Data related to anaerobic digestion of bioplastics: Images and properties of digested bioplastics and digestate, synthetic food waste recipe and packaging information

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A B S T R A C T

The data presented in this article are related to the research article entitled ‘Degradation of some EN13432 compliant plastics in simulated mesophilic anaerobic digestion of food waste’ (W. Zhang, S. Heaven, C. Banks, 2018). Zhang et al., 2018. They include quantification of residual materials from preparation of a synthetic food waste feedstock; photographic images of the physical appearance of the test plastics after prolonged exposure to microbial degradation in a continuously-operated anaerobic digestion trial; microscopic images of selected plastics after anaerobic biodegradation; test data and results for a Biochemical Methane Potential assay for the plastics; analytical data for potentially toxic elements in the plastics; and values for residual biogas potential of the digestate. Additional data on experimental methods is given, including a recipe for a synthetic food waste specifically designed for use in anaerobic digestion simulation studies; and details on adjustment of calculations after amendment of the digestate sampling methodology used in the main study.

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1. Data

The data presented in this document are related to a work on degradation of some EN13432 compliant plastics in simulated mesophilic anaerobic digestion of food waste [1].

1.1. Residual materials from synthetic food waste recipe

During preparation of the synthetic food waste (SFW) used in the trial, the packaging material in which it came was separated (Fig. 1) and weighed. The total unsorted weight of material including all food items and packaging was 101.836 kg, of which the rejected packaging stream made up 4.604 kg. Plastic film made up 774 g or 0.76% of the total unsorted weight, while solid plastics (trays, pots and bottles) made up a further 880 g or 0.86%, giving a plastics total of 1.62% on a wet weight basis (Table 1). Further details of the mixed SFW and card packaging (CP) feedstock used in the trial are given in section 2.1.

1.2. Physical appearance, weight and numbers of plastic tokens after digestion

Table 2 lists the types of plastic used in the trial in [1]. Fig. 2 shows the plastic tokens removed from the digestate sampled on day 98 of the trial, with the left-hand images showing the total amount recovered in each case. Numbers and weights of tokens during and at the end of the trial are shown in Table 9 and Fig. 11 in Section 2.
1.3. Images from microscopy

Fig. 3–7 present micrographs of selected plastic pieces recovered from the digestate samples taken on day 98. No special measures were taken to preserve these pieces at the time of sampling. Figs. 3–6 were taken with light and dark field microscopy and Fig. 7 with confocal microscopy.

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Table 1
Food and packaging streams from SFW materials.

| Item                                | Weight (g) | % of total unsorted weight (including food items) |
|-------------------------------------|------------|--------------------------------------------------|
| Plastic bottles                     | 140        | 0.14%                                            |
| Plastic trays                       | 446        | 0.44%                                            |
| Plastic containers/pots             | 294        | 0.29%                                            |
| Subtotal solid plastic              | 880        | 0.86%                                            |
| Plastic film                        | 774        | 0.76%                                            |
| Total plastic (not including Tetra pak components) | 1654       | 1.62%                                            |
| Tetra pak - mixed materials         | 88         | 0.09%                                            |
| Aluminium trays                     | 59         | 0.06%                                            |
| Metal cans                          | 141        | 0.14%                                            |
| Card packaging                      | 1207       | 1.19%                                            |
| Glass bottles and jars inc tops     | 1455       | 1.43%                                            |
| Total packaging                     | 4604       | 4.52%                                            |
| Unmacerated food - eggshell, pepper top, onionskin | 541       | 0.53%                                            |
| Total reject stream                 | 5145       | 5.05%                                            |
| Food materials - macerated to form SFW | 96691    | 94.95%                                           |
| Total weight of material            | 101836     | 100.00%                                          |

Table 2
Plastic materials used in trial.

| Abbreviation          | Average token weight (mg) 10 × 10 mm square |
|-----------------------|---------------------------------------------|
| Polypropylene film    | PP                                          | 2.61                                         |
| Low density polyethylene film | LDPE                       | 5.14                                         |
| Cellulose-based metallised film | CBM                                        | 3.42                                         |
| Cellulose-based heat-sealable film | CBHS                      | 4.28                                         |
| Cellulose-based high barrier heat-sealable film | CBHB              | 6.68                                         |
| Cellulose-based non heat-sealable film | CBnHS                | 6.24                                         |
| Cellulose diacetate film | CDF                                       | 6.50                                         |
| Starch-based film blend 1 | SBF1                                      | 2.17                                         |
| Starch-based film blend 2 | SBF2                                      | 4.29                                         |
| Polylactic Acid Film   | PLAF                                        | 3.71 Pellet                                  |
| Polylactic Acid Blend  | PLAB                                        | 24.7                                         |
1.4. Biodegradability of plastics as assessed by the BMP assay

Data from Biochemical Methane Potential (BMP) assays on the feedstock materials (SFW, CP and plastics) used in the trial are shown in Fig. 8 and Table 3. During the BMP assays one replicate for CP and one for PLAB suffered a small loss of digester contents. These replicates were omitted from the BMP calculation and graphical data are presented only up to the point before this loss occurred. Results from another test carried out in accordance with DIN 38414 Teil 8 (high-rate dry fermentation at 50 °C) [2] were made available by the funders of the trial, and are included in Table 3 for comparison.

