Data Article

Datasets on chemical composition and anaerobic digestion of organic fraction of municipal solid waste (OFMSW), digested sewage sludge (inoculum) and ashes from incineration or gasification

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\begin{abstract}
This article contains data on the chemical composition and anaerobic digestion of different residue streams including OFMSW, digested sewage sludge, low-carbon (LC) ashes from incineration subdivided into LC coarse and LC fly ash as well as high-carbon (HC) ashes from gasification subdivided into HC reactor and HC fly ash. All materials were collected in accordance to standard procedures in southern Germany. The data presented in this article include (1) dry matter (2) organic dry matter (3) elemental analysis (4) trace elements and (5) cumulative biogas and CH\textsubscript{4} yields. Researchers and waste management companies on lab-/pilot-/industrial-scale can rely on the presented data for classification and comparison of biogenic waste streams. For further discussion, please refer to the scientific article entitled “Optimizing anaerobic..."
\end{abstract}

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bic digestion of organic fraction of municipal solid waste (OFMSW) by using biomass ashes as additives" [1].

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### Specifications table

| Subject | Environmental Engineering |
| --- | --- |
| Specific subject area | Waste characterization, optimizing anaerobic digestion and potentials of biomass ashes, creation of synergies by combined utilization of residue streams |
| Type of data | Datasets for OFMSW, digested sewage sludge, low-carbon (LC) and high-carbon (HC) ashes were acquired using typical physico-chemical analyzers and instruments: Fresh mass (FM) and dry matter (DM) through oven drying (UNP 700, Memmert, Schwabach, Germany) Organic dry matter (oDM) through muffle furnace (AAF 1100, Carbolite, Neuhaueden, Germany) C, H, N through elemental analysis (vario MACRO cube, elementar, Langenselbold, Germany) Trace elements (TE) through inductively coupled plasma-optical emission spectroscopy (ICP-OES) (Spectro Blue, ASX-260 auto sampler, SPECTRO Analytical Instruments, Kleve, Germany) Biogas and CH₄ yields through batch-digesters (own construction, [1]) CH₄ concentrations were measured by a portable biogas monitor (BIOGAS 5000, Geotech, Coventry, UK) |
| How data were acquired | After collection in 2018/2019 and processing (drying, sorting, sieving, crushing), each sample was stored airtight as DM until further experiments were carried out (from February to June 2019). All analyzes were performed with 3–6 repetitions. All digestion experiments were conducted at 35 °C considering temperatures within the digesters and ambient conditions. Biogas and CH₄ yield data were expressed on standard conditions (1013 hPa, 0 °C, dry gas). Extensive waste characterization with the aim to create synergy effects in the treatment (combined treatment) of residue streams origin from different processes. The following data, inter alia, include: FM, DM, oDM and in total 37 elements (C, H, N, O, Al, Ag, As, B, Ba, Be, Bi, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, Pb, Sb, Se, Sr, Ti, Tl, V, Zn, Ga, In, Sn, P, S). Through batch tests in triplicate (series 1) and duplicate (series 2), the anaerobic digestion behavior and the impact of wood ashes in nine different configurations (mixing ratios) was measured. |
| Data format | Raw, processed (mean values) |
| Parameters for data collection | All materials were collected in the state of Baden-Württemberg (southern Germany) |
| Description of data collection | Data are available in this article |
| Data source location | Data are available in this article |
| Related research article | Sailer, G.; Eichermüller, J.; Poetsch, J.; Paczkowski, S.; Pelz, S.; Oechsner, H.; Müller, J., 2020. Optimizing anaerobic digestion of organic fraction of municipal solid waste (OFMSW) by using biomass ashes as additives, Waste Management 109 (2020), 136–148, doi: 10.1016/j.wasman.2020.04.047. |

### Value of the data

- This data article provides a large characterization of six highly relevant waste types (OFMSW, digested sewage sludge as well as wood ashes from incineration and gasification) and demonstrates the impact of wood ashes on the anaerobic digestion of OFMSW.
- This data will be useful for other researchers in the field of bio- and thermo-chemical biomass conversion (comparison, data basis). Managers of biogenic waste streams, biogas plant operators can rely on the data for optimization and identification of waste treatment concepts.
Table 1
Acronyms for each material and annotations.

| Material            | Annotation                                                                 | Acronym |
|---------------------|---------------------------------------------------------------------------|---------|
| OFMSW               | Separately collected; coarse impurities (stones, metals, plastics) were manually removed before further processing and analytics | OFMSW   |
| Sewage sludge(digested) | Used as inoculum for digestion experiments. Treatment of wastewater and storage of sewage sludge at a mesophilic temperature of 37 °C at the sewage plant | SEWS    |
| HC fly ash          | From a full-scale wood gasification plant (fixed bed, 150 kWel, 300 kWel) | HC-FA   |
| HC reactor ash      | From a full-scale wood gasification plant (fixed-bed, 150 kWel, 300 kWel) | HC-RA   |
| LC fly ash          | From a full-scale heating plant (50 MW, grate firing) using landscape management material and forest residues (50:50) | LC-FA   |
| LC coarse ash       | From a full-scale heating plant (50 MW, grate firing) using landscape management material and forest residues (50:50) | LC-CA   |

Table 2
Raw data and mean values for DM contents and total amount of FM in each material.

