methane production, with SMP around 175% of that in the CS controls in Trial 1, and VMP increasing by around 330%, 430% and 560% at OLR 3, 4 and $5 \text{ g VS L}^{-1} \text{ day}$, respectively. VMP and SMP are important parameters for the economic viability of both new and existing AD plants, justifying the ongoing interest in the co-digestion of these feedstocks. These increases were even more marked in Trial 2, where the CS was energy-depleted after storage. While the trials were not intended to replicate the effects of on-farm storage, the difference provides a useful insight into the comparative behaviour of high and low-energy CS.

Table 3 shows the applied OLR and HRT in the two trials with predicted-versus-actual SMP values. For Trial 1, one set of predicted SMP values was based on BMP values and coefficients for the individual substrates in Table 1 and on the actual HRT. The experimental values were 91–96% of the predicted SMP, reflecting the difference in batch and semi-continuous operating modes and kinetics. Predicted SMP based on the experimental SMP for the individual substrates was even closer at 95–98%, indicating that the co-substrate mix is not very sensitive to changes in HRT. This can also be seen from the feedstock and co-digestion characteristics in Tables 1 and A1: adding a proportion of FW will cause relatively little change in the HRT for CS digestion, while the rapidly degradable nature of FW means the reduction in HRT will also have little effect. For co-digestion, VMP showed a strong relationship with OLR ($R^2 = 0.9822$, $p < 0.0005$, $n = 6$) in Trial 1, indicating the systems were not overloaded and were performing well, as was also confirmed by the similarity in SMP at all OLR.

In Trial 2, experimental SMP values were slightly higher than predicted from the individual substrates by 103–113% (Table 4). Possible explanations might include synergy between substrates, e.g., through improved nutrient access, or dilution of some inhibitory factor produced by storage, although no evidence of VFA accumulation or other signs of instability were seen in the CS controls. No prediction of SMP based on BMP was made for Trial 2 as CS BMP was not measured after storage. VMP and OLR again showed a strong relationship ($R^2 = 0.9740$, $p < 0.0005$, $n = 6$), but SMP appeared to show a slight decline with increasing OLR ($R^2 = 0.6336$, $p < 0.06$, $n = 6$), probably indicating that the shorter HRTs in this trial were having some effect.

The properties of FW from previously-studied collection systems are fairly well established, although these may alter with changing patterns of consumption and disposal: major initiatives to reduce the amount of avoidable post-consumer FW are planned or in progress in many countries and appear to be having an effect in some cases [28–31]. As noted above, CS shows more variation both with origin and subsequent handling, but, again, there is a substantial body of literature on its properties in different conditions. The achievable SMP and VMP will thus vary according to these circumstances; but the above results show that values for individual co-substrates can provide reasonably robust predictions of methane productivity in co-digestion, both in specific cases and more broadly e.g., as a basis for policymaking and assessment.

Table 3. Predicted SMP values based on BMP and semi-continuous trials.

Trial 1	Unit	Co-Digestion			CS Control	FW Control
Applied OLR ^a	g VS L ⁻¹ day ⁻¹	3.1	4.1	5.1	1.6	3.2
FW addition	g WW day ⁻¹	30.0	40.0	50.0	0.0	52.4
	g VS L ⁻¹ day ⁻¹	1.85	2.46	3.08	0.00	3.23
CS addition	g WW day ⁻¹	90	120	150	120	0
	g VS L ⁻¹ day ⁻¹	1.22	1.62	2.03	1.62	0.00
HRT ^a	days	33.3	25.0	20.0	33.3	76.3
Predicted SMP ^b	L CH ₄ g ⁻¹ VS	0.353	0.348	0.343	0.193	0.460
Predicted/Actual SMP ^b	%	91.3	91.2	95.9	95.1	94.4
Predicted SMP ^c	L CH ₄ g ⁻¹ VS	0.335	0.335	0.335	0.183	0.434
Predicted/Actual SMP ^c	%	96.2	94.7	98.3	-	-

Trial 2	Unit	Co-digestion			CS Control	FW Control
Applied OLR ^a	g VS L ⁻¹ day ⁻¹	2.9	3.8	4.8	2.9	2.9
FW addition	g WW day ⁻¹	22.2	29.6	37.0	0.0	58.0
	g VS L ⁻¹ day ⁻¹	1.12	1.49	1.86	0.00	2.91
CS addition	g WW day ⁻¹	133.2	177.6	222.0	216.5	0.0
	g VS L ⁻¹ day ⁻¹	1.76	2.34	2.93	2.86	0.00
HRT ^a	days	25.7	19.3	15.4	18.5	69.0
Predicted SMP ^c	L CH ₄ g ⁻¹ VS	0.212	0.212	0.212	0.058	0.456
Predicted/Actual SMP ^c	%	114.2	105.1	101.8	-	-

^a based on average feedstock VS during each trial; these varied slightly from values in Table A1; ^b calculated from ratio of individual feedstocks, BMP values and kinetic coefficients for pseudo-parallel model in Table 1, and actual HRT; ^c calculated from the ratio of individual feedstocks and their experimental SMP values.

Table 4. Average values and range for digestion parameters in Trial 2 in last 7 weeks of operation.

Parameter	Unit	Co-Digestion			Control	
					CS	FW
Digester		3-1 and 3-2	4-1 and 4-2	5-1 and 5-2	C-1 and C-2	F-1 and F-2
VBP	L L ⁻¹ day ⁻¹	1.13 ± 0.05	1.39 ± 0.01	1.67 ± 0.00	0.26 ± 0.01	2.19 ± 0.08
VMP	L CH ₄ L ⁻¹ day ⁻¹	0.70 ± 0.04	0.86 ± 0.01	1.04 ± 0.01	0.15 ± 0.00	1.33 ± 0.07
SMP	L CH ₄ g ⁻¹ VS	0.242 ± 0.013	0.223 ± 0.002	0.216 ± 0.001	0.058 ± 0.001	0.456 ± 0.023
CH ₄ content	% v/v	61.6 ± 0.4	61.7 ± 0.1	62.2 ± 0.3	56.6 ± 0.2	60.7 ± 0.9
Digestate TS	% WW	8.18 ± 0.06	8.14 ± 0.10	8.37 ± 0.12	7.68 ± 0.00	9.82 ± 0.11
Digestate VS	% WW	5.23 ± 0.01	5.35 ± 0.05	5.50 ± 0.05	4.92 ± 0.03	6.80 ± 0.23
VS destruction	% VS	43.9 ± 0.0	42.5 ± 1.6	37.3 ± 0.5	18.6 ± 0.8	–
pH	–	7.75 ± 0.00	7.76 ± 0.00	7.75 ± 0.00	7.76 ± 0.02	8.13 ± 0.07
TA	g CaCO ₃ kg ⁻¹ WW	18.0 ± 0.6	16.8 ± 0.1	16.2 ± 0.2	13.8 ± 0.5	31.8 ± 2.8
PA	g CaCO ₃ kg ⁻¹ WW	11.5 ± 0.1	10.7 ± 0.0	10.3 ± 0.1	9.0 ± 0.3	21.2 ± 4.2
IA	g CaCO ₃ kg ⁻¹ WW	6.5 ± 0.4	6.1 ± 0.1	5.9 ± 0.1	4.9 ± 0.2	10.6 ± 1.4
IA/PA ratio	–	0.57 ± 0.03	0.57 ± 0.00	0.58 ± 0.01	0.54 ± 0.00	0.54 ± 0.17
TAN	g N kg ⁻¹ WW	1.99 ± 0.00	1.82 ± 0.02	1.75 ± 0.00	1.38 ± 0.03	6.06 ± 0.09
Total VFA	g L ⁻¹	0.04 ± 0.00	0.06 ± 0.02	0.31 ± 0.05	0.05 ± 0.00	11.46 ± 7.74

Stable operation was successfully demonstrated for all co-digestion variants, while mono-digestion of FW without TE supplementation showed accelerating instability. The role of TE in digestion at high ammonia concentrations is now widely recognised [32]. The TE profile of the CS in this study was similar to others in the literature: typical values are shown in Table A2 in the Appendix B, with supporting calculations in Table A3. On a mass balance basis, co-digestion with CS in Trials 1 and 2 raised the concentrations of

Mo and Ni to those suggested for stable FW digestion [33], while the Se concentration was lower but still represented a useful increase. In practice, quantification of both TE requirements and ammonia toxicity thresholds is complex as these depend on multiple interdependent parameters, from chemical speciation and bioavailability to metabolic pathway and microbial community structure. In this study, however, the key factor was almost certainly dilution, as TAN concentrations in the FW digesters were at or above the limit of 4 g N kg⁻¹ WW proposed for stable mesophilic digestion [34]; while in the co-digesters TAN was comfortably below this value. The current work thus adds further support to the view that co-digestion of CS with FW may assist stable operation both by reducing TAN concentrations and contributing useful TE.

The results obtained in the current work are comparable to those from other studies, selected examples of which are given in Table A2 (Appendix B). They thus provide further confidence that the findings can be generalised as a basis for policy making and scenario assessment.

2.2. Implications of Food Waste Addition to Supplement AD in UK Dairy Herds

2.2.1. Cattle Numbers, Herd Sizes, Slurry Production and Feedstock Parameters

Defra dairy cattle data [35] show that in 2022, the majority of the approximately 1.8 million national dairy production herd lived in England (59%), followed by Northern Ireland (17%), Wales (14%) and Scotland (10%). The number of dairy holdings fall roughly into the same percentages. Table 5 shows, however, that the majority of cows reside in herds of >150 animals, except in Northern Ireland, where the majority (by a small margin) are in herds of <150 animals with the smallest average herd size at 124. Scotland has the largest average herd size at 208, with the overall UK average herd size at 160 (AH). This was deemed to be close enough to the data band of >150 cows for the purposes of further scenario analysis.