Degradation of the cellulose based plastics appeared to show inhibition in the first two days of the BMP assay. Table 4 gives the time of onset of inhibition in each case.
Fig. 2. Continued.
The BMP tests for CDF, SBF1, SBF2, PLAF and PLAB (at both I/S ratios) were left running until day 103. All but PLAF showed little or no change in methane production rate or final yield. PLAF continued to produce methane at a higher rate than in the first 50 days. After 103 days it had produced a further $0.119 \text{ m}^3 \text{ CH}_4 \text{ kg}^{-1} \text{ VS added}$, giving a total of $0.216 \text{ m}^3 \text{ CH}_4 \text{ kg}^{-1} \text{ VS}$ with good agreement between replicates.

1.5. Potentially toxic elements

Table 5 shows the concentration of Potentially Toxic Elements (PTE) in the feedstock materials. The method for comparing these with the limit value in the UK’s PAS110 standard [3] is outlined in section 2.4.

1.6. Residual biogas potential of digestate

The Residual Biogas Potential of the digestate from the trial in Ref. [1] was $0.084 \text{ L biogas kg}^{-1} \text{ VS}$ ($0.070 \text{ L CH}_4 \text{ kg}^{-1} \text{ VS}$) at day 28. The digestate sample continued to produce gas after the 28-day...
standard test duration: Fig. 9 shows the data for the cumulative net specific methane production up to day 45. The kinetic constants obtained using two modelling approaches described in Section 2.5 are given in Table 6.

2. Experimental design, materials and methods

2.1. Synthetic food waste and card packaging

A synthetic food waste, based on materials purchased for the purpose from supermarkets, was prepared for the trial in Ref. [1] as described below. This approach was adopted to ensure that the feedstock for the trial was not contaminated with other plastics, which would have been difficult to avoid using either post-supermarket or post-consumer food waste. A study on post-consumer UK food waste [4] with data categorised into the 100 items most commonly thrown away by households (Table 7) was used as the basis for selection of the materials used. These were further grouped by
category according to data provided by a major UK supermarket chain. The selected products were then purchased in appropriate proportions on a fresh weight basis (Table 8), and processed in a macerating grinder (SS2/010, IMC Limited, UK) (Fig. 10).

Fig. 6. CBnHS. (a) Dark field low magnification clearly showing perforation of film as bright areas where light penetrates thinner sections. (b) Phase contrast showing extensive surface pitting. Images by Prof Francisco Torrella, University of Murcia.

Fig. 7. CBHS. Combined fluorescent and differential interference contrast images for sample CBHS showing pitting and microbial attack. Sample viewed using a Leica TCS SP2 confocal laser scanning microscope. Images courtesy of Dr Yue Zhang, University of Southampton.
2.2. Semi-continuous digestion trials: adjustment of calculations after amendment of digestate sampling methodology

Semi-continuous digestion trials designed to simulate full-scale operating modes with the addition of plastic tokens were set up and run as described in Ref. [1].

The number and weight of tokens added to each digester, removed each week during the trial, and remaining in each digester at the end of the trial is shown in Table 9. If the sampling method used is representative and the plastic shows little or no degradation, the expected number of tokens removed in any week is simply equal to the number present in the digester multiplied by the fraction of digestate volume removed, and it is easy to keep a running total. For the first weeks of the trial in Ref. [1] the

Table 3

65-day BMP values for plastic samples.

| Sample          | This work m³ CH₄ kg⁻¹ VS ± | DIN 8414 m³ CH₄ kg⁻¹ VS | DIN 38414 days | Comments                        |
|-----------------|-----------------------------|-------------------------|----------------|--------------------------------|
| PP              | 0.025 ± 0.030               | –                       | –              | –                              |
| LDPE            | 0.018 ± 0.007               | 0.360                   | 28             | –                              |
| CBM             | 0.374 ± 0.009               | 0.398                   | 28             | –                              |
| CBHS            | 0.433 ± 0.009               | 0.340                   | 42             | –                              |
| CBHB            | 0.413 ± 0.015               | 0.397                   | 28             | –                              |
| CBnHS           | 0.410 ± 0.021               | 0.259                   | 28             | –                              |
| CDF             | 0.050 ± 0.005               | 0.108                   | 64             | –                              |
| SBF1            | 0.113 ± 0.016               | 0.069                   | 64             | –                              |
| SBF2            | 0.069 ± 0.005               | 0.058                   | 28             | –                              |
| PLAF            | 0.097 ± 0.032               | 0.014                   | 28             | –                              |
| PLAB            | 0.017 ± 0.005               | –                       | –              | –                              |
| Card packaging (CP) | 0.274 ± 0.046         | –                       | –              | –                              |
| Food waste (SFW) | 0.471 ± 0.013            | –                       | –              | –                              |
| Cellulose control | 0.391 ± 0.002           | –                       | –              | –                              |