| Material | Annotation                              | FM[g] | DM[% FM] |
|----------|-----------------------------------------|-------|----------|
| OFMSW    | Mainly food waste                       | 1450  | 21.93    |
| OFMSW    | Mixture                                 | 1397  | 37.01    |
| OFMSW    | Mixture                                 | 2833  | 34.27    |
| OFMSW    | Mixture                                 | 1968  | 34.15    |
| OFMSW    | Mixture                                 | 2897  | 35.59    |
| **Weighted mean** |                                      | **10,545** | **33.28** |
| SEWS     | Digestion experiments, test series 1    | 43.13 | 3.96     |
| SEWS     | Digestion experiments, test series 1    | 49.30 | 3.99     |
| SEWS     | Digestion experiments, test series 1    | 47.03 | 3.98     |
| **Weighted mean** |                                      | **139.46** | **3.98** |
| SEWS     | Digestion experiments, test series 2    | 20.98 | 3.26     |
| SEWS     | Digestion experiments, test series 2    | 20.68 | 3.26     |
| SEWS     | Digestion experiments, test series 2    | 27.12 | 3.26     |
| **Weighted mean** |                                      | **68.78** | **3.26** |
| HC-FA    | Samples were provided as DM             | –     | –        |
| HC-RA    | Samples were provided as DM             | 285.47| 24.46    |
| LC-FA    | Samples were provided as DM             | –     | –        |
| LC-CA    | Samples were provided as DM             | –     | –        |

- Researchers and developers in the fields of treatment, recycling and disposal of bio-waste (lab-, pilot-, and industrial-scale) can rely on the presented data for classification and comparison of data and replication/variation of the conducted experiments.
- In general, data on the characteristics and bio-chemical treatment of German OFMSW and ashes from wood gasification processes are lacking. Datasets are relevant for the determination of practical application and synergy possibilities of OFMSW, sewage sludge and biomass ashes.

1. Data description

This Data in Brief article provides the raw data for chemical composition and anaerobic digestion of OFMSW together with digested sewage sludge and low-carbon (LC) ashes from incineration as well as high-carbon (HC) ashes from gasification. All data are presented within this article.

Table 1 defines acronyms and additional information for all materials. Tables 2 and 3 present all raw data and weighted mean values for fresh mass (FM) [g], dry matter (DM) [% FM] and organic dry matter (oDM) [% DM] contents. Table 4 shows measured raw data and mean values for C, H and N [% DM]. Based on C, H and N, stoichiometric biogas and CH₄ yields can be cal-
Table 3
Raw data and mean values for oDM contents in each material.

| Material | Annotation                          | oDM[\% DM] |
|----------|-------------------------------------|-------------|
| OFMSW    |                                     | 75.89       |
| OFMSW    |                                     | 76.83       |
| OFMSW    |                                     | 78.70       |
| OFMSW    |                                     | 79.77       |
| OFMSW    |                                     | 78.21       |
| **Mean** |                                     | **77.88**   |
| SEWS     | Digestion experiments, test series 1| 64.23       |
| SEWS     | Digestion experiments, test series 1| 64.02       |
| SEWS     | Digestion experiments, test series 1| 64.03       |
| **Mean** |                                     | **64.09**   |
| SEWS     | Digestion experiments, test series 2| 63.13       |
| SEWS     | Digestion experiments, test series 2| 63.00       |
| SEWS     | Digestion experiments, test series 2| 63.03       |
| **Mean** |                                     | **63.07**   |
| HC-FA    |                                     | 73.60       |
| HC-FA    |                                     | 73.30       |
| HC-FA    |                                     | 73.65       |
| **Mean** |                                     | **73.51**   |
| HC-RA    |                                     | 75.85       |
| HC-RA    |                                     | 77.50       |
| HC-RA    | Measured value (52.72) defined as outlier and discarded | – |
| **Mean** |                                     | **76.68**   |
| LC-FA    |                                     | 0.03        |
| LC-FA    |                                     | 0.05        |
| LC-FA    | Measured value (−0.07) not plausible and discarded | – |
| **Mean** |                                     | **0.04**    |
| LC-CA    |                                     | 0.91        |
| LC-CA    |                                     | 0.89        |
| LC-CA    |                                     | 0.71        |
| **Mean** |                                     | **0.84**    |

Calculated according to [2, 3]. Values for S can be obtained by using the data from the inductively coupled plasma-optical emission spectroscopy (ICP-OES, Table 8). O [\% DM] is defined as 100% subtracted by the contents [% DM] of C, H, N, S and ash. By including oDM data of Table 3, O can be calculated. Single and mean values for 33 trace elements (TE) (Al, Ag, As, B, Ba, Be, Bi, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, Pb, Sb, Se, Sr, Ti, Tl, V, Zn, Ga, In, Si, P, S) measured by ICP-OES are presented in Table 5-8.

Table 9–11 present data for the first digestion experiment subdivided into the experimental set-up (Table 9), measured CH₄ concentrations (Table 10) and cumulative gas yields for each time step and digester (Table 11). Table 12–15 show data for the second digestion experiment subdivided into the experimental set-up (Table 12), measured CH₄ concentrations (Table 13) and cumulative gas yields for each time step and digester (Tables 14 and 15).

2. Experimental design, materials and methods

Detailed descriptions for all experiments can be found in the original research paper [1].

2.1. Sampling

OFMSW (untreated) was collected at a full-scale thermophilic plug-flow biowaste fermentation plant in southern Germany according to standard procedures defined in the German biowaste ordinance [4] Digested sewage sludge as residue after anaerobic digestion of wastewater (used as inoculum for digestion experiments) was collected at the local municipal sewage
Table 4

Raw data and mean values for C, H and N in all materials. For determination of stoichiometric CH₄ yields, S can be calculated by using data from ICP-OES (Table 8). O is defined as 100% DM - X C, H, N, S, Ash (% DM). SEWS represented a composite sample of SEWS (test series 1) and SEWS (test series 2).