Table 5. UK average herd size and distribution of dairy cows by herd size by country.

	England		Northern Ireland		Wales ^a		Scotland		United Kingdom ^b	
	Number	% England	Number	% NI	Number	% Wales	Number	% Scotland	Number	%
Average herd size	166		124		164		208		160	
Cows per holding in herds > 500 cows	758		632		819		824		769	
Number of dairy cattle										
In herds < 150	294,680	28%	173,875	55%	67,617	26%	38,146	22%	574,318	32%
In herds > 150	769,939	72%	142,900	45%	188,304	74%	137,158	78%	1,238,301	68%
TOTAL	1,064,619		316,775		255,921		175,304		1,812,619	
In herds > 500	178,995		13,262		41,792		41,191		275,240	15%
Number of dairy holdings										
<150 animals	7091	73%	2587	81%	1642	70%	1071	71%	12,391	74%
>150 animals	2611	27%	598	19%	702	30%	442	29%	4353	26%
TOTAL	9702		3185		2344		1513		16,744	
>500 animals	236		21		51		50		358	2%

^a Categories for Wales are misaligned with the other countries, so the 100–249 category were assumed to be one-third up to 149 and two thirds 150–249 herd size. ^b UK totals shown here differ from Defra figures for England, likely due to timing differences.

Dairy cattle numbers have nevertheless decreased over the past two decades, between 2005 and 2024, with the UK dairy herd falling from 1,997,716 to 1,836,442, a reduction of 8.1%. These figures hide significant regional differences: in England and Scotland, cattle numbers dropped by 15.3% and 8.7%, respectively, whilst in Wales and Northern Ireland,

numbers rose by 5.4% and 13.3%, respectively [35]. In a similar timeframe (2009–2023), EU14 cattle numbers decreased by 2.9%, with EU13 numbers down by 22.3%, again with major regional differences [36].

Agricultural emissions have fallen by 12% in the years between 1990 and 2021, due to reductions in animal numbers and synthetic fertiliser use, although emissions have remained relatively similar since 2010 [37]. In the dairy industry, two trends suggest increasing intensification: an increase in herd size, with its potential for year-round housing [38] and larger slurry stores, and a consistent increase in annual milk production per cow. Between 2001 and 2021, the average herd size in the UK grew by 88% to an average of 160 animals, again with significant regional differences: in Scotland, herd sizes grew by 72% (from 121 to 208); England by 88% (from 89 to 166); and NI by 100% (62–124) and Wales by 104% (80–164) as shown in Table 5.

The average UK milk yield increased from 6450 L year⁻¹ in 2002/03 to 8096 L year⁻¹ in 2021/22 and continues on a general upward trend, influenced by a number of factors, including improved breeding techniques and improved feed conversion [39]. For the purposes of estimating slurry production, the AHDB Slurry Wizard model considers that cows producing between 6000 to 9000 L year⁻¹ of milk are of a medium size and would produce 53 kg day⁻¹ of slurry, of which 25% could be collected during the grazing season when cows come in for milking [40]. For cows that are housed in winter, the housing period can be from 3 months in mild parts of the country to 6 months in colder, wetter areas, and a value of 183 days was assumed for the purposes of calculation.

As noted above, the feedstock characteristics of CS can vary, but most successful operations ensure the slurry reaches the digester within a maximum of 24 h from it being produced and with a minimum of added water. The CS used in the experimental work in this study had a TS content of 8.44% as a percentage of WW; a rather low VS of 67.54% of TS, and a BMP value of 0.193 L CH₄ g⁻¹ VS (Table 3). ADAT data which are based on a range of data sources characterises CS as 9% TS, with a VS of 83% and a BMP value of 0.185 L CH₄ g⁻¹ VS; thus, TS and BMP figures align well, but VS slightly less so. After comparing the VS value with the literature data and industry-standard operational data such as KTBL [41] or FNR [42], it was decided that the ADAT VS figure reflected a more typical mid-range CS value, so these were adopted for further calculations.

ADAT and experimental FW values aligned well with each other, so the default ADAT values for source segregated FW of 24% TS, 92% VS (as a percentage of TS) and a BMP of 0.420 L CH₄ g⁻¹ VS were used in further calculations.

2.2.2. Energy Production Potential from CS and FW for UK

CS feedstock characteristics were used to calculate the potential energy production through AD of slurry from the UK's 1.8 million dairy cattle, assuming each cow produces 53 kg day⁻¹ of slurry. As a theoretical maximum, if all cows were housed 100% of the time, this could produce nearly 485 million m³ of methane per year, or the direct energy equivalent to meet the energy demands of nearly 1.5 million houses with electricity or 438,000 with gas [43].

These aggregated UK figures indicate sufficient potential to make consideration of CS AD at farm level worthwhile, but many factors such as herd size, housing period, housing type and feeding practices will determine whether its introduction to a particular business would be economic. English cattle survey data [44] state that only 9% of cattle farms utilise a year-round grazing system, and 4% of cattle are housed all year round, with the majority of cattle farms (87%) using a mixture of housing and grazing. Smaller herds (<50) are more likely to graze year-round (17%). For farms where cattle are grazed seasonally, further AD feedstocks are likely to be required in summer. This may be for economic or technical

reasons, e.g., because the capital cost of AD installation means that energy production needs to be maximized to maintain the income stream or, if there is a CHP, it may be too problematic or inefficient to operate under conditions of reduced biogas production.

For the scenarios under study in this work, Table 6 shows the energy production, feeding pattern, digester size and retention time for AH (160 cows) and LH (770 cows) for CS-only digestion, i.e., with no FW addition (S1-AH and S1-LH), and with a housed season FW addition at ratios of 6:1 (S2-AH and S2-LH) and 3:1 (S3-AH and S3-LH).

Table 6. Feedstock and digester characteristics for average and large dairy herds housed seasonally.

Parameter	Unit	S1-AH	S1-LH	S2-AH	S2-LH	S3-AH	S3-LH
Housed season—digester feed and configuration							
CS	t WW day ^{−1}	8.5	40.8	8.5	40.8	8.5	40.8
FW at given ratio	t WW day ^{−1}	—	—	1.4	6.8	2.8	13.6
Total daily feed	t WW day ^{−1}	8.5	40.8	9.9	47.6	11.3	54.4
CS VS	kg VS day ^{−1}	633.46	3048.51	633.46	3048.51	633.46	3048.51
FW VS	kg VS day ^{−1}	—	—	312.06	1501.81	624.13	3003.62
Total VS	kg VS day ^{−1}	633	3049	946	4550	1258	6052
Digester size (assuming 28-day retention for S1, and OLR of 5 kg VS m ³ day ^{−1} for S2, S3)	m ³	237	1143	189	910	252	1210
Retention time	days	28	28	19	19	22	22
Energy production	MJ day ^{−1}	4198	20,202	8893	42,795	13,587	65,389
CHP size	kWe	16	77	34	163	52	250
Grazing season—digester feed and configuration							
CS	t WW day ^{−1}	2.1	10.2	2.1	10.2	2.1	10.2
FW (at given ratio plus extra for CS shortfall)	t WW day ^{−1}	—	—	2.4	11.4	3.8	18.2
Total daily feed	t WW day ^{−1}	2.1	10.2	4.5	21.6	5.9	28.4
CS VS	kg VS day ^{−1}	158	762	158	762	158	762
FW VS	kg VS day ^{−1}	—	—	521	2509	833	4011
Total VS	kg VS day ^{−1}	158	762	680	3271	992	4773
Retention time	days	28	28	30	30	34	34
Energy production	MJ day ^{−1}	1049	5050	8893	42,795	13,587	65,389
CHP size	kWe	4	19	34	163	52	250
Yearly feed							
CS: housed season	t WW yr ^{−1}	1552	7468	1552	7468	1552	7468
CS: grazing season	t WW yr ^{−1}	386	1857	386	1857	386	1857
Total CS fed yearly	t WW yr ^{−1}	1938	9325	1938	9325	1938	9325
FW: housed season	t WW yr ^{−1}	—	—	259	1245	517	2489
FW: grazing season	t WW yr ^{−1}	—	—	430	2068	687	3306
Total FW fed yearly	t WW yr ^{−1}	—	—	688	3313	1204	5795
Total combined yearly feed	t WW yr ^{−1}	1938	9325	2626	12,638	3142	15,120
Yearly energy production							
Gross energy value	MJ year ^{−1}	959,180	4,616,052	3,245,777	15,620,300	4,959,384	23,867,037
CHP electricity	kWh year ^{−1}	83,308	400,919	281,906	1,356,672	430,738	2,072,927
Biomethane	kg	19,200	92,398	64,970	312,668	99,271	477,741

For the CS-only digesters, the choice of digester size was driven by England's regulatory requirement for a 28-day retention time, which reduced the OLR to 2.7 kg VS L^{−1} day^{−1}. However, it may be interesting to note that from a process point of view, 20 days' retention time is usually considered sufficient for CS, and if this were adopted, the required digester size would reduce to 170 m³ and 816 m³ for AH and LH, respectively. The CS:FW co-digesters (S2 and S3) are sized to meet the feedstock requirements of the housed period based on a combined OLR of 5 kg VS m³ day^{−1}. These digesters have retention times of only 19 and 22 days, respectively. The experimental results indicate that SMP will likely be reduced at this OLR. This small reduction in SMP could be recovered in the digestate post storage tank, however, particularly if it is heated and/or mixed.