Fig. 8. Data from BMP tests on feedstock components: (a) PLAB (I/S ratio 3.8, 4–6 = I/S ratio 1.9), cellulose control; (b) SFW, CP, CBM and CBnHS; (c) PP, CBHS, CBHB, LDPE; (d) CDF, SBF1, SBF2, PLAF. I/S ratio = inoculum to substrate ratio used in the assay.
sampling method was not representative, and tended to remove proportionately larger numbers of denser plastic tokens and smaller numbers of less dense tokens. The number of tokens actually removed is still known, however, and if no tokens are lost through degradation the number remaining in the digester at the point when the sampling method was modified can therefore be calculated by simple arithmetic. This value can then be used as the start point for calculating the expected number removed once the sampling method has been adjusted. There are thus two ways to check the assumptions made:

1. The number of tokens removed or present in the digestate at the end of the run should equal the total number added; and
2. Once the revised sampling method is adopted the number of tokens removed each week should approximately match the expected number.

In the case of the PP control, for example, Table 9 shows that a total of 8906 tokens were added throughout the trial. Of these 8842 were accounted for, either removed with the digestate or present in the digester at the end. Since this material is considered non-degradable, this corresponds to an error of 64 tokens or 0.7% of the total. The equivalent figures for the LDPE control were 4293 tokens with an error of 6 tokens or 0.1%. In Fig. 11 it can also be seen that the expected number of tokens removed showed a reasonably good match to the actual number, once the sampling method had been adjusted and the actual number of tokens present at that point taken into account. This validated the approach used. The same approach could then be applied to plastics such as SBF1 and PLAB, where the number of tokens removed in the first weeks of operation was higher than expected, but the total recovery at the end indicated little or no degradation, as did the other methods of assessment used. In Table 9 it can be

### Table 4
Onset of inhibition in BMP test for Cellulose-based plastics.

| Plastic | Onset of inhibition - Days from start of test |
|---------|----------------------------------------------|
| CBM     | 1.49–1.52                                    |
| CBHS    | 1.35–1.39                                    |
| CBHB    | 1.28–1.30                                    |
| CBnHS   | 1.50–1.55                                    |

### Table 5
Concentration of PTE in feedstock and plastic materials.

| Unit       | Mercury (Hg) | Cadmium (Cd) | Chromium (Cr) | Copper (Cu) | Lead (Pb) | Nickel (Ni) | Zinc (Zn) |
|------------|--------------|--------------|---------------|-------------|------------|-------------|-----------|
| PAS110 limit value a kg tonne⁻¹ WW | 0.08 | 0.12 | 8 | 16 | 16 | 4 | 32 |
| Cardboard mg kg⁻¹ TS BDL | 0.37 | 4.1 | 46.8 | 8.8 | 2.37 | 42.8 |
| SFW mg kg⁻¹ TS BDL | 0.02 | 1.4 | 3.2 | 0.08 | 0.619 | 17.8 |
| PP mg kg⁻¹ TS BDL | 0.080 | 0.5 | 0.4 | BDL | 0.42 | 3.0 |
| LDPE mg kg⁻¹ TS BDL | 0.19 | 0.3 | 5.4 | 1.3 | 0.28 | 4.1 |
| CBM mg kg⁻¹ TS BDL | 0.693 | 0.1 | 0.2 | 0.2 | 0.44 | 4.6 |
| CBHS mg kg⁻¹ TS BDL | 0.06 | BDL | BDL | 0.2 | 0.26 | 1.6 |
| CBHB mg kg⁻¹ TS BDL | 0.04 | BDL | BDL | BDL | 0.876 | 0.2 |
| CBnHS mg kg⁻¹ TS BDL | 0.079 | 0.2 | BDL | BDL | 0.48 | 0.4 |
| CDF mg kg⁻¹ TS BDL | 0.12 | 0.2 | 0.2 | 0.1 | 0.12 | 1.4 |
| SBF1 mg kg⁻¹ TS BDL | 0.064 | 0.5 | 2.0 | 0.2 | 0.41 | 1.3 |
| SBF2 mg kg⁻¹ TS BDL | 0.16 | 0.1 | 0.4 | 0.1 | 0.18 | 2.2 |
| PLAF mg kg⁻¹ TS BDL | 0.15 | 0.3 | 1.0 | 0.4 | 0.21 | 1.7 |
| PLAB mg kg⁻¹ TS BDL | 0.068 | 10.0 | BDL | BDL | 3.49 | 0.3 |

BDL = Below Detection Limit of 0.1 mg kg⁻¹ TS.

a PAS110 limit values in kg tonne⁻¹ WW at a digestate total N concentration <1 kg N tonne⁻¹ WW [3].

### Table 6
Kinetic parameters for specific methane yield from digestate.

| Model | Ym | P | k₁ | k₂ | R² ave |
|-------|----|---|----|----|--------|
| 1     | 0.085 | 1 | 0.10 | 0.000 | 0.9796 |
| 2     | 0.085 | 0.3 | 0.90 | 0.060 | 0.9976 |
seen that the discrepancies in final token numbers for these plastics were 3.4% and 2.4%, only slightly above those for the control plastics; while Fig. 11 again shows good agreement between expected and actual recovery with the adjusted value for tokens once the revised sampling method has been adopted.