| Material  | C[\% DM] | H[\% DM] | N[\% DM] |
|-----------|----------|----------|----------|
| OFMSW     | 42.17    | 5.64     | 2.21     |
| OFMSW     | 40.58    | 5.46     | 2.59     |
| OFMSW     | 35.32    | 4.72     | 1.71     |
| OFMSW     | 39.90    | 5.34     | 2.00     |
| Mean      | 39.49    | 5.29     | 2.13     |
| SEWS      | 29.83    | 4.36     | 4.02     |
| SEWS      | 29.60    | 4.40     | 3.37     |
| SEWS      | 29.84    | 4.43     | 3.74     |
| SEWS      | 29.45    | 4.40     | 3.81     |
| Mean      | 29.68    | 4.40     | 3.83     |
| HC-FA     | 68.90    | 0.75     | 1.16     |
| HC-FA     | 70.68    | 0.77     | 0.74     |
| HC-FA     | 70.12    | 0.77     | 0.32     |
| HC-FA     | 68.78    | 0.75     | 0.51     |
| Mean      | 69.62    | 0.76     | 0.68     |
| HC-RA     | 73.71    | 0.72     | 0.62     |
| HC-RA     | 73.47    | 0.76     | 0.65     |
| HC-RA     | 73.56    | 0.77     | 0.55     |
| HC-RA     | 73.29    | 0.76     | 0.60     |
| Mean      | 73.51    | 0.75     | 0.61     |
| LC-FA     | 2.76     | 0.23     | 0.14     |
| LC-FA     | 2.22     | 0.24     | 0.16     |
| LC-FA     | 1.87     | 0.22     | 0.15     |
| LC-FA     | 2.54     | 0.23     | 0.10     |
| Mean      | 2.35     | 0.23     | 0.14     |
| LC-CA     | 1.32     | 0.29     | 0.11     |
| LC-CA     | 1.26     | 0.40     | 0.18     |
| LC-CA     | 1.13     | 3.23 (discarded) | 0.18     |
| LC-CA     | 1.15     | 0.23     | 0.74 (discarded) | 0.16 |
| Mean      | 1.22     | 0.31     | 0.16     |

Treatment plant (Rottenburg-Kiebingen, Germany) following [5]. LC coarse and LC fly ash from a 50 MW heating plant in southern Germany with a grate fired furnace using a fuel mixture of 50:50 landscape management material and forest residues was provided within another project [6]. HC reactor (minor quantities) and fly ash (major proportion) from a full-scale fixed-bed wood gasifier (Konstanz-Mainau, Germany) fueled with untreated natural wood chips were provided by the plant operator (sampling according to standard procedures). Only HC fly ash was used for digestion experiments because this fraction showed a higher relevance from a disposal perspective. However, both ashes were characterized in order to gain insights in special wood ashes and to compare their TE profiles with OFMSW and sewage sludge. An overview of all materials is provided in Table 1.

2.2. DM, processing and oDM

DM (Table 2) was determined through drying at 105 °C in a drying oven for at least 24 h [7]. The fresh OFMSW sample was manually sorted into fractions to determine the DM content for food waste separately. Before further processing, impurities were removed and the remaining DM was re-combined as well as milled to particle sizes of approximately 1 mm with a cutting mill. The dry sewage sludge was manually crushed in a ceramic mortar (no prior sorting was required). From the dry LC coarse ash, impurities (metals) were removed by manual sorting and sieving with mesh sizes of 16 mm, 8 mm and 3.15 mm. The remaining DM was ground to a particle size of 1 mm by a jaw crusher followed by an orbital mono mill. The dry HC reactor ash...
Table 5
Raw data and mean values for TE measured by ICP-OES. Values marked with * were at detection limit. All values relate to mg/kg DM.

| Material | Al  | Ag  | As  | B   | Ba  | Be  | Bi  | Ca  | Cd  |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| OFMSW    | 6084.76 | 0.21 | 2.39 | 2.12* | 88.40 | 0.02* | 0.66 | 28,270.76 | discarded |
| OFMSW    | 7345.80 | 0.02* | 2.32 | 2.13* | 86.59 | 0.02* | 1.20 | 43,638.44 | 0.41 |
| OFMSW    | 6247.57 | 0.14 | 4.79 | 2.17* | 88.11 | 0.02* | 0.02* | 25,320.14 | 0.20 |
| OFMSW    | 5546.85 | 0.32 | 1.86 | 2.00* | 74.20 | 0.02* | 0.02* | 21,512.88 | 0.15 |
| Mean     | 6306.25 | 0.17 | 2.84 | 2.11 | 84.32 | 0.02* | 0.47 | 29,685.55 | 0.25 |
| SEWS     | 19,789.67 | 1.01 | 4.17 | 2.14* | 6277.2 | 0.02* | 3.54 | 47,342.26 | 1.45 |
| SEWS     | 20,125.29 | 0.98 | 4.17 | 2.19* | 654.66 | 0.02* | 3.66 | 49,099.45 | 1.49 |
| SEWS     | 19,310.18 | 1.22 | 4.20 | 2.21* | 621.15 | 0.02* | 2.90 | 47,217.84 | 1.38 |
| SEWS     | 18,884.97 | 1.10 | 4.18 | 2.16* | 612.33 | 0.02* | 3.20 | 46,743.74 | 1.33 |
| Mean     | 19,527.53 | 1.08 | 4.18 | 2.18 | 628.97 | 0.02* | 3.32 | 47,600.82 | 1.41 |
| HC-FA    | 697.63 | 1.66 | 0.06* | 6.63* | 633.73 | 0.06* | 0.06* | 103,964.50 | 2.90 |
| HC-FA    | 649.94 | 2.39 | 0.06* | 6.85* | 624.24 | 0.06* | 0.06* | 101,162.79 | 2.63 |
| HC-FA    | 648.65 | 2.96 | 0.06* | 7.21* | 597.88 | 0.06* | 0.06* | 98,455.60 | 2.32 |
| HC-FA    | 499.20 | 1.70 | 0.05* | 5.59* | 482.97 | 0.05* | 0.05* | 76,773.23 | 1.80 |
| Mean     | 623.86 | 2.18 | 0.06 | 5.67 | 584.70 | 0.06* | 0.06* | 95,089.03 | 2.41 |
| HC-RA    | 434.32 | 1.36 | 0.04* | 5.00* | 289.90 | 0.04* | 0.04* | 60,277.03 | 0.04* |
| HC-RA    | 1156.13 | 2.17 | 0.12* | 13.90* | 771.71 | 0.12* | 0.12* | 159,925.56 | 0.12* |
| HC-RA    | 567.03 | 0.14 | 0.06* | 6.47* | 378.00 | 0.06* | 0.06* | 76,501.15 | 0.06* |
| HC-RA    | 476.91 | 0.05* | 0.05* | 5.93* | 346.72 | 0.05* | 0.05* | 103,125.00 | 0.05* |
| Mean     | 657.47 | 0.93 | 0.07 | 7.82 | 446.58 | 0.07 | 0.07 | 99,957.19 | 0.07 |
| LC-FA    | 24,309.57 | 0.03* | 25.05 | 269.97 | 167.49 | 0.03* | 0.03* | 237,062.71 | 8.48 |
| LC-FA    | 25,144.84 | 0.03* | 25.10 | 272.78 | 150.66 | 0.03* | 0.03* | 231,580.69 | 8.86 |
| LC-FA    | 24,971.34 | 0.03* | 23.65 | 260.11 | 145.82 | 0.03* | 0.03* | 218,610.01 | 8.14 |
| LC-FA    | 25,322.28 | 0.03* | 21.32 | 276.43 | 191.11 | 0.03* | 0.03* | 186,472.15 | 7.76 |
| LC-FA    | 25,943.27 | 0.03* | 22.33 | 278.56 | 193.68 | 0.03* | 0.03* | 194,854.88 | 8.64 |
| LC-FA    | 26,290.62 | 0.03* | 20.77 | 266.02 | 191.43 | 0.03* | 0.03* | 186,690.89 | 7.79 |
| Mean     | 25,330.32 | 0.03 | 23.04 | 270.64 | 1725.03 | 0.03 | 0.03 | 209,211.89 | 8.28 |
| LC-CA    | 24,186.22 | 0.03* | 6.06 | 93.90 | 732.70 | 0.03* | 0.03* | 140,936.06 | 0.10 |
| LC-CA    | 24,115.81 | 0.03* | 6.30 | 85.70 | 695.54 | 0.03* | 0.03* | 143,766.40 | 0.10 |
| LC-CA    | 23,873.10 | 0.03* | 6.69 | 83.32 | 711.93 | 0.03* | 0.03* | 145,748.19 | 0.10 |
| LC-CA    | 24,370.87 | 0.03* | 6.44 | 72.32 | 866.25 | 0.03* | 0.03* | 171,796.57 | 0.07 |
| LC-CA    | 24,219.55 | 0.03* | 6.95 | 75.44 | 843.98 | 0.03* | 0.03* | 162,442.40 | 0.10 |
| LC-CA    | 24,871.74 | 0.03* | discarded | 75.88 | 784.27 | 0.03* | 0.03* | 160,509.14 | 0.07 |
| Mean     | 24,272.88 | 0.03 | 6.49 | 81.10 | 772.44 | 0.03 | 0.03 | 154,199.79 | 0.09 |