The CS-only digesters S1-AH (S1-LH) could produce 16 kWe (77 kWe) during the winter months, but only 4 kWe (19 kWe) from the proportion of slurry that could be captured during the grazing season. In most circumstances, operators would prefer to

maintain a consistent year-round energy production to maximise their CHP efficiency and income from energy production. To achieve this, the data in Table 6 confirm effectiveness of the intake of FW as co-substrate.

2.2.3. Food Waste Quantities and Availability

It can be seen from Table 6 that FW is fed consistently all year round in S2 and S3, but that the summer grazing shortfall requires an extra 0.95 tonnes day⁻¹ to be sourced for the AH or an extra 4.56 tonnes day⁻¹ for the LH to make up for the loss of cattle slurry input. Extra FW might be available in summer (e.g., in tourist areas such as Devon and Cornwall), but if it could not be obtained and consistent energy output was still required, then other feedstock sources would need to be found.

Access to kerbside source segregated household FW can be problematic because local government often contracts its collection to waste handlers; and such wastes can also contain plastics and other indigestible materials. However, utilising the 2021 UK per capita FW figure of 116 kg, the farm would have to access FW from 5934, 28,448, 10,381 and 49,960 people for scenarios S2-AH and LH, and S3-AH and LH, respectively. While access to wastes from these population sizes may be possible in some areas, it could be a challenge in very rural areas, particularly for larger digesters. In this case other sources of FW would need to be found, e.g., commercial and industrial (C&I) waste from places such as pubs and restaurants, food processing operations and business premises.

Whilst reasonably robust statistics on household FW in the UK are available in areas where it is collected separately, quantities and locations of C&I FW are generally less well understood [45], not least due to poor waste auditing practices, differing definitions of waste and because its removal is generally contracted directly from a business to a private waste contractor. The UK's Waste and Resources Action Programme estimates that the hospitality and food service sector generated around 800,000 tonnes of FW annually, with food manufacturers wasting 706,000 tonnes, at a combined cost of £4.06 billion [5]. The Sustainable Restaurant Association calculated that 'on average, a UK restaurant produces 21 tonnes of food waste annually', with 0.48 kg per meal being wasted via preparation, spoilage and leftovers [46]. If this average figure is utilised in the above scenarios, farms would have to access FW from 33, 158, 57 and 276 'average' restaurants annually for scenarios S2-AH and LH, and S3-AH and LH, respectively; if the summer grazing shortfall was met through the acquisition of agricultural wastes, then these numbers would drop to 25, 118, 49 and 236.

2.2.4. Implications for Farms and Policymaking

If capital and operating costs can be made attractive enough, co-digestion of CS with higher energy FW, could benefit farm businesses by shielding them from energy price fluctuations, reducing their carbon footprint and enabling them to produce their own energy year-round.

Dairy farms are significant users of energy [47], with consistent electricity use for milk cooling, water heating and milking [48]. A 2020 analysis from AHDB categorised dairy farms into low, average and high energy users [49]. This analysis was adapted for the above data and is shown in Table 7 using the average annual milk production figure of 8096 L cow⁻¹. All digester scenarios cover the low and average electricity on farm usage, although the seasonality of electricity production on S1-AH/S1-LH is likely to be problematic. High-consumption users would need feedstock supplementation to produce all of their own energy.

Table 7. Low, average and high energy requirements for dairy farms in the UK.

Consumption Type User	kWh Cow ⁻¹ yr ⁻¹	AH (160)	LH (770)	kWh/1000 Litres Milk	AH (1,295,360 L)	LH (6,233,920 L)
High	687	109,920	528,990	98.2	127,204	612,171
Average	405	64,800	311,850	54.17	70,170	337,691
Low	264	42,240	203,280	41.71	54,029	260,017

On-site energy production shields the farm business from energy price fluctuations: these have been particularly evident during recent years, when average non-domestic energy prices have risen 150% over the decade to Q2 2024, with particular spikes since 2020 [50]. Farmers are ‘price takers’, so often have little control over the price they get for their commodities. Such fluctuations jeopardise farm profitability, so renewable energy generation is particularly important for such businesses. The capital cost of producing renewable energy from anaerobic digestion can discourage uptake [51], so minimising cost and/or maximising income is imperative.

From a policymaker’s perspective, promoting on-farm co-digestion with FW could be a valuable tool for increasing the viability of CS digestion and thus reducing emissions from the farming sector [52]. If FW is introduced to an AD system, however, Animal By-Product Regulations (ABPR) mandate that it must be macerated and pasteurised to certain standards and pre- and post-treatment materials must be carefully segregated with no possibility of cross-contamination. If this is not feasible on site, other options such as a ‘Hub and PoD’ system could be considered, whereby a centralised processing facility (Hub) or mobile pasteurisation vehicle transports suitably treated FW to the ‘Point of Digestion’ on the farm [3,18]. The economics of this would have to be examined on a case-by-case basis. It is, therefore, likely that the logistics of acquiring the extra FW would be dependent upon local circumstances.

Interventions in reducing agricultural emissions are necessary, as these have not significantly decreased in the UK since the 2000s [37], with agriculture responsible for 49% of UK’s methane emissions, and 54% and 87% of its nitrous oxide and ammonia emissions, respectively.

One policy intervention could involve covering slurry stores and capturing and utilising the off-gases. Recent research by Ward et al. [53] measured methane emissions from slurry stores and suggested that the environmental impact of slurry storage is greater than has previously been calculated. Increasingly, 6 months of covered slurry storage is regarded as best practice, and schemes such as England’s Slurry Infrastructure Grant (SIG) [54] require this capacity. With a regulatory future which appears increasingly to be mandating 6 months’ worth of covered storage to minimise agricultural emissions, a small number of companies are installing systems in the UK to capture and utilise the gas which is produced during slurry storage, essentially, a ‘passive’ AD system. Sufficient robust methane production data for these passive types of systems in UK are still being established [53], but they may provide a low cost option for CS only AD or CS:FW co-digestion, with the appropriate FW pre-treatment, if permitting restrictions allow for co-digestion.

Recent UK policy initiatives have removed support for electricity generation through biogas CHP in favour of gas grid injection and use of biomethane in transport fuels, but encouraging small AD plants on dairy farms to meet their energy requirements by onsite electricity and heat production could offer an efficient way to further reduce emissions [52,55]. Biogas/biomethane CHP’s can also be utilised in micro-grids, as part of a group of distributed energy resources which can operate in island mode (as an entity) or as part of the wider grid [56,57]. On-site biogas upgrading and biomethane production offers further flexibility because of its wider potential for use in transport, for space heating

on-site or as part of a virtual pipeline (where gas is transported by vehicle to its destination) or through a biomethane CHP.

There is currently no UK policy framework for off-grid biomethane production apart from a volatile market-based incentive for vehicle fuel, but commercial systems for small-scale biogas upgrading already exist [58,59]. Biomethane upgrading equipment can be capital intensive, but there are options for spreading the cost, by either piping the biogas from co-located digesters to a centralised upgrading site [60] or by utilising mobile upgrading equipment [61].

Upgraded biogas could be used to fuel tractors, such as that produced by Case New Holland [62]; used by vehicles doing local deliveries; or used in the dairy supply chain for milk collection. Arla [63] is trialling two biomethane fuelled milk tankers as part of a number of initiatives to reduce the company's CO₂ emissions in its dairy supply chain. The reported fuel consumption of a 410 hp 40 tonne GVW Scania biomethane truck is 4 km kg⁻¹ CH₄ [64], so biomethane production from the smallest to largest systems above could drive such a vehicle for 4800 to 120,000 km year⁻¹.

In addition to its use in transport options, on-farm biomethane could be used in a generator (including for large-scale battery charging for load balancing and income optimisation during peak load times or to support unstable or end-of-line rural electricity grids), for heating, or as part of a virtual pipeline in rural areas without a gas grid.

Local virtual pipelines using biomethane could provide an environmentally effective way of decarbonising space heating in rural areas, particularly where the electricity grid is too weak to support widespread heat pump installation. A combination of factors make this an attractive option in the UK [65]:

- Of homes in rural areas, 20% are in the lowest energy efficiency bands (compared to 2.4% in urban areas);
- 'Off gas-grid' houses are mainly sited in rural areas and due to the higher carbon intensity of heating oil and LPG, account for a proportionally higher level (23%) of heating emissions;
- The combination of poor housing and expensive heating often drives rural households into fuel poverty.

Initiatives to promote the adoption of FW:CS digesters could include the following:

- Farmer access to soft loans with below-market interest rates, delayed repayments or other flexible terms are policy interventions which could provide access to capital for such systems, and/or business tax breaks which recognise their environmental value;
- Incentive schemes which recognise and encourage flexible use of the biogas/biomethane for the many uses described above;
- Tax-based incentives in the food supply chain to encourage AD, e.g., where dairy processors pay farmers more for their milk (so they can fund an AD plant), but this is recouped through tax breaks for the processors to reduce their Scope 3 emissions, rather than passing the increased milk cost on to consumers;
- Where market-based incentives for biogas/biomethane production exist, there could be a guaranteed floor price for the energy, which could be set to a level to make an AD plant worth building from an economic point of view;
- A permitting regime which takes a risk-based but flexible approach to adding FW to these smaller CS digesters;
- Valuing, through direct subsidies, grants, or carbon reduction valuation (or a combination) the hard-to-monetise or 'public good' aspects of AD, such as nutrient recycling, local FW treatment, energy security, decarbonisation of household heating, grid balancing and pollution mitigation;

- Using penalties or incentives to encourage waste hauliers and local government to adhere to the proximity principle for FW treatment where possible.