This method cannot be reliably applied to more readily degradable plastics without making further assumptions, since the number of tokens recovered is also affected by degradation. The final number and weight of tokens can still be used to estimate the degree of degradation, however. The only readily degradable plastic, which showed clear, signs that a larger than expected number of tokens were being removed during the first few weeks was CDF. In this case no attempt was made to correct the number of tokens present when the sampling method was adjusted (Fig. 11).

2.3. BMP test

The conditions used in the BMP assay are described in Ref. [1]. The BMP for a given test substrate was obtained by calculating the cumulative volume of methane produced from each test digester; subtracting the average cumulative STP methane production from the inoculum-only controls; and dividing the result by the weight of substrate volatile solids added to each test digester. The average value in L CH$_4$ g$^{-1}$ VS for all test digesters fed on a given substrate was taken as the final BMP value. All gas volumes are reported at STP of 101.325 kPa and 0 °C.

The BMP of the cellulose controls was used to indicate whether the test conditions are satisfactory: the value of 0.391 m$^3$ CH$_4$ kg$^{-1}$ VS added in this case was very close to the theoretical value of 0.3415 m$^3$ CH$_4$ kg$^{-1}$ VS added. The SFW and CP had BMP values of 0.471 and 0.274 m$^3$ CH$_4$ kg$^{-1}$ VS added respectively, both typical of these types of material. The control plastics PP and LDPE showed very low but non-zero values of 0.025 and 0.018 m$^3$ CH$_4$ kg$^{-1}$ VS added respectively, corresponding to around 5% of the methane yield of the controls and indicating the probable limit of accuracy of the assay.

The data for the cellulose-based plastics were not ideal for the purposes of determining the BMP and the calculation was thus adapted to accommodate this. All four plastics produced methane at a rapid and consistent rate from the start of the test until between 1.2 and 1.5 days (Fig. 8b and c), when methane production relative to the inoculum-only controls dropped sharply. Inhibition of this type is often due to production of volatile fatty acid (VFA) intermediates at a rate greater than the capacity of the methanogenic population to process the VFA into methane, and this in turn indicates a very readily
Table 7
Most common post-consumer food items for disposal (based on [4]).

| No | Item                  | All (kg) | Short life only (kg) |
|----|-----------------------|----------|---------------------|
| 1  | Potatoes              | 359000   | 9.7%                |
| 2  | Bread slices          | 328000   | 8.9%                |
| 3  | Apples                | 190000   | 5.1%                |
| 4  | Meat or fish meals    | 161000   | 4.4%                |
| 5  | World breads          | 102000   | 2.8%                |
| 6  | Veg mixed meals       | 96000    | 2.6%                |
| 7  | Pasta mixed meals     | 87000    | 2.4%                |
| 8  | Bread rolls/baguette   | 86000    | 2.3%                |
| 9  | Rice mixed meals      | 85000    | 2.3%                |
| 10 | Mixed meals           | 85000    | 2.3%                |
| 11 | Bananas               | 84000    | 2.3%                |
| 12 | Bread loaves          | 75000    | 2.0%                |
| 13 | Yoghurts/drinks       | 67000    | 1.8%                |
| 14 | Sandwiches            | 63000    | 1.7%                |
| 15 | Cakes                 | 62000    | 1.7%                |
| 16 | Lettuce               | 61000    | 1.7%                |
| 17 | Tomatoes              | 61000    | 1.7%                |
| 18 | Cabbage               | 56000    | 1.5%                |
| 19 | Cooked rice           | 55000    | 1.5%                |
| 20 | Mixed veg             | 53000    | 1.4%                |
| 21 | Oranges               | 51000    | 1.4%                |
| 22 | Carrots               | 46000    | 1.2%                |
| 23 | Onions                | 43000    | 1.2%                |
| 24 | Pears                 | 42000    | 1.1%                |
| 25 | Sodas                 | 42000    | 1.1%                |
| 26 | Milk                  | 40000    | 1.1%                |
| 27 | Cheese                | 40000    | 1.1%                |
| 28 | Mixed salads          | 37000    | 1.0%                |
| 29 | Cooked pasta          | 36000    | 1.0%                |
| 30 | Mixed snacks          | 36000    | 1.0%                |
| 31 | Melons                | 35000    | 0.9%                |
| 32 | Coleslaw              | 33000    | 0.9%                |
| 33 | Pizzas                | 32000    | 0.9%                |
| 34 | Chicken portions      | 32000    | 0.9%                |
| 35 | Cucumbers             | 32000    | 0.9%                |
| 36 | Chocolates/sweets     | 31000    | 0.8%                |
| 37 | Sweetcorn             | 30000    | 0.8%                |
| 38 | Sausages              | 30000    | 0.8%                |
| 39 | Pork portions         | 29000    | 0.8%                |
| 40 | Biscuits/crackers     | 27000    | 0.7%                |
| 41 | Water                 | 27000    | 0.7%                |
| 42 | Beans (not baked)     | 26000    | 0.7%                |
| 43 | Grapes                | 22000    | 0.6%                |
| 44 | Ham                   | 22000    | 0.6%                |
| 45 | Plums                 | 20000    | 0.5%                |
| 46 | Squashes/cordials     | 20000    | 0.5%                |
| 47 | Breakfast cereals     | 20000    | 0.5%                |
| 48 | Cook-in sauces        | 19000    | 0.5%                |
| 49 | Fruit juices          | 19000    | 0.5%                |
| 50 | Eggs                  | 19000    | 0.5%                |
| 51 | Fish                  | 19000    | 0.5%                |
| 52 | Beef portions         | 18000    | 0.5%                |
| 53 | Dough                 | 18000    | 0.5%                |
| 54 | Celery                | 17000    | 0.5%                |
| 55 | Strawberries          | 16000    | 0.4%                |
| 56 | Peppers               | 15000    | 0.4%                |
| 57 | Chicken drumsticks    | 15000    | 0.4%                |
| 58 | Flour                 | 15000    | 0.4%                |
| 59 | Chicken breasts       | 15000    | 0.4%                |
| 60 | Mushrooms             | 15000    | 0.4%                |