was milled by an orbital mono mill to particle size of 1 mm without prior sorting. The particle sizes of HC and LC fly ashes already were below 1 mm. Therefore, no further treatment was necessary. oDM (Table 3) was determined by using approximately 1 g of DM in a ceramic crucible by a muffle furnace [8].

2.3. C, H, N, S, O

Elemental analysis (C, H, N) was carried out [9] for all materials containing oDM (sewage sludge, OFMSW and HC ashes; Table 4). Approximately 40 mg per sample were pressed into a zinc foil coated tablet. S was not measured simultaneously in favor of the measurement accuracy of C, H and N (S was measured via ICP-OES). The measured values for C, H, N, S and ash were used to determine O contents.

2.4. TE

TE (Tables 5, 6, 7, 8) were measured via ICP-OES [10] after digestion in aqua regia. Therefore, 300 mg DM per sample were transferred into 50 mL Teflon vessels and combined with 1 mL H₂O₂. Before microwave digestion at 190°C, 3 mL HNO₃ (69%) and 9 mL HCl (35%) were
added. The digested residues were aliquotted to 50 mL with aqua bidest and measured at the ICP-OES system. Solid residues (Si) were separated by a centrifuge before the spectroscopy and their weight was deducted from the sample weight. Therefore, values for Si only represented a partial amount of the total amount (not completely digestible in aqua regia). When evaluating ICP-OES data, all values below the detection limit were equated with this limit. Hence, some of those values might be slightly overestimated as the actual values could be even lower than the detection limit (0 < value < detection limit).

### 2.5. Digestion experiments

The volumetric biogas production was measured using glass manometers whenever the manometer functioning as 1 L gas storage was nearly full, considering the temperature within the digester (2-L insulated glass vessel) and ambient conditions. After several days, the CH₄ concentration was analyzed with a portable biogas analyzer. Specific biogas and CH₄ productions were related to oDM and calculated for standard conditions (1013 hPa, 0 °C, dry gas). Experiments were conducted in two batch test series for 40 days (series 1) and 42 days (series 2).
Table 7

Raw data and mean values for TE measured by ICP-OES. Values marked with * were at detection limit. All values relate to mg/kg DM.