2.3. Limitations of the Study and Research Needs

The data shown in Table 5 indicate that any policy intervention (including CS:FW AD) in England, Wales and Scotland could focus on less than 30% of the holdings (i.e., those with herd sizes >150 animals), while still reaching more than 70% of those nations' animals and their corresponding climate impact. By targeting very large herds with more than 500 cows (average ~ 770 cows), a policy focus on 2% of the holdings could impact 15% of the UK's breeding herd.

With the largest number of cattle residing in England, further rural/urban analysis by county/unitary authority identified the top five dairying counties as Devon (predominantly rural), followed by Somerset (predominantly rural), Cornwall/Isles of Scilly (predominantly rural), East Cumbria (predominantly rural), and Staffordshire (urban with significant rural). These counties house 415,841 animals and represent more than 39% of the total dairy cattle population in England. It is likely that significant FW miles will be incurred in transferring FW from these highly rural areas to large, centralised digestion plants elsewhere, and local FW treatment would thus reduce the expense and carbon footprint of valorising FW. The introduction of mandatory household food waste collections by 31 March 2026 in England [66] presents an opportunity for areas such as these to better understand their local CS and FW geographical arisings.

However, without this mapping, the potential benefits of the adoption of this solution on UK dairy farms can only be estimated at this highest aggregated level. Whilst this analysis suggests some potential policy approaches, the level of detail with view to local contexts is limited, and a better understanding of the volumes and geographical distribution of rural FW arisings and their proximity to dairy cattle farms would provide a clearer picture to policymakers. Such mapping exercises are expensive and time consuming, but this study suggests that further research could focus on the most rural regions with the largest numbers of cattle in the smallest number of holdings in order to make the biggest impact. Such data could not only be used to better understand whether the farming practices on those holdings would lend themselves to CS or CS:FW AD as an approach, it would also provide data for further techno-economic and LCA analysis.

There is also a need to understand in more detail how FW co-digestion influences the nutrient balances of different farm types and in different regions, including countries other than the UK. FW intake brings additional nutrients to the farm, which may balance nutrients that leave the farm with the sold products and thus reduce the need for synthetic fertilisers [3]. However, in some contexts there may be a risk of inducing a nutrients surplus, undermining the overall environmental benefits. Furthermore, with a view to economic viability in different contexts and countries, specific costs such as food waste collection costs, and possible revenue related to different biogas valorisation options merit more detailed analysis.

3. Materials and Methods

3.1. Methodological Approach of the Study

The results from a co-digestion experiment run on CS and FW, using the two CS:FW ratios at a specific loading rate which demonstrated stable digestion, were combined with UK dairy cow data to provide indicative energy production figures at UK aggregate level and two herd sizes, namely an average-sized herd (AH) and a large-sized herd (LH). Dairy cattle distribution and herd size data were further analysed to provide insights as to what policy approaches could be adopted for encouraging FW co-digestion at dairy farms, as

well as to enable findings on practical considerations for the implementation of FW:CS AD, and identification of data and knowledge gaps.

3.2. Experimental Work

3.2.1. Feedstocks, Inoculum and Trace Elements

Source-separated domestic FW from municipal collection services was taken in two batches (FW1 and FW2) of around 200 kg each from sites in Ludlow, Shropshire and Otterbourne, Hampshire, UK. It was hand-sorted to remove a small proportion of contaminants (e.g., packaging materials), passed through a macerating grinder (S52/010, IMC Ltd., Wrexham, UK), mixed thoroughly and stored in 4-L plastic containers at $-20\text{ }^{\circ}\text{C}$. CS was obtained from an organic dairy farm in Wrexham, Wales in a single batch of approximately 400 kg. Around half of this was processed immediately, while the remainder was stored for some months. The CS was processed by grinding and freezing as for FW. When needed, FW and CS were thawed at room temperature then stored at $4\text{ }^{\circ}\text{C}$ and used within a few days. Composition and characteristics of the feedstocks are documented in Table A1 (Appendix A.1).

Inoculum for batch and semi-continuous digestion studies was taken from a mesophilic digester processing municipal wastewater biosolids in Southampton, UK.

Trace element solutions were formulated to give the following additional concentrations within the digester when in normal use (mg L^{-1}): Al, Bo, Cu 0.1; Mo, Se, W, Zn 0.2; Co, Mn, Ni 1.0; Fe 5.0 [33].

3.2.2. Equipment and Experimental Set-Up

Five pairs of continuously stirred tank reactor (CSTR) digesters were used, each with a total volume of 5 L and a working volume of 4 L. The digesters were made of PVC tubing with a gas-tight base and a top plate fitted with a gas outlet, a feed port and a liquid-seal draught tube. Mixing was carried out at 40 rpm by an asymmetric-bar stirrer entering through the draft tube powered by a motor mounted directly above the top plate (see Figure 3). A temperature of $35 \pm 0.5\text{ }^{\circ}\text{C}$ was maintained by circulating water through external heating coils. Biogas volumes were recorded using tipping-bucket gas counters, with calibration checked weekly by collecting the gas produced during one daily feed-cycle in a gas-impermeable bag and measuring its volume in a weight-type gasometer [67].

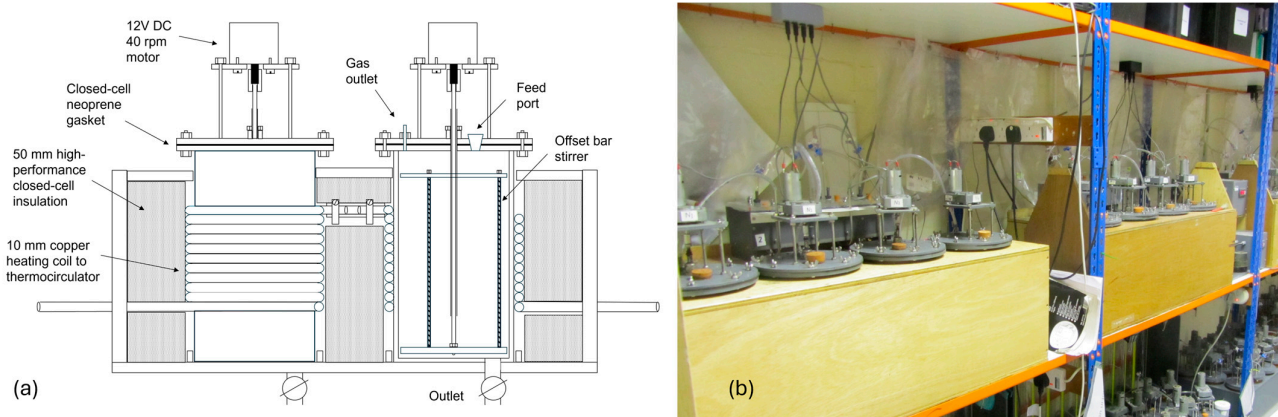


Figure 3. Experimental set-up: (a) CSTR schematic and (b) CSTRs in the laboratory.

The co-digestion performance of the cattle slurry and FW was assessed in terms of biogas production and process stability at different organic loading rates. For this purpose, a commonly studied wet weight ratio of CS to FW of 3:1 was chosen to provide a baseline close to values used in other studies (Table A2). To ensure the practical relevance of this

work, and to allow for comparison of the performance at two ratios, a second CS:FW ratio of 6:1 was also used which was chosen to reflect the estimated actual wet-weight ratio of both feedstocks in the UK.

Semi-continuous co-digestion trials were carried out in duplicate for CS and FW at wet weight (WW) ratios of 3:1 (Trial 1, using FW1) and 6:1 (Trial 2, using FW2) at target organic loading rates (OLR) of 3, 4 and 5 g VS L⁻¹ day⁻¹. CS-only and FW-only controls were also run in duplicate, at target OLR from 1.7 to 3.0 g VS L⁻¹ day⁻¹ (details indicated below). Duplicate digesters for each set of conditions and are designated as X-1 and X-2, where X represents 3, 4 or 5 for co-digestion at the corresponding OLR, respectively, and C for CS-only, F for FW-only.

At the start of Trial 1, all digesters were filled with inoculum. To initiate digestion before the actual experimental testing, for the first 37 days all digesters received FW at an OLR of 1 g VS L⁻¹ day⁻¹. Then, in the co-digesters, CS was added to the feed from day 38, at a 3:1 ratio with the FW. The combined CS and FW feed was then increased stepwise from day 47 to reach the target OLR of 3, 4 and 5 g VS L⁻¹ day⁻¹ by days 57, 68 and 78, respectively. In the CS-only digesters, on day 38, the feed was changed from FW to CS at 1 g VS L⁻¹ day⁻¹, then increased stepwise to the target OLR of 1.7 g VS L⁻¹ day⁻¹ by day 74. For the FW-only digesters, from day 38 to day 56, the OLR was increased stepwise to the target value of 3 g VS L⁻¹ day⁻¹.

Based on previous observations that the addition of trace elements can assist in a more rapid acclimatisation to changes such as the introduction of new feedstocks and increases in OLR [36], a one-off dose of trace elements (see Section 2.2.1) was added to all digesters on day 46. No other regular trace element supplementation was performed for any of the reactors, but when the VFA in the FW digesters eventually accumulated at a critical level at a late stage of the experiment, trace elements were added to prevent digester failure (see Section 3.2.1 for details).