(continued on next page)
degradable material and an insufficient I/S ratio in the test. To confirm the cause would require sampling an additional replicate to measure system parameters such as pH, alkalinity and VFA concentration, but this was not carried out in the current work. An alternative explanation of some inhibitory component in the heat-sealable and moisture-resistant surface layers of the plastics was ruled out, as the same effect also occurred in CBnHS without these additional layers. The onset of inhibition appeared to be a characteristic of the material, as there was little overlap between the different plastics (Table 4). Unfortunately recovery from this type of inhibition generally shows considerable variation between replicates, and can have some impact on the final BMP value, as seen in Fig. 8b and c. The outlying values for CBM, CBHB and CBnHS were therefore ignored in calculating the average BMP for each material. Despite this issue, the BMP values showed reasonable correspondence with those obtained from the DIN 38414 test (Table 3), especially when the degree of completion of some of the DIN 38414 test runs is taken into account.

Of the remaining plastics, SBF2 showed a very low BMP of 0.069 m$^3$ CH$_4$ kg$^{-1}$ VS added, while SBF1 had a slightly higher value of 0.113 m$^3$ CH$_4$ kg$^{-1}$ VS added. In both cases the similarity to DIN 38414 test values may be coincidental, as gas production was still continuing at a low but steady rate at the end of