| Material  | Na     | Ni  | Pb     | Sb     | Se     | Sr     | Ti     | TI     | V     |
|-----------|--------|-----|--------|--------|--------|--------|--------|--------|-------|
| OFMSW     | 5450.51| 4.74| 71.58  | 0.02*  | 0.02*  | 59.97  | 269.59 | 3.43   | 10.41 |
| OFMSW     | 5290.73| 5.22| 31.62  | 0.02*  | 0.02*  | 70.66  | 240.18 | 0.13   | 12.36 |
| OFMSW     | 5292.78| 6.03| 40.05  | 0.02*  | 0.02*  | 53.92  | 224.84 | 0.02*  | 10.21 |
| OFMSW     | 5231.04| 6.01| 30.13  | 0.02*  | 0.02*  | 47.84  | 228.86 | 0.02*  | 9.66  |
| Mean      | 5316.27| 5.50| 43.34  | 0.02   | 0.02   | 58.10  | 240.87 | 0.90   | 10.66 |
| SEWS      | 6905.54| 20.15|31.76  | 4.26   | 0.02*  | 388.72 | 296.26 | 0.02*  | 54.55 |
| SEWS      | 7396.05| 20.91|34.55  | 4.27   | 0.02*  | 403.48 | 275.34 | 0.02*  | 56.38 |
| SEWS      | 8069.46| 22.20|30.78  | 4.34   | 0.02*  | 383.98 | 299.81 | 0.02*  | 53.69 |
| SEWS      | 7476.69| 22.06|27.80  | 4.12   | 0.02*  | 377.65 | 275.62 | 0.02*  | 52.10 |
| Mean      | 7461.93| 21.33|31.22  | 4.25   | 0.02   | 388.46 | 286.76 | 0.02   | 54.18 |
| HC-FA     | 1660.36| 315.15|9.35   | 0.06*  | 1.07   | 557.87 | 55.98  | 3.08   | 0.65  |
| HC-FA     | 1525.70| 113.65|9.98   | 0.06*  | 0.73   | 548.78 | 59.00  | 1.59   | 0.37  |
| HC-FA     | 1704.63| 225.55|9.01   | 0.06*  | 0.45   | 536.36 | 49.55  | 1.48   | 0.71  |
| HC-FA     | 1292.71| 91.31 |6.49   | 0.05*  | 0.05*  | 417.53 | 49.20  | 1.45   | 1.55  |
| Mean      | 1545.85| 186.41|8.71   | 0.06   | 0.57   | 515.13 | 53.43  | 1.90   | 0.82  |
| HC-RA     | 1424.04| 40.97 |1.34   | 0.04*  | 0.04*  | 285.21 | 36.71  | 0.27   | 1.14  |
| HC-RA     | 4093.05| 147.77|1.61   | 0.12*  | 0.12*  | 750.50 | 92.37  | 1.74   | 0.31  |
| HC-RA     | 1750.00| 70.09 |0.98   | 0.06*  | 0.06*  | 358.14 | 42.70  | 1.10   | 1.65  |
| HC-RA     | 1800.32| 69.07 |1.69   | 0.05*  | 0.42   | 349.36 | 38.10  | 1.43   | 3.84  |
| Mean      | 2266.85| 81.98| 1.41   | 0.07   | 0.16   | 435.80 | 46.39  | 1.13   | 1.73  |
| LC-FA     | 3674.92| 35.18 |417.82 | 16.47  | 0.03*  | 429.70 | 253.10 | 0.03*  | 55.41 |
| LC-FA     | 3721.56| 34.42 |426.59 | 16.40  | 0.03*  | 423.28 | 255.86 | 0.03*  | 55.32 |
| LC-FA     | 3609.35| 33.00 |400.86 | 15.91  | 0.03*  | 404.81 | 251.12 | 0.03*  | 55.40 |
| LC-FA     | 4167.77| 36.51 |426.72 | 18.60  | 0.03*  | 364.06 | 322.12 | 0.03*  | 57.86 |
| LC-FA     | 4058.38| 44.95 |464.05 | 20.65  | 0.03*  | 376.32 | 303.00 | 0.03*  | 55.44 |
| LC-FA     | 4153.90| 35.01 |420.41 | 19.02  | 0.03*  | 371.53 | 328.70 | 0.03*  | 57.23 |
| Mean      | 3897.65| 36.51 |426.07 | 17.84  | 0.03   | 394.95 | 285.33 | 0.03   | 56.11 |
| LC-CA     | 2846.41| 38.07 |35.33  | 1.12   | 0.03*  | 247.17 | 2302.57 |0.03   | 41.89 |
| LC-CA     | 2788.39| 40.16 |33.43  | 0.66   | 0.03*  | 254.59 | 2355.97 |0.03   | 42.09 |
| LC-CA     | 2816.41| 28.71 |27.29  | 0.76   | 0.03*  | 259.89 | 2451.88 |0.03   | 43.34 |
| LC-CA     | 2905.88| 28.17 |discarded | 3.43   | 0.03*  | 295.64 | 2288.97 |0.03   | 42.47 |
| LC-CA     | 2929.23| 23.77 |42.23  | 0.86   | 0.03*  | 302.86 | 2354.84 |0.03   | 43.98 |
| LC-CA     | 2888.05| 27.64 |58.58  | 2.06   | 0.03*  | 303.95 | 2393.28 |0.03   | 43.28 |
| Mean      | 2862.40| 31.09 |39.37  | 1.48   | 0.03   | 277.35 | 2357.92 |0.03   | 42.84 |

in triplicate and duplicate, respectively (set-ups visible in Table 9 and Table 12). All tests were carried out according to [5].

In series 1, the influence of LC coarse and LC fly ashes on the anaerobic digestion process was determined (Table 11). In series 2, multiple configurations of OFMSW as a baseline feedstock mixed with LC and HC ashes at different ratios were tested (Table 14 and Table 15). Based on the data of series 1, LC coarse ash was used instead of LC fly ash. The remaining oDM content of HC ashes was neglected in calculations as it is considered to be not available for microorganisms. For both series, blind variants were carried out, determining the residual biogas potential of the digested sewage sludge/inoculum.
### Table 8
Raw data and mean values for TE measured by ICP-OES. Values marked with * were at detection limit. All values relate to mg/kg DM.