Before initiating Trial 2, the co-digestion and CS-only digesters were filled with fresh inoculum. These digesters were then initially fed on FW only at an OLR of 2 g VS L⁻¹ day⁻¹. From day 62, this was changed to a 6:1 mixture of CS and FW at the same overall OLR, and from day 76, the mixed feed was increased stepwise to reach the target OLR of 3, 4 and 5 g VS L⁻¹ day⁻¹ by days 79, 83 and 86, respectively. In the CS-only controls, the feed was changed to CS at 2 g VS L⁻¹ day⁻¹ on day 62, and increased stepwise to 3 g VS L⁻¹ day⁻¹ between days 76 and 104. The FW-only controls were not re-started with fresh inoculum due to the relatively long HRT in these digesters, and to allow for any effects of trace element washout to become evident. Therefore, the FW-only controls were continued after Trial 1, and switched to FW2 from day 368, corresponding to 176 days before the start of Trial 2; feeding then continued on FW2 throughout Trial 2.

In addition to these semi-continuous experiments, batch-operated biochemical methane potential (BMP) testing was performed for the two feedstock types under study. The BMP was measured in CSTRs with a working volume of 1.5 L, operated in a water bath at 35 °C. The gas outlet of each reactor was connected to a liquid-displacement gasometer containing a 75% saturated NaCl solution acidified to pH 2, to minimise CH₄ dissolution. Gas composition was analysed each time a gasometer was refilled. Positive controls (cellulose) and inoculum-only blanks were run in parallel with test samples, all in duplicate. The BMP value for a given feedstock was obtained by calculating the cumulative methane production for each test reactor; subtracting the average cumulative methane production of the inoculum-only blanks; and dividing the result by the weight of feedstock VS added to each test reactor. The final BMP value was taken as the average for the test reactors, expressed as L CH₄ g⁻¹ VS.

All gas volumes are reported as dry gas at a standard temperature and pressure (STP) of 0 °C, 101.325 kPa.

3.2.3. Analytical Methods

Total solids (TS) and volatile solids (VS) were determined according to Standard Method 2540 G [APHA]. The pH was measured with a Jenway 3010 m (Bibby Scientific Ltd., Stone, UK) calibrated in buffers at pH 4, 7 and 9.2. Alkalinity was determined by titration with 0.25 N H₂SO₄ to endpoints at pH 5.75 and 4.3 using an automatic titration system (SCHOTT titroline easy, Schott Instruments GmbH, Mainz, Germany) to allow for the calculation of total (TA), partial (PA) and intermediate alkalinity (IA) [68]. Total ammonia nitrogen (TAN) was quantified by steam distillation and titration using a K-350 BÜCHI Distillation Unit (Büchi Labortechnik AG, Flawil, Switzerland). Total Kjeldahl nitrogen (TKN) was determined after acid digestion in a K-435 BÜCHI Digestion Unit, followed by measurement as TAN. Volatile fatty acid (VFA) concentrations were determined by gas chromatography (Shimadzu GC-2010, Shimadzu Europa GmbH, Duisburg, Germany) with a flame ionisation detector and capillary column (SGE BP-21), and helium as the carrier gas, at a flow of 190.8 mL min⁻¹ and a split ratio of 100 to give a flow rate of 1.86 mL min⁻¹ in the column and a 3.0 mL min⁻¹ purge. Samples were acidified with formic acid and measured against mixed standards containing 50, 250 and 500 mg L⁻¹ of acetic, propionic, iso-butyric, n-butyric, iso-valeric, valeric, hexanoic and heptanoic acid. Biogas composition (CH₄ and CO₂) was determined using a Varian Star 3400 CX Gas Chromatograph (GC) (Varian Inc., Walnut Creek, CA, USA) with a TCD detector, calibrated with a standard gas made up of 65%:35% CH₄ and CO₂ (v/v).

Further characterisation was carried out on samples air-dried to constant weight and milled to ≤0.5 mm in a micro-hammer mill (Retsch, Haan, Germany). Trace element content was determined following digestion of the dried samples in hydrochloric and nitric acid, by ICP-MS (Severn Trent Services, Coventry, UK). Carbon, hydrogen, nitrogen and sulphur contents were determined in a FlashEA 1112 Elemental Analyser (Thermo Fisher Scientific Inc., Monza, Italy), with the oxygen content calculated by difference.

3.2.4. Calculations for Experimental Digestion Study

Theoretical methane potential (TMP) and biogas composition for the two feedstocks were estimated using the Buswell equation (Symons and Buswell, 1933) [69]. Theoretical calorific values (ThCV) were calculated using a version of the Dulong equation [70].

VS destruction was estimated using Equation (1).

$$VS_{destruction} = \frac{Feed(g) \times VS_{feed} - Digestate(g) \times VS_{digestate}}{Feed(g) \times VS_{feed}} \quad (1)$$

where *Feed* = wet weight (WW) of feed added to digester each week in g WW, *VS_{feed}* = VS content of feed expressed as % WW, *Digestate* = weight of digestate removed from digester each week in g WW, and *VS_{digestate}* = VS content of digestate as % WW.

BMP data were fitted using both the modified Gompertz model (Equation (2), Tsapekos et al. 2018 [25]) and a pseudo-parallel first-order model (Equation (3), Rao et al. 2000 [71]).

$$M(t) = M_m \exp \left(-\exp \left[\frac{R_m}{M_m} (\lambda - t)e + 1 \right] \right) \quad (2)$$

where $M(t)$ = cumulative methane yield at time t in $\text{L CH}_4 \text{ g}^{-1} \text{ VS}$, M_m = ultimate methane yield in $\text{L CH}_4 \text{ g}^{-1} \text{ VS}$, R_m = maximum methane production rate in $\text{L CH}_4 \text{ g}^{-1} \text{ VS day}^{-1}$, λ = duration of lag phase in days and e = Euler's number (approximately 2.7183).

$$M(t) = M_m \left(1 - P \exp^{-k_1 t} - (1 - P) \exp^{-k_2 t} \right) \quad (3)$$

where P = proportion of readily degradable material, k_1 = First-order rate constant for readily degradable material. k_2 = first-order rate constant for less readily degradable material.

In the semi-continuous digestion trials, reported values for specific methane production (SMP, in $\text{L CH}_4 \text{ g}^{-1} \text{ VS}$) and volumetric methane production (VMP, in $\text{L CH}_4 \text{ L}^{-1}$ of digester working volume day^{-1}) are based on daily biogas production multiplied by the relevant gas composition (%), with the latter measured once or twice weekly. The measured volumetric biogas production (VBP) is additionally reported.

3.3. Approach for the Analysis of Adding Food Waste to UK Dairy Farm Slurry

To better formulate potential policy approaches and to estimate energy production for scenarios based on co-digestion of dairy cattle slurry and FW, it was necessary to establish cattle numbers, herd sizes, country distribution and slurry production profiles during housed and grazing seasons. The most recent data (2022) from the Agriculture and Horticulture Development Board (AHDB) for breeding herd dairy cow numbers and dairy holdings by herd size and country (Scotland, England, Wales, Northern Ireland) were analysed [36] and cross-checked against the Defra time series dairy herd numbers for 2022 [35] for consistency. The general trend for dairy herd size from 2005–2024 was analysed to see whether there had been any large variations. For wider context, this was compared with the AHDB figures for EU14 and EU13, which excluded UK figures. The average herd sizes for each of the four UK countries (England, Scotland, Northern Ireland and Wales) between 2000 and 2021 were also examined.

Farmers manage their slurry storage volumes and soil nutrient levels by utilising knowledge resources such as the Slurry Wizard from AHDB [40] or the 4 Point Plan from Farming & Water Scotland [72]. These provide daily slurry production volumes for a cow, given its age, size and milk production volume. The average UK milk yield for 2022 was used to estimate the cow size and therefore slurry production volume per cow based on Slurry Wizard figures and cross-checked with the 4 Point Plan data. The period that cattle would be housed in barns in winter was established.

The experimental feedstock characteristics for CS and FW were compared with those in the literature and in the ADAT model to establish realistic DM, VS and BMP figures for farm AD operation. ADAT (Anaerobic Digestion Assessment Tool) [16], is the University of Southampton's AD mass and energy balance model. It has been developed and refined in the course of several research projects under leadership of the University of Southampton and with support from the IEA (International Energy Agency) Task 37 UK, and it has been applied as a standard in numerous studies [6,73–76].

Energy production data were calculated using the lower heating value (LHV) for methane of 35.82 MJ/m^3 at the specified STP. The CHP size was calculated using an electrical efficiency of 33%, slightly lower than the ADAT default of 35% to reflect the smaller CHP sizes which tend to be less efficient. Yearly electrical production in kWh was calculated by multiplying the CHP plant size by the number of hours in a year and applying the guideline ADAT CHP load factor of 95%.

The feedstock characteristics combined with the total UK dairy cow numbers were used to calculate the energy potential if all that feedstock were to be processed through AD systems, assuming that animals were housed 100% of the time. This provided data to ascertain whether further examination at herd level was indicated.

Three scenarios (S1, S2, S3) were examined for two herd sizes, i.e., an average-sized herd (AH) and a large-sized herd (LH). Scenario 1 calculated energy production and digester size using CS only as a feedstock based on a 28-day retention time in the seasonal housing period (S1-AH and S1-LH, respectively). No extra feedstock was added to make up for the reduced amount of CS collected during the grazing season. Scenarios 2 and 3 calculated digester energy production, digester size and retention times based on an OLR of 5 kg VS m³ day⁻¹, utilising CS:FW ratios of 6:1 (S2-AH, S2-LH) and 3:1 (S3-AH, S3-LH), respectively, based on the values selected for the experimental study.

The amount of slurry which could be collected for AD during the grazing season was estimated using data from AHDB [40] and March et al. [7], since cows still come indoors, e.g., for milking. To maintain a consistent energy production profile such as that preferred for efficient CHP plant utilisation, it was assumed that extra FW could be sourced during the grazing season to compensate for the seasonal reduction in available slurry. The required amounts of FW were calculated for S2-AH, S2-LH, S3-AH and S3-LH. This meant that during the grazing season, the CS:FW ratios deviated from that in the housed season.