### Table 7 (continued)

| No | Item                  | All (kg) | Short life only (kg) |
|----|-----------------------|----------|---------------------|
| 61 | Broccoli              | 15000    | 0.4% 15000          |
| 62 | Sandwich spreads      | 14000    | 0.4% 14000          |
| 63 | Baked beans           | 14000    | 0.4%                |
| 64 | Bacon                 | 14000    | 0.4% 14000          |
| 65 | Peaches               | 14000    | 0.4% 14000          |
| 66 | Milk drinks           | 13000    | 0.4% 13000          |
| 67 | Crisps                | 12000    | 0.3% 12000          |
| 68 | Lemons                | 12000    | 0.3% 12000          |
| 69 | Beetroot              | 12000    | 0.3% 12000          |
| 70 | Fruit pies            | 12000    | 0.3% 12000          |
| 71 | Jams                  | 11000    | 0.3%                |
| 72 | Pheasants             | 11000    | 0.3% 11000          |
| 73 | Dips                  | 10000    | 0.3% 10000          |
| 74 | Mixed fruits          | 10000    | 0.3% 10000          |
| 75 | Butter/margarine      | 10000    | 0.3% 10000          |
| 76 | Herbs/spices          | 10000    | 0.3%                |
| 77 | Dessert cakes/gateaux | 9000     | 0.2% 9000           |
| 78 | Cream                 | 9000     | 0.2% 9000           |
| 79 | Pineapples            | 9000     | 0.2% 9000           |
| 80 | Crumpets              | 9000     | 0.2% 9000           |
| 81 | Pastry                | 9000     | 0.2% 9000           |
| 82 | Chicken products      | 9000     | 0.2% 9000           |
| 83 | Pet food              | 9000     | 0.2%                |
| 84 | Yorkshire pudding and batters | 8000 | 0.2% 8000 |
| 85 | Cauliflowers          | 8000     | 0.2% 8000           |
| 86 | Uncooked pasta        | 8000     | 0.2%                |
| 87 | Leeks                 | 8000     | 0.2% 8000           |
| 88 | Milk pudding (custards etc) | 8000 | 0.2% 8000 |
| 89 | Doughnuts             | 8000     | 0.2% 8000           |
| 90 | Oils                  | 8000     | 0.2% 8000           |
| 91 | Mayonnaise/salad cream | 7000 | 0.2% 7000 |
| 92 | Spring onions         | 6000     | 0.2% 6000           |
| 93 | Peas                  | 6000     | 0.2% 6000           |
| 94 | Turnips/swedes        | 6000     | 0.2% 6000           |
| 95 | Parsnips              | 6000     | 0.2% 6000           |
| 96 | Burgers               | 6000     | 0.2% 6000           |
| 97 | Lamb                  | 6000     | 0.2% 6000           |
| 98 | Pickles               | 6000     | 0.2%                |
| 99 | Nuts                  | 6000     | 0.2% 6000           |
| 100| Mangoes               | 6000     | 0.2% 6000           |
|    | Subtotal              | 3691000  | 100.0% 2913000       |
|    | UK total              | 4080000  | 90.5%              |
| Produce                        | Bakery                      | kg  | Dry goods                      | kg  | Dairy                  | kg  | Meat and Fish                        | kg  | Ready meals | kg  |
|-------------------------------|-----------------------------|-----|--------------------------------|-----|------------------------|-----|-------------------------------------|-----|-------------|-----|
| Potatoes 10.000               | White sliced bread         | 5.650 | Bottled water - still          | 1.700 | Yoghurt                | 2.000 | Barbecue mix (sausages, burgers, chicken drumsticks | 2.600 | Cottage pie | 2.000 |
| Apples 6.057                  | Wholemeal flour            | 1.740 | Potatoes for crisps            | 1.319 | Milk                   | 2.000 | Chicken breasts frozen               | 1.100 | Beef lasagne | 2.000 |
| Tomatoes 2.518                | Sliced wholemeal bread     | 1.512 | Chocolate and confectionery    | 0.640 | Cooked rice            | 1.175 | White fish fillet frozen             | 0.750 | Cooked plain pasta                   | 1.775 |
| Lettuce 2.479                 | White bread flour          | 1.500 | Mixed breakfast cereal         | 0.547 | Fruit juice            | 1.000 | Breaded chicken breasts              | 0.640 | Pizza                    | 0.930 |
| Bananas 2.270                 | Pitta bread                | 1.309 | Cook-in sauce Eggs             | 0.540 | Coleslaw               | 0.875 | Lamb mince                            | 0.454 | Ocean pie                | 0.900 |
| Oranges 2.048                 | Wholemeal rolls            | 1.013 | Eggs                            | 0.510 | Pasta salad (Chicken/tuna) | 0.600 | Bacon                                 | 0.400 | Steak pie                | 0.800 |
| Mixed vegetables frozen 2.000 | Christmas pudding          | 0.850 | Bottled water - sparkling      | 0.450 | Sandwich filling (tuna, onion) | 0.750 | Ham                                   | 0.400 | Spinach and ricotta cannelloni     | 0.600 |
| Melon 1.778                   | Eggs for cake etc Tortilla | 0.690 | Baked beans Tinned pet food    | 0.420 | Mayonnaise             | 0.500 | Salami                                | 0.343 | Pork pies                 | 0.459 |
| Cucumber 1.525                | Rye bread                  | 0.495 | Jaffa cakes                     | 0.300 | Custard (liquid)       | 0.475 | –                                    | –    | Spaghetti bolognese         | 0.450 |
| Pineapple 1.089               | Apple tart                 | 0.450 | Fruit cordial                   | 0.300 | Cheddar                | 0.444 | –                                    | –    | Mushroom                | 0.450 |
| Onion 1.009                   | White rolls                | 0.420 | Uncooked pasta                  | 0.250 | Fruit dessert          | 0.400 | –                                    | –    | Tagliatelle               | 0.400 |
| Broccoli mix frozen 1.000     | Wholemeal finger rolls     | 0.400 | Granulated white sugar          | 0.240 | Edam                    | 0.320 | –                                    | –    | Stir fry frozen vegetables   | 0.397 |
| Casserole vegetable mix frozen|                           | 1.000 |                                |       |                        |       |                                      |      | Cauliflower cheese grills     |         |
| Sweet corn frozen 1.000       | Doughnut                   | 0.330 | Jam                             | 0.210 | Cottage cheese         | 0.300 | –                                    | –    | Chicken curry             | 0.375 |
| Pear 0.860                   | Crumpet                    | 0.280 | Herbs and spices (dry) Honey    | 0.200 | Houmous                | 0.300 | –                                    | –    | Chicken curry 2            | 0.375 |
| Carrots 0.629                 | Naan bread                 | 0.270 |                                |       |                        |       |                                      |      | Cheese and onion crisp bakes | 0.360 |
| Lemons 0.537                  | Malt bread rolls           | 0.230 | Mixed nuts                      | 0.200 | Brie                    | 0.200 | –                                    | –    | Beef and yorkshire pudding ready meal | 0.360 |
| Celery 0.520                  | Wholemeal loaf             | 0.220 | Chocolate mini rolls            | 0.120 | –                       | –    | –                                    | –    | Vegetable grills           | 0.340 |