| Material    | Zn    | Ga    | In    | Si    | P     | S     |
|-------------|-------|-------|-------|-------|-------|-------|
| OFMSW       | 96.07 | 12.40 | 13.31 | 5870.12 | 3350.59 | 2237.54 |
| OFMSW       | 88.10 | 11.72 | 13.03 | 7395.75 | 7129.32 | 2006.61 |
| OFMSW       | 98.57 | 10.34 | 10.50 | 5553.36 | 3145.71 | 2157.90 |
| OFMSW       | 85.74 | 8.74  | 5.60* | 6007.33 | 2792.38 | 2040.56 |
| **Mean**    | **92.12** | **10.80** | **10.61** | **6206.64** | **4104.50** | **2110.65** |
| SEWS        | 1297.14 | 29.46 | 5.98* | 6353.54 | 35411.09 | 12630.98 |
| SEWS        | 1338.11 | 29.29 | 6.13* | 5922.67 | 37039.94 | 13091.43 |
| SEWS        | 1273.69 | 30.51 | 6.18* | 6265.19 | 36345.70 | 12613.85 |
| SEWS        | 1247.60 | 30.67 | 6.03* | 6855.68 | 35414.26 | 12676.11 |
| **Mean**    | **1289.13** | **29.98** | **6.08** | **6349.27** | **36052.75** | **12753.09** |
| HC-FA       | 1241.42 | 15.92* | 124.67 | 2052.66 | 4837.87 | 866.12 |
| HC-FA       | 623.01 | 16.46* | 118.18 | 1917.38 | 4523.87 | 740.36 |
| HC-FA       | 953.67 | 17.44 | 115.77 | 1945.30 | 4348.78 | 842.82 |
| HC-FA       | 566.93 | 13.44* | 101.85 | 1410.09 | 3419.58 | 592.78 |
| **Mean**    | **846.26** | **15.81** | **115.12** | **1832.36** | **4282.52** | **760.52** |
| HC-RA       | 154.29 | 12.02* | 46.29 | 1571.49 | 2896.85 | 643.16 |
| HC-RA       | 486.48 | 33.37* | 125.68 | 4510.12 | 7745.66 | 1816.87 |
| HC-RA       | 157.97 | 15.53* | 60.22 | 2028.29 | 3827.37 | 872.06 |
| HC-RA       | 230.93 | 14.25* | 8.05* | discarded | 4308.79 | 1182.94 |
| **Mean**    | **257.42** | **18.79** | **60.06** | **1941.03** | **4687.17** | **1128.76** |
| LC-FA       | 1908.58 | n.a. | n.a. | n.a. | n.a. | n.a. |
| LC-FA       | 1927.25 | n.a. | n.a. | n.a. | n.a. | n.a. |
| LC-FA       | 1781.62 | n.a. | n.a. | n.a. | n.a. | n.a. |
| LC-FA       | 1910.48 | n.a. | n.a. | n.a. | n.a. | n.a. |
| LC-FA       | 2156.99 | n.a. | n.a. | n.a. | n.a. | n.a. |
| LC-FA       | 1968.30 | n.a. | n.a. | n.a. | n.a. | n.a. |
| **Mean**    | **1942.20** | **n.a.** | **n.a.** | **n.a.** | **n.a.** | **n.a.** |
| LC-CA       | 291.53 | n.a. | n.a. | n.a. | n.a. | n.a. |
| LC-CA       | 305.28 | n.a. | n.a. | n.a. | n.a. | n.a. |
| LC-CA       | 270.44 | n.a. | n.a. | n.a. | n.a. | n.a. |
| LC-CA       | 450.46 | n.a. | n.a. | n.a. | n.a. | n.a. |
| LC-CA       | 343.65 | n.a. | n.a. | n.a. | n.a. | n.a. |
| LC-CA       | 317.20 | n.a. | n.a. | n.a. | n.a. | n.a. |
| **Mean**    | **329.76** | **n.a.** | **n.a.** | **n.a.** | **n.a.** | **n.a.** |

### Table 9
Experimental set-up in test series 1 (operating temperature 35°C, reactors stirred 60 s/h). oDM delivered by LC-CA and LC-FA (Table 3) was neglected.

| Digester     | Variant            | Inoculum  | Additional feedstock [g DM] | Retention time [d] | Total DM<sub>Digester</sub> [g] | oDM<sub>Digester</sub> [g] |
|--------------|--------------------|-----------|----------------------------|--------------------|--------------------------------|----------------------------|
| 1            | SEWS (blank)       | 2 L SEWS  | –                          | 40                 | 79.56 + 0                     | 50.99 + 0                   |
| 2            | SEWS (blank)       | 2 L SEWS  | –                          | 40                 | 79.56 + 0                     | 50.99 + 0                   |
| 3            | SEWS (blank)       | 2 L SEWS  | –                          | 40                 | 79.56 + 0                     | 50.99 + 0                   |
| 4            | SEWS + LC-CA       | 2 L SEWS  | 16.72 (LC-CA)             | 40                 | 79.56 + 16.72                 | 50.99 + 0                   |
| 5            | SEWS + LC-CA       | 2 L SEWS  | 15.12 (LC-CA)             | 40                 | 79.56 + 15.12                 | 50.99 + 0                   |
| 6            | SEWS + LC-CA       | 2 L SEWS  | 16.43 (LC-CA)             | 40                 | 79.56 + 16.43                 | 50.99 + 0                   |
| 7            | SEWS + LC-FA       | 2 L SEWS  | 14.04 (LC-FA)             | 40                 | 79.56 + 14.04                 | 50.99 + 0                   |
| 8            | SEWS + LC-FA       | 2 L SEWS  | 13.93 (LC-FA)             | 40                 | 79.56 + 13.93                 | 50.99 + 0                   |
| 9            | SEWS + LC-FA       | 2 L SEWS  | 14.59 (LC-FA)             | 40                 | 79.56 + 14.59                 | 50.99 + 0                   |

### Table 10
Measured CH₄ concentrations [%] and weighted mean values for each digester (D1-D9) in test series 1.

| Time [d] | D-1 CH₄ | D-2 CH₄ | D-3 CH₄ | D-4 CH₄ | D-5 CH₄ | D-6 CH₄ | D-7 CH₄ | D-8 CH₄ | D-9 CH₄ |
|----------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| 0        | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       |
| 6.10     | 64.83   | 65.37   | 64.76   | 65.85   | 65.62   | 65.06   | 71.92   | 71.87   | 72.08   |
| 39.86    | 67.94   | 68.00   | 67.96   | 68.09   | 68.27   | 69.65   | 70.61   | 72.26   | 73.29   |
| **Weighted mean** | **66.04** | **66.37** | **65.89** | **66.66** | **66.63** | **66.54** | **71.42** | **72.02** | **72.60** |
### Table 11