Whilst a detailed mapping exercise was beyond the scope of this work, dairy breeding herd data exist for England, broken down by Upper Tier county/unitary authority [77]. The top ten dairy intensive areas were identified and classified under the 2011 3-fold and 6-fold Rural–Urban classification areas [78] to better understand whether these areas were highly urbanised, in which case FW transport to large centralised FW digesters would be feasible or whether local FW co-digestion could potentially minimise waste-miles.

Finally, the approximate number of restaurants or individual households that would be required to provide sufficient FW in each scenario was estimated.

4. Conclusions

CS:FW co-digestion was stable under a range of experimental conditions spanning the expected ratios of production and availability in the UK, lending itself to wider adoption on farms to improve energy production and treat FW locally, particularly on dairy farms which house the majority of UK's cattle.

Whilst most of England's dairy cattle numbers are concentrated in counties which are highly rural and might thus be ideal for local FW:CS co-digestion to minimise FW miles, reduce fossil fertiliser use and support the weak economics of CS-only AD, an improved understanding of commercial and industrial FW arisings would inform better policy initiatives. To help reduce agricultural emissions, policy interventions could concentrate on the average herd size, but the data indicate that a proportionally higher impact could be made by targeting a relatively small number of holdings with the largest herd sizes. Flexible support for biogas/biomethane use cases in CHP, transport and virtual pipelines could provide wider rural benefits.

There are a range of policy options which should be considered for improving AD plant economics through FW:CS co-digestion, not only because of its contribution to energy production and nutrient recycling, but also for its myriad of contribution to 'public good' in the farm business and rural communities.

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Abbreviations

The following abbreviations are used in this manuscript:

AD	Anaerobic digestion
ADAT	Anaerobic digestion assessment tool
AH	Average herd size
AHDB	Agriculture and Horticulture Development Board
BMP	Biochemical methane potential
CHP	Combined heat and power plant
CS	Cow slurry
CSTR	Continuously stirred tank reactor
Defra	Department of Food and Rural Affairs
FNR	Fachagentur Nachwachsende Rohstoffe e.V.
FW	Food waste
GHG	Greenhouse gas
GJ	Gigajoules
HaFS	Hospitality and food service
HRT	Hydraulic retention time
IA	Intermediate alkalinity
KTBL	Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V.
kWh	Kilowatt hour
LH	Large herd size
MJ	Megajoule
NVZ	Nitrate vulnerable zone
OLR	Organic loading rate
PA	Partial alkalinity
PVC	Polyvinyl chloride
SMP	Specific methane production
STP	Standard temperature and pressure
TA	Total alkalinity
TAN	Total ammoniacal nitrogen
TCD	Thermal conductivity detector
ThCV	Theoretical calorific value
TKN	Total Kjeldahl nitrogen
TMP	Theoretical methane potential
TS	Total solids
UK	United Kingdom
VFA	Volatile fatty acid
VBP	Volumetric biogas production
VMP	Volumetric methane production
VS	Volatile solids
WRAP	Waste Resources Action Programme

WW Wet weight

Appendix A

Appendix A.1. Feedstock Characteristics

The feedstock characteristics for the substrates used in the experimental part of this work are listed in Table A1. The two sets of FW were closely similar to one another and to other examples of the same type of material in the literature (e.g., Banks et al. [18]). CS, in general, is a more variable material in its occurrence in practice, reflecting both differences in farming practice and seasonal changes; but the analytical results confirm that the characteristics of the CS used in this work were within the typical range for the literature values for dairy manure.

Table A1. Characteristics of feedstocks used in the experiments.

Parameter	Unit	FW1	FW2	CS
Total solids (TS)	% WW	24.30	23.09	8.44
Volatile solids (VS)	% WW	22.90	20.39	5.70
Total Kjeldahl nitrogen (TKN)	mg kg ⁻¹ WW	7503	6693	3029
Trace elements				
Cobalt (Co)	mg kg ⁻¹ TS	0.10	0.15	1.76
Copper (Cu)	mg kg ⁻¹ TS	5.85	5.20	64.60
Iron (Fe)	mg kg ⁻¹ TS	88.9	125.7	1330.9
Manganese (Mn)	mg kg ⁻¹ TS	92.1	86.9	94.8
Molybdenum (Mo)	mg kg ⁻¹ TS	0.37	0.33	5.24
Nickel (Ni)	mg kg ⁻¹ TS	0.73	0.62	19.5
Selenium (Se)	mg kg ⁻¹ TS	0.17	0.17	0.24
Zinc (Zn)	mg kg ⁻¹ TS	35.7	18.9	123.1
Elemental composition				
Carbon (C)	% TS	59.00	59.08	38.99
Hydrogen (H)	% TS	6.74	7.18	4.67
Oxygen (O) (by difference)	% TS	29.95	29.83	25.76
Nitrogen (N)	% TS	3.98	3.61	2.18
Sulphur (S)	% TS	0.34	0.30	0.48
Calculated from elemental composition				
Theoretical methane potential (TMP)	m ³ kg ⁻¹ VS	0.609	0.624	0.540
Biogas methane content	% CH ₄ (v/v)	55.3	56.6	53.5
Theoretical calorific value (ThCV)	MJ kg ⁻¹ VS	24.4	24.8	21.9

Appendix A.2. BMP Assay

Figure A1 shows the net specific methane yields from the BMP assay for CS, and FW1 and FW2 as the feedstocks under study. The control was operated on cellulose, and for the completeness of information, these results are shown as well.

In general, gas production profiles during the BMP testing followed smooth curves, with no marked discontinuities or disturbances. The average net specific methane production for the positive controls was 0.408 L CH₄ g⁻¹ VS, very close to the theoretical value of 0.415 L CH₄ g⁻¹ VS, giving confidence in the assay results. The differences between replicates and between FW from different sources can be attributed to slight inhomogeneities in feedstock sub-samples at this scale, and to variations in FW composition with time and origin even in bulk samples.

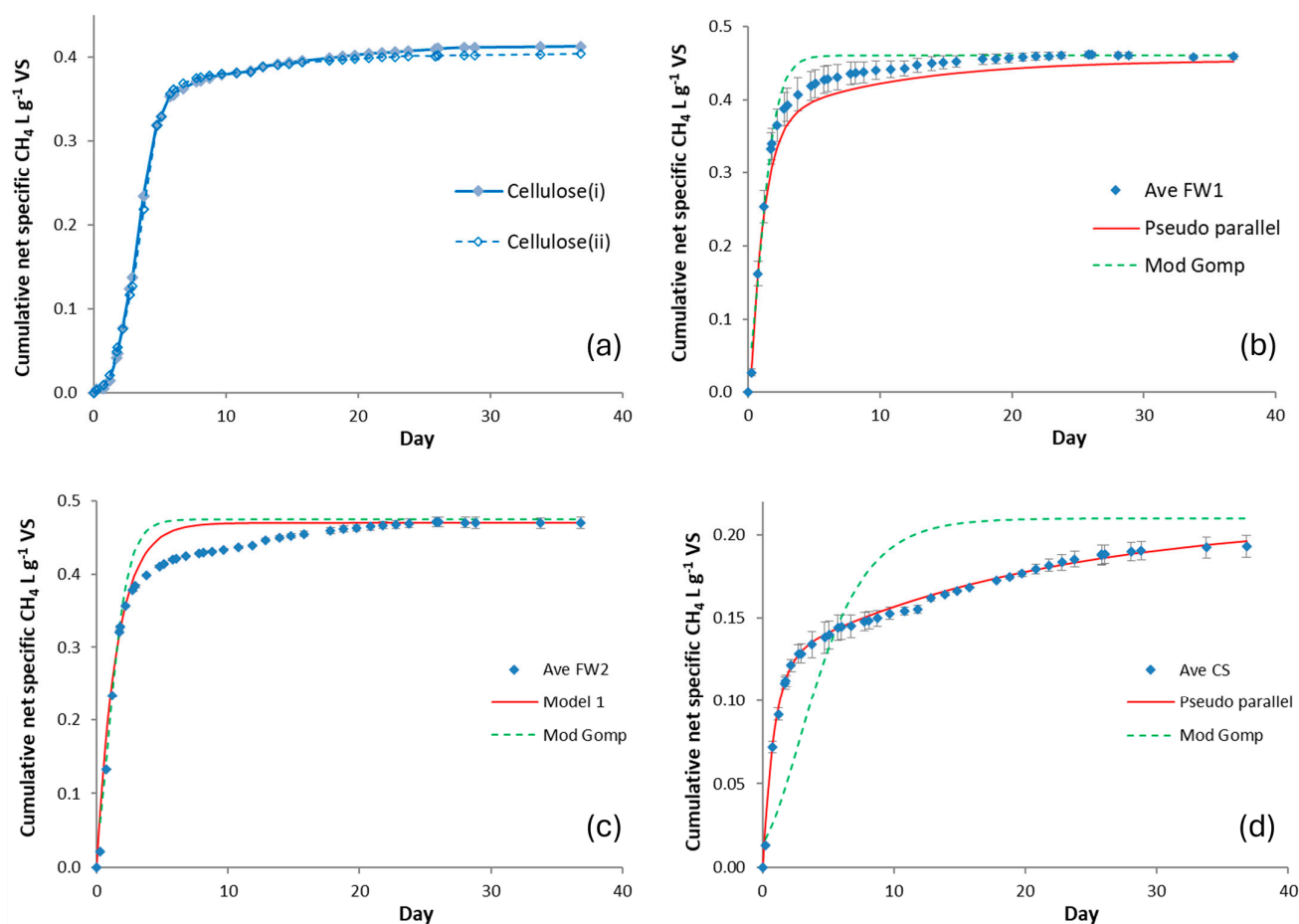


Figure A1. Cumulative net specific CH_4 production in BMP assay for (a) duplicate positive controls, and real and modelled results (pseudo-parallel model and modified Gompertz equation) for (b) FW1, (c) FW2 and (d) CS. Error bars for (b–d) show a range of duplicates: where not visible, they are smaller than symbols. Note the different y -axis scale in (d).