(continued on next page)
| Produce     | kg  | Bakery                        | kg  | Dry goods         | kg  | Dairy          | kg  | Meat and Fish | kg  | Ready meals | kg  |
|-------------|-----|-------------------------------|-----|-------------------|-----|---------------|-----|--------------|-----|-------------|-----|
| Grapes      | 0.500 | Water for bread dough    | 0.200 | Chutney       | 0.100 | —             | —   | —            | —   | Vegetable lasagne | 0.300 |
| Beetroot    | 0.500 | Breadsticks       | 0.200 | Tartare sauce | 0.060 | —             | —   | —            | —   | Yorkshire pudding  | 0.290 |
| Plums       | 0.500 | Powdered milk        | 0.100 | —             | —   | —             | —   | —            | —   | Stir fry frozen veg | 0.400 |
| Pepper      | 0.498 | Gingerbread         | 0.050 | —             | —   | —             | —   | —            | —   | —           | —   |
| Peaches     | 0.433 | Yeast              | 0.015 | —             | —   | —             | —   | —            | —   | —           | —   |
| Mushrooms   | 0.350 | —                | —   | —             | —   | —             | —   | —            | —   | —           | —   |
| Spring onion| 0.160 | —                | —   | —             | —   | —             | —   | —            | —   | —           | —   |
| Subtotal    | 41.260 | 18.424          | 8.706 | 12.323        | 6.787 | 14.336        | —   | —            | —   | —           | —   |
| % of total  | 40.5% | 18.1%           | 8.5%  | 12.1%         | 6.7%  | 14.1%         | —   | —            | —   | —           | —   |
the DIN 38414 test. For CDF film there was a considerable difference between the value of 0.05 m$^3$ CH$_4$ kg$^{-1}$ VS added in this work and the DIN 38414 test value of 0.259 m$^3$ CH$_4$ kg$^{-1}$ VS added, suggesting that this material may be more amenable to degradation under thermophilic conditions than in a wet mesophilic system. The BMP value in this work of 0.097 m$^3$ CH$_4$ kg$^{-1}$ VS added for PLAF was higher than the DIN 38414 test value, but the DIN 38414 test ran for only 28 days and gas production was continuing steadily at the end (Table 3). In the current work there appeared to be a slight increase in methane production from PLAF from day 50 onwards (Fig. 8d). On the basis of this, the BMP tests for CDF, SBF1, SBF2, PLAF and PLAB (at both I/S ratios) were left running until day 103.

2.4. Potentially toxic elements

Potentially Toxic Elements in the plastic samples were measured by NRM Ltd. The limiting factor for plastic addition can be determined by comparison with the permissible loadings under the UK’s PAS110 standard [3], in which application rates are based on the total nitrogen content of the digestate. The following simple assumptions were made to assess this. If a digester were fed on 100% plastic and achieved a 95% degradation rate, then only one material (PLAB) would exceed the standard for chromium and nickel, with five others (CBM, CBnHS, CDF, SBF2 and PLAF) slightly exceeding the cadmium standard. In practice however the concentration of plastic in a mixed feedstock is unlikely to exceed 2%, and degradation rates are generally below 95%. At the bioplastics loading required for compliance with the PAS110 physical contaminants specification, for example, the materials could not cause the

### Table 9

Data for final balance based on no. and weight of tokens and experimentally determined values for degradation constants.

|          | PP  | LDPE | CBM  | CBHS | CBHB | CbH5S | CDF  | SBF1 | SBF2 | PLAF | PLAB |
|----------|-----|------|------|------|------|--------|------|------|------|------|------|
| No. of tokens added | 8906 | 4293 | 7884 | 6278 | 3942 | 4380   | 3796 | 11096| 5548 | 6278 | 999  |
| Actual no. of tokens in digester at end | 3137 | 2256 | 565  | 918  | 1038 | 286    | 671  | 3638 | 1992 | 1327 | 320  |
| Actual no. of tokens removed in run | 5705 | 2043 | 1540 | 1826 | 1230 | 320    | 1261 | 7082 | 3337 | 1274 | 655  |
| Predicted total no. of tokens recovered $^a$ | 3034 | 1533 | 466  | 595  | 476  | 76     | 440  | 3174 | 1773 | 757  | 297  |
| Actual total no. of tokens recovered | 8842 | 4299 | 2104 | 2743 | 2268 | 606    | 1932 | 10720| 5329 | 2601 | 975  |
| Balance (no. at end + no. out - no. in) | $-64$ | 6    | $-5780$ | $-3535$ | $-1675$ | $-3774$ | $-1864$ | $-376$ | $-219$ | $-3678$ | $-24$ |
| No. of tokens destroyed | 0.7% | $-0.1\%$ | 73.3% | 56.3% | 42.5% | 86.2%  | 49.1% | 3.4% | 3.9% | 58.6% | 2.4% |
| Weight added (g) | 23.29 | 22.06 | 26.97 | 26.89 | 26.34 | 24.68  | 24.05 | 23.78 | 23.31 | 24.69 |
| Predicted weight in digester at end (g) $^a$ | 7.93 | 7.88 | 1.59  | 2.55  | 3.18  | 0.47   | 2.86  | 6.90  | 7.60  | 2.81  | 7.36 |
| Actual weight in digester at end (g) | 8.56 | 10.85 | 1.67  | 3.28  | 5.25  | 0.98   | 7.64  | 8.69  | 5.13  | 7.86  |
| Recovery at end | 107.9% | 137.7% | 104.7% | 128.5% | 164.9% | 206.1% | 119.0% | 110.8% | 114.3% | 182.6% | 106.8% |
| Predicted weight removed in run (g) $^a$ | 15.35 | 14.19 | 4.29  | 6.62  | 8.04  | 1.33   | 7.26  | 15.24 | 15.70 | 7.10  | 16.58 |
| Actual weight removed in run (g) | 15.51 | 11.38 | 4.22  | 5.90  | 5.97  | 0.82   | 6.71  | 14.50 | 14.60 | 4.78  | 16.08 |
| Recovery in run | 101.0% | 80.2%  | 98.3% | 89.1% | 74.3% | 62.0%  | 92.5% | 95.2% | 93.0% | 67.3% | 97.0% |
| Actual total weight recovered (g) $^a$ | 24.08 | 22.23 | 5.89  | 9.17  | 11.22 | 1.80   | 10.12 | 22.14 | 23.29 | 9.91  | 23.93 |
| Actual total weight recovered (%) $^a$ | 103% | 101% | 100%  | 100%  | 100%  | 100%   | 100%  | 100%  | 100%  | 100%  |
| Balance (end + out - in) (g) | 0.79 | 0.16 | $-21.09$ | $-17.72$ | $-15.12$ | $-25.52$ | $-14.57$ | $-1.91$ | $-0.49$ | $-13.40$ | $-0.76$ |
| Weight destroyed | $-3.4\%$ | $-0.7\%$ | 78.2% | 65.9% | 57.4% | 93.4%  | 59.0% | 7.9% | 2.1% | 57.5% | 3.1% |
| 1st order degradation $k$ | 0.00 | 0.00 | 0.10  | 0.06  | 0.04  | 0.39   | 0.04  | 0.00  | 0.04  | 0.00  |
| VS destruction potential $^c$ | 0.0% | 0.0% | 82.7% | 72.3% | 64.7% | 94.9%  | 66.2% | 12.4% | 2.9% | 64.8% | 6.2% |