Biogas (Bg) and CH4 yields (cumulative value) for each time-step and digester (D1-D9) in test series 1. All values related to mL/g oDM for standard conditions (1013 hPa, 0 °C, dry gas).

| Time [d] | D-1 Bg | D-2 Bg | D-3 Bg | D-4 Bg | D-5 Bg | D-6 Bg | D-7 Bg | D-8 Bg | D-9 Bg |
|----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 0        | 0      | 0      | 0      | 0      | 0      | 0      | 0      | 0      | 0      |
| 0.11     | 3      | 2      | 4      | 2      | 3      | 2      | 4      | 3      | 2      |
| 0.22     | 5      | 3      | 5      | 3      | 5      | 3      | 4      | 3      | 4      |
| 0.74     | 21     | 14     | 21     | 14     | 21     | 14     | 21     | 14     | 21     |
| 1.03     | 27     | 17     | 27     | 17     | 27     | 17     | 27     | 17     | 27     |
| 1.29     | 32     | 20     | 32     | 20     | 32     | 20     | 32     | 20     | 32     |
| 1.77     | 43     | 28     | 43     | 28     | 43     | 28     | 43     | 28     | 43     |
| 2.11     | 50     | 33     | 50     | 33     | 50     | 33     | 50     | 33     | 50     |
| 2.80     | 61     | 40     | 61     | 40     | 61     | 40     | 61     | 40     | 61     |
| 3.00     | 65     | 42     | 65     | 42     | 65     | 42     | 65     | 42     | 65     |
| 3.93     | 74     | 48     | 74     | 48     | 74     | 48     | 74     | 48     | 74     |
| 4.97     | 82     | 53     | 82     | 53     | 82     | 53     | 82     | 53     | 82     |
| 6.10     | 90     | 59     | 90     | 59     | 90     | 59     | 90     | 59     | 90     |
| 7.01     | 94     | 61     | 94     | 61     | 94     | 61     | 94     | 61     | 94     |
| 7.88     | 98     | 64     | 98     | 64     | 98     | 64     | 98     | 64     | 98     |
| 8.84     | 101    | 66     | 101    | 66     | 101    | 66     | 101    | 66     | 101    |
| 10.23    | 106    | 69     | 106    | 69     | 106    | 69     | 106    | 69     | 106    |
| 11.19    | 109    | 71     | 109    | 71     | 109    | 71     | 109    | 71     | 109    |
| 12.08    | 111    | 73     | 111    | 73     | 111    | 73     | 111    | 73     | 111    |
| 13.07    | 115    | 75     | 115    | 75     | 115    | 75     | 115    | 75     | 115    |
| 14.08    | 117    | 77     | 117    | 77     | 117    | 77     | 117    | 77     | 117    |
| 15.86    | 120    | 79     | 120    | 79     | 120    | 79     | 120    | 79     | 120    |
| 17.95    | 125    | 82     | 125    | 82     | 125    | 82     | 125    | 82     | 125    |
| 20.94    | 128    | 84     | 128    | 84     | 128    | 84     | 128    | 84     | 128    |
| 26.96    | 136    | 90     | 136    | 90     | 136    | 90     | 136    | 90     | 136    |
| 34.98    | 144    | 95     | 144    | 95     | 144    | 95     | 144    | 95     | 144    |
| 39.86    | 148    | 98     | 148    | 98     | 148    | 98     | 148    | 98     | 148    |

### Table 12

Experimental set-up in test series 2 (operating temperature 35 °C, reactors stirred 60 s/h). oDM contents delivered by ashes (Table 3) were neglected as they were either negligible (LC) or "not available for microorganisms" (HC).

| Digestor | Variant | Inoculum | Additional feedstock [g DM] | Retention time [d] | Total DM<sub>Digester</sub> [g] | Total oDM<sub>Digester</sub> [g] |
|----------|---------|----------|-----------------------------|-------------------|---------------------------------|---------------------------------|
| 1        | SEWS    | 1 L SEWS | –                           | 42                | 32.60 + 0                       | 20.56 + 0                       |
| 2        | SEWS    | 1 L SEWS | + 1 L tap water             | 42                | 32.60 + 0                       | 20.56 + 0                       |
| 3        | SEWS + OFMSW | 1 L SEWS | + 1 L tap water             | 42                | 32.60 + 0.92                    | 20.56 + 7.66                    |
| 4        | SEWS + OFMSW | 1 L SEWS | + 1 L tap water             | 42                | 32.60 + 9.50                    | 20.56 + 7.41                    |
| 5        | SEWS + OFMSW | 1 L SEWS | + LC-CA (1:1) + 1 L tap water | 42            | 32.60 + 9.59 + 9.87             | 20.56 + 7.48 + 0               |
| 6        | SEWS + OFMSW | 1 L SEWS | + LC-CA (1:1) + 1 L tap water | 42            | 32.60 + 8.96 + 9.94             | 20.56 + 6.99 + 0               |
| 7        | SEWS + OFMSW | 1 L SEWS | + LC-CA (1:1) + 1 L tap water | 42            | 32.60 + 9.54 + 32.13            | 20.56 + 7.44 + 0               |
| 8        | SEWS + OFMSW | 1 L SEWS | + LC-CA (1:3) + 1 L tap water | 42            | 32.60 + 9.86 + 32.57            | 20.56 + 7.69 + 0               |
| 9        | SEWS + OFMSW | 1 L SEWS | + LC-CA (1:3) + 1 L tap water | 42            | 32.60 + 9.70 + 92.05            | 20.56 + 7.56 + 0               |
| 10       | SEWS + OFMSW | 1 L SEWS | + LC-CA (1:10) + 1 L tap water | 42           | 32.60 + 8.69 + 90.19            | 20.56 + 6.78 + 0              |
| 11       | SEWS + OFMSW | 1 L SEWS | + LC-CA (1:10) + 1 L tap water | 42           | 32.60 + 8.77 + 9.11             | 20.56 + 6.84 + 0              |
| 12       | SEWS + OFMSW | 1 L SEWS | + LC-CA (1:1) + 1 L tap water | 42            | 32.60 + 9.04 + 8.97            | 20.56 + 7.05 + 0              |
Table 13
Measured CH₄ concentrations [%] and weighted mean values for each digester (D1-D12) in test series 2.