Appendix A.3. Trials 1 and 2 Operating Parameters

Figures A2 and A3 show the operating parameters for trials 1 and 2, respectively.

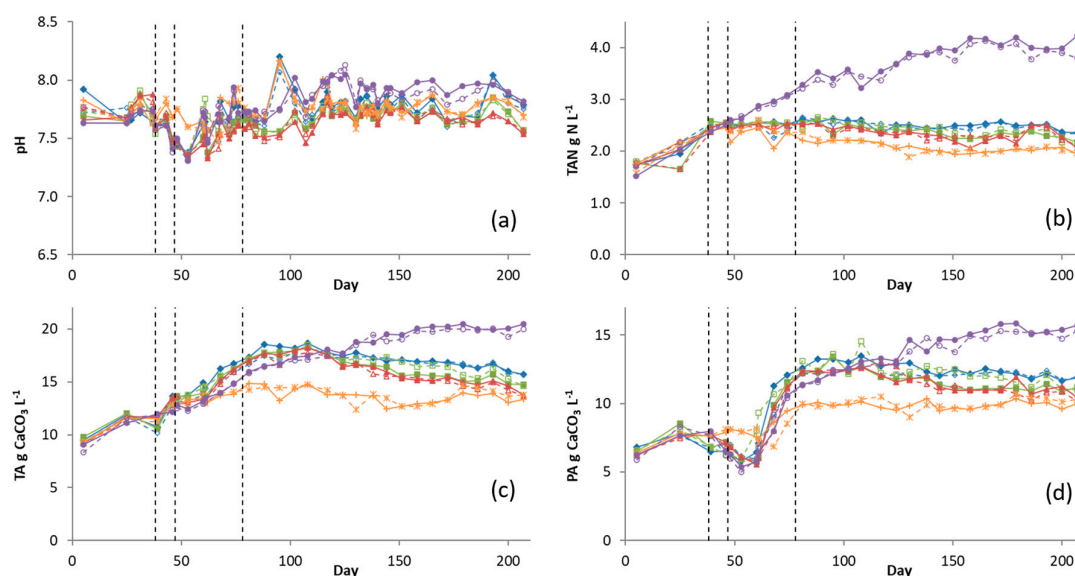


Figure A2. Cont.

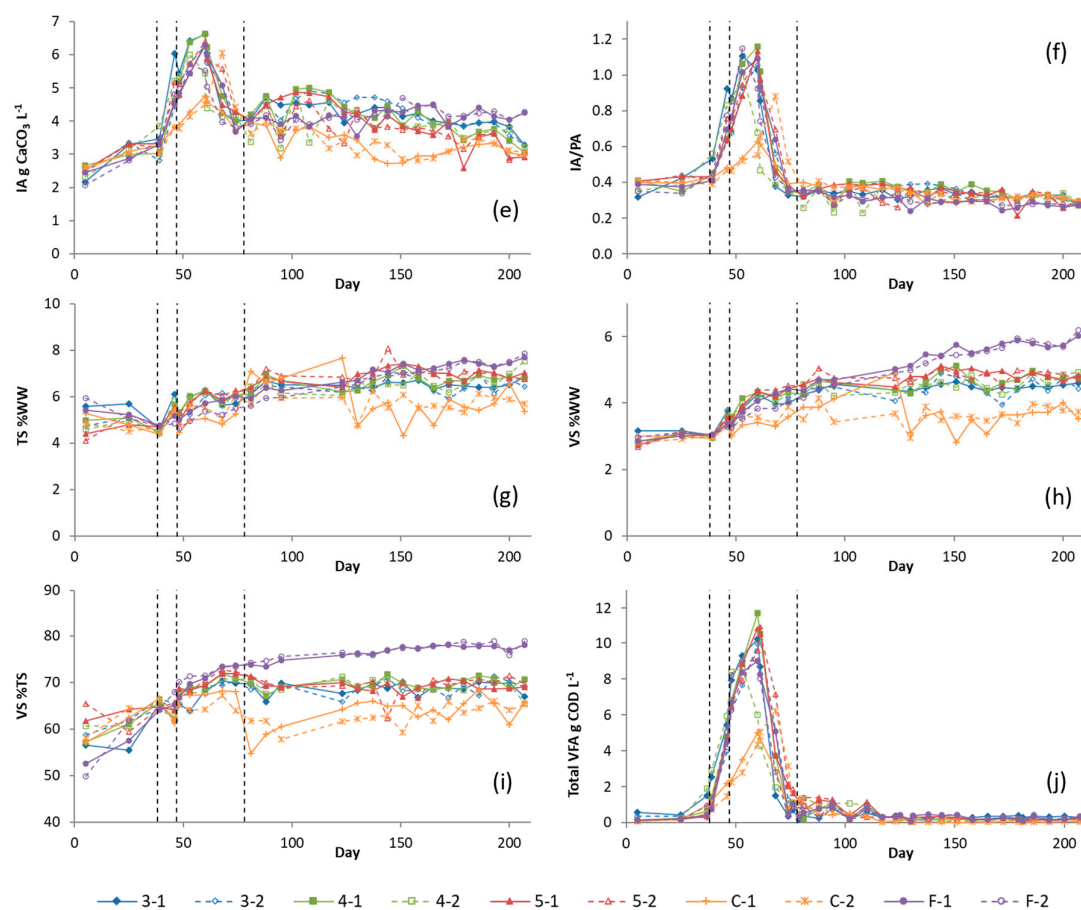


Figure A2. Operating parameters during Trial 1: (a) pH, (b) TAN, (c) TA, (d) PA, (e) IA, (f) IA/PA, (g) TS, (h) VS, (i) VS %TS and (j) total VFA. Vertical dotted lines indicate change in feeding regime for co-digesters on days 38, 47 and 78.

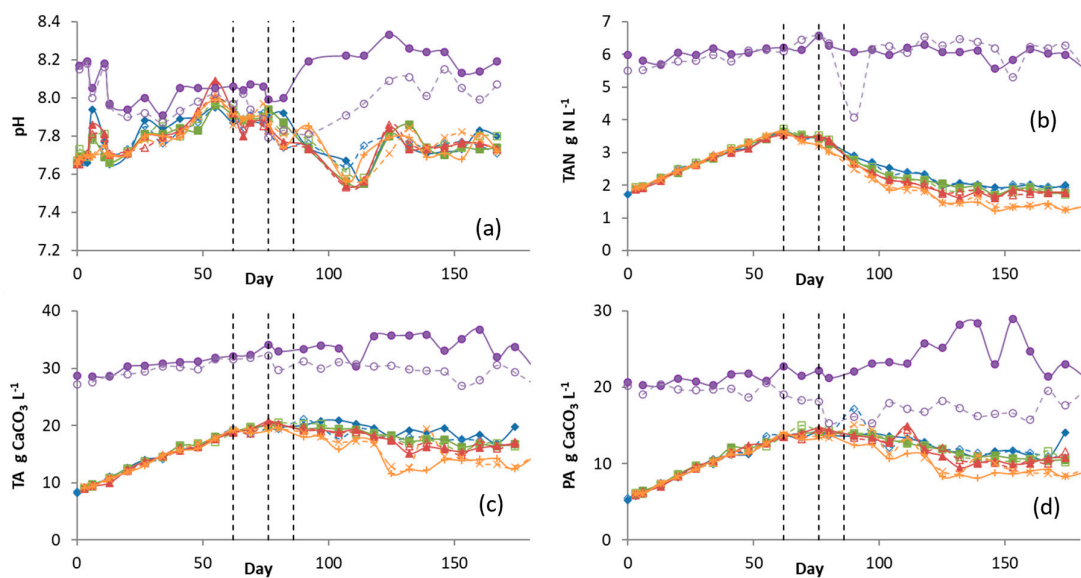


Figure A3. Cont.