$^a$ Based on 1st-order degradation coefficient.

$^b$ Actual total weight recovered = Actual weight in digester at end + Actual weight removed in run.

$^c$ Based on value from longer-term modelling with 1st-order degradation coefficient.
digestate to exceed the specified limit values for PTE. The determining factor for metals concentrations in the digestate will therefore be that in the food waste and card packaging components.

2.5. Methodology for residual biogas potential of digestate

In order to determine whether the mixed whole digestate from the trial in Ref. [1] was likely to meet the requirements of the PAS110 standard [3], one of the duplicate LDPE control reactors was sacrificed on day 126 and the digestate was tested for residual biogas production (RBP). The test was carried out in triplicate in static reactors with a sewage sludge inoculum according to the methodology used in OFW004-005 (2009) [5]. To provide additional information on the stability of the material, the methane content of the biogas was also measured to give a static batch test BMP value.

To determine kinetic constants, the specific methane production was modelled using two sets of assumptions: simple first-order degradation (Model 1), and a pseudo-parallel first-order model (Model 2). For model 1 the methane production is given by

\[ Y = Y_m (1 - e^{-kt}) \]  

(1)

Where:

- \( Y \) is the cumulative methane yield at time \( t \).
- \( Y_m \) is the ultimate methane yield.
- \( k \) is the first order rate constant.

Rao (2002) [6] suggests that for certain materials it may be better to consider that the gas production curve corresponds to the rapid breakdown of readily degradable components followed by a
much slower degradation of the remaining material. The methane production is therefore governed by two rate constants $k_1$ and $k_2$ rather than by a single constant:

$$Y = Y_m (1 - Pe^{-k_1 t} - (1-P) e^{-k_2 t})$$

(2)

Where:
- $Y$ is the cumulative methane yield at time $t$.
- $Y_m$ is the ultimate methane yield.
- $k_1$ is the first order rate constant for the proportion of readily degradable material.
- $k_2$ is the first order rate constant for the proportion of less readily degradable material.
- $P$ is the proportion of readily degradable material.

Model 1 gave only a moderately good fit to the data ($R^2 = 0.98$). A much better fit was obtained using model 2 ($R^2 = 0.998$), especially in the early stages of the digestion period. The data showed that while the material is depleted it still contains a more rapidly-degradable fraction, as expected for a fully-mixed system.

The estimated final BMP value of 0.085 m$^3$ CH$_4$ kg$^{-1}$ VS added was compared with limit value of 0.45 L biogas kg$^{-1}$ VS in the UK’s PAS110 [3] to confirm that digestate would meet the standard and be suitable for disposal. The 45-day residual methane production of 0.087 m$^3$ CH$_4$ kg$^{-1}$ VS from the CSTR trial was compared with the static BMP test and showed good agreement. The 45-day biogas yield of 0.137 m$^3$ kg$^{-1}$ VS reflects the absence of losses due to CO$_2$ dissolution using this method, compared to methods involving collection under a barrier solution.

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**Transparency document**

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**Fig. 11.** No. of plastic tokens recovered from digestate sample, predicted no. assuming no destruction, and predicted no. modelled using an empirical first-order decay coefficient for (a) PP, (b) LDPE1, (c) LDPE2, (d) SBF1, (e) PLAB, (f) CDF, (g) CBM, (h) CBHS, (i) CBHB, (j) CBnHS, (k) PLAF and (l) SBF2.