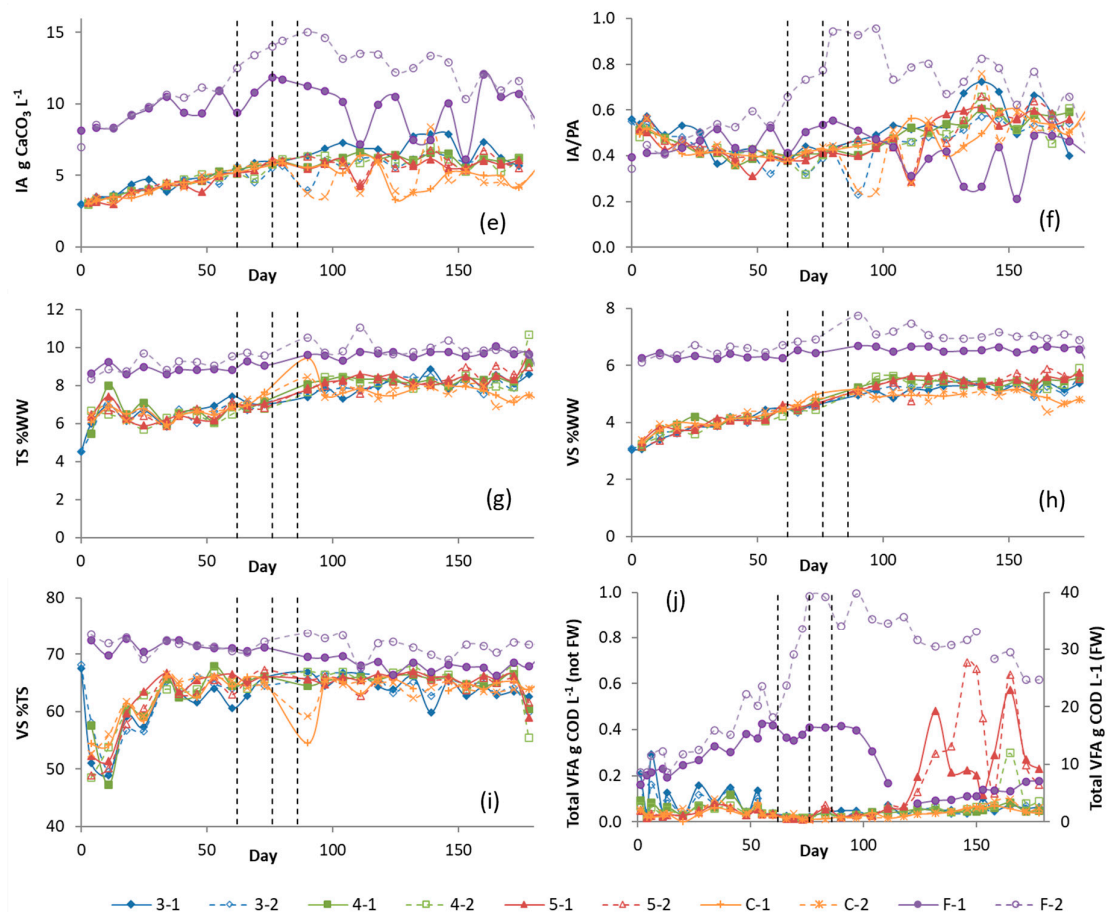


Figure A3. Operating parameters during Trial 2: (a) pH, (b) TAN, (c) TA, (d) PA, (e) IA, (f) IA/PA, (g) TS, (h) VS, (i) VS %TS and (j) total VFA. Vertical dotted lines indicate change in feeding regime for co-digesters on days 62, 76 and 86.

Appendix B. Literature Data

Table A2 presents literature data related to the co-digestion of cattle manure (CM) and FW, and Table A3 presents literature data related to trace element concentrations in cattle manure and slurry.

Table A2. Results from studies on the co-digestion of cattle manure and food waste.

Ref.	Manure	Temp (°C)	CM (g kg ⁻¹ WW)			FW (g kg ⁻¹ WW)			CM/FW		OLR (g VS L ⁻¹ day ⁻¹)			HRT (days)	SMP (mL CH ₄ g ⁻¹ VS)	Methane (% v/v)
			TS	VS	VS % TS	TS	VS	VS % TS	VS Basis	WW Basis	CM	FW	all			
[79]	Beef	35	23.4	13.8	59.0	221.2	172.1	77.8	CM only		1.2	0.0	1.2	12.0	67	n/r
									1.00	12.5	0.6	0.6	1.2	12.0	159	n/r
									0.50	6.2	0.4	0.8	1.2	12.0	194	n/r
									0.33	4.2	0.3	0.9	1.2	12.0	233	n/r
									FW only		0.0	1.2	1.2	12.0	145	n/r
[80]	Dairy	35	28.0	21.0	75.0	266.0	254.0	95.5	0.79	9.5	0.6	0.8	1.4	14.4	210–260	64–67%
[21,26]*	Dairy	36	93.1	65.2	70.0	237.4	217.1	91.4	0.25	0.8	0.4	1.6	2.0	30.0	218	62.7
									0.67	2.2	0.8	1.2	2.0	30.0	241	57.9
									0.67	2.2	1.2	1.8	3.0	30.0	221	59.2
									1.50	5.0	1.8	1.2	3.0	30.0	298	59.2
									1.50	5.0	2.4	1.6	4.0	30.0	306	59.8
[81]	Dairy	55	98.0	50.9	51.9	232.0	220.0	94.8	2.08	9.0	4.7	2.2	6.9	20.0	330	68.7

Table A2. Cont.

Ref.	Manure	Temp (°C)	CM (g kg ⁻¹ WW)			FW (g kg ⁻¹ WW)			CM/FW		OLR (g VS L ⁻¹ day ⁻¹)			HRT (days)	SMP (mL CH ₄ g ⁻¹ VS)	Methane (% v/v)
			TS	VS	VS % TS	TS	VS	VS % TS	VS Basis	WW Basis	CM	FW	all			
[14]	n/r	35	163.0	132.0	81.0	185.0	170.0	91.9	0.50 0.50 0.50 CM only FW only	0.6 0.6 0.6 4.0 0.0	4.0 5.0 6.0 4.0 0.0	8.0 10.0 12.0 0.0 8.0	12.0 15.0 18.0 4.0 8.0	12.9 10.3 8.6 33.0 21.3	388 317 139 69 347	62.3 60.2 39.7 33.5 61.2
[82]	Dairy	36	n/r	96.8	–	n/r	293.0	–	1.0 1.0 1.0	3.0 3.0 3.0	0.5 1.0 1.5	0.5 1.0 1.5	1.0 2.0 3.0	160.0 80.0 54.0	460–530 470–630 470–510	64.2–67.5 64.9–74.1 69.8–72.2
[83]	Dairy	37	122.6 123.4 120.6	105.5 106.7 103.6	86.1 86.5 85.9	136.7	131.7	96.3	CM only 10.1 4.9 3.0 2.1 1.6 1.3 1.0	15.6 7.3 4.6 3.4 2.6 2.1 1.7	2.0 2.0 2.0 2.0 2.0 2.0 2.0	0.0 0.2 0.4 0.7 1.2 1.5 1.9	2.0 2.2 2.4 2.7 3.2 3.5 3.9	25.0 25.0 25.0 25.0 25.0 25.0 25.0	215 231 245 255 259 282 289 297	56.8 58.7 57.6 56.3 57.4 58.3 58.1 58.3
[84]	Dairy	55	67.3	57.0	84.7	339	321.7	94.9	CM only 1.60 0.71 0.41 0.53	9.0 4.0 2.3 3.0	2.7 2.4 2.3 2.0 2.1	– 1.5 3.2 4.8 4.0	2.7 3.9 5.5 6.9 6.2	21.0 21.0 21.0 21.0 21.0	207 281 370 290 385	n/r n/r n/r n/r n/r
[85]	Dairy	37	62.3	47.4	76.1	187.0	175.7	94.0	CM only 1.58 0.83 0.57	6.1 3.1 2.1	1.8 1.8 1.8 1.8	0.0 1.2 2.2 3.2	1.8 3.0 4.0 5.0	25.9 22.1 19.5 17.5	218 358 402 445	62.6 62.8 63.3 63.7
[86]	n/r	37	103.0	86.0	83.5	238.0	229.0	96.2	0.18 0.19 0.21 0.22	0.41 0.42 0.46 0.48	0.2 0.4 0.7 1.0	1.2 2.4 3.7 4.5	1.4 2.8 4.4 5.5	32.1 33.5 29.5 29.5	293 347 372 unstable	53 60 64 64
[87]	n/r	37	n/r 77.0	n/r 60.0	– 77.9	n/r for mixed substrates	n/r for mixed substrates	–	2 2 2 2 2 2 2	n/r n/r n/r n/r n/r n/r n/r	– – – – – – –	– – – – – – –	2.4 3.0 4.0 6.0 8.6 12.0 15.0	25.0 20.0 15.0 10.0 7.0 5.0 4.0	257 246 236 198 170 126 0	67 68 66 67 62 56 –
This study	Dairy	35	76.0 84.4 89.3	54.2 57.0 52.7	71.3 67.5 59.1	260.3 243.0 227.98 230.9	246.4 229.0 200.94 203.9	94.7 94.2 88.1 88.3	0.66 1 1 1.58 2 2	3 3 3 6 6 6	1.2 1.6 2.0 1.8 2.3 2.9	1.8 2.5 3.1 1.1 1.5 1.9	3.1 4.1 5.1 2.9 3.8 4.8	33.3 25.0 20.0 25.7 19.3 15.4	322 318 329 242 223 216	60.5 60.9 60.9 61.6 61.7 62.2

* Additional data provided by authors.

Table A3. Trace element concentrations in cattle manure and slurry (mg kg⁻¹ TS).

Element	Major Surveys		Co-digestion Studies ^d				
	McBride and Spiers (2001) ^a [88]	Sager (2007) ^b [89]	Sheppard and Sanipelli (2012) ^c [90]	Agyeman et al. (2014) [82]	El-Mashad and Zhang (2010) [91]	Adam (2019) [92]	This study
Al	–	1670	–	–	1.72	–	–
B	8.1	–	24.3	–	0.07	–	–
Co	2.5	2.1	1.61	–	–	1.26	1.76
Cu	139	51	75.7	123	110	55.7	64.6
Fe	–	1970	879	705	2100	1202	1331
Mn	–	180	311	176	210	150.4	94.8
Mo	2.5	3.5	4.55	1.6	<0.02	4.27	5.24
Ni	8	6.3	4.59	–	<0.02	9	19.5
Se	3	0.59	1.16	–	–	0.79	0.24
W	–	–	–	–	–	–	–
Zn	191	164	350	233	280	131.5	123

^a 20 samples; ^b no. of samples not reported, multi-year programme; ^c 30 samples; ^d single example.

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