| Time [d] | D-1 CH₄ | D-2 CH₄ | D-3 CH₄ | D-4 CH₄ | D-5 CH₄ | D-6 CH₄ | D-7 CH₄ | D-8 CH₄ | D-9 CH₄ | D-10 CH₄ | D-11 CH₄ | D-12 CH₄ |
|----------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| 0        | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       |
| 26.97    | 71.94   | 72.66   | 64.57   | 64.74   | 68.61   | 68.61   | 75.80   | 78.98   | 96.57   | -       | 71.22   | 71.66   |
| 41.95    | 74.19   | 74.88   | 71.55   | 68.23   | 72.82   | 72.82   | 75.09   | 76.19   | 97.02   | 98.51   | 69.29   | 71.01   |
| Weighted mean | 72.25   | 72.98   | 65.08   | 65.03   | 68.98   | 68.98   | 75.75   | 78.72   | 96.71   | 98.51   | 70.96   | 71.57   |

Table 14
Biogas (Bg) and CH₄ yields (cumulative value) for each time-step and digester (D1-D8) in test series 2. All values related to mL/g oDM for standard conditions (1013 hPa, 0°C, dry gas).

| Time [d] | D-1 Bg CH₄ | D-2 Bg CH₄ | D-3 Bg CH₄ | D-4 Bg CH₄ | D-5 Bg CH₄ | D-6 Bg CH₄ | D-7 Bg CH₄ | D-8 Bg CH₄ |
|----------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| 0        | 0           | 0           | 0           | 0           | 0           | 0           | 0           | 0           |
| 0.33      | 5           | 3           | 5           | 4           | 7           | 4           | 8           | 5           |
| 0.90      | 14          | 10          | 14          | 10          | 28          | 18          | 28          | 18          |
| 1.38      | 19          | 19          | 14          | 14          | 44          | 28          | 44          | 28          |
| 1.96      | 23          | 16          | 24          | 17          | 60          | 39          | 62          | 40          |
| 2.27      | 25          | 18          | 25          | 18          | 67          | 43          | 71          | 46          |
| 2.98      | 30          | 21          | 31          | 22          | 79          | 51          | 84          | 55          |
| 4.10      | 36          | 26          | 37          | 27          | 94          | 61          | 100         | 65          |
| 5.98      | 46          | 33          | 46          | 33          | 113         | 73          | 118         | 77          |
| 7.34      | 52          | 37          | 52          | 38          | 124         | 80          | 129         | 83          |
| 8.01      | 54          | 39          | 54          | 39          | 129         | 83          | 134         | 87          |
| 9.01      | 58          | 42          | 58          | 42          | 135         | 87          | 139         | 90          |
| 10.01     | 62          | 44          | 61          | 45          | 140         | 91          | 145         | 94          |
| 14.05     | 73          | 52          | 72          | 52          | 153         | 99          | 159         | 103         |
| 16.24     | 77          | 56          | 77          | 56          | 159         | 103         | 165         | 107         |
| 19.90     | 85          | 61          | 84          | 61          | 166         | 107         | 173         | 112         |
| 23.96     | 92          | 66          | 92          | 67          | 173         | 111         | 181         | 117         |
| 26.97     | 97          | 70          | 96          | 70          | 176         | 114         | 185         | 120         |
| 30.26     | 101         | 73          | 100         | 73          | 180         | 116         | 190         | 123         |
| 34.08     | 105         | 76          | 105         | 76          | 183         | 119         | 194         | 126         |
| 37.25     | 108         | 78          | 108         | 79          | 186         | 121         | 197         | 128         |
| 41.95     | 113         | 81          | 113         | 82          | 190         | 124         | 202         | 131         |

Table 15
Biogas (Bg) and CH₄ yields (cumulative value) for each time-step and digester (D9-D12) in test series 2. All values related to mL/g oDM for standard conditions (1013 hPa, 0°C, dry gas).

| Time [d] | D-9 Bg CH₄ | D-10 Bg CH₄ | D-11 Bg CH₄ | D-12 Bg CH₄ |
|----------|-------------|-------------|-------------|-------------|
| 0        | 0           | 0           | 0           | 0           |
| 0.33     | 0           | 0           | 0           | 0           |
| 0.90     | 0           | 0           | 0           | 0           |
| 1.38     | 0           | 0           | 0           | 0           |
| 1.96     | 0           | 0           | 0           | 0           |
| 2.27     | 0           | 0           | 0           | 0           |
| 2.98     | 1           | 1           | 4           | 4           |
| 4.10     | 2           | 2           | 6           | 6           |
| 5.98     | 3           | 3           | 9           | 9           |
| 7.34     | 5           | 4           | 11          | 11          |
| 8.01     | 5           | 5           | 12          | 12          |
| 9.01     | 6           | 6           | 13          | 13          |
| 10.01    | 8           | 7           | 14          | 14          |
| 14.05    | 11          | 11          | 16          | 16          |
| 16.24    | 15          | 14          | 17          | 17          |
| 19.90    | 35          | 34          | 18          | 17          |
| 23.96    | 61          | 59          | 20          | 19          |
| 26.97    | 70          | 67          | 23          | 23          |
| 30.26    | 77          | 75          | 31          | 31          |
| 34.08    | 90          | 87          | 54          | 53          |
| 37.25    | 96          | 92          | 65          | 64          |
| 41.95    | 102         | 98          | 71          | 70          | 184         | 130         | 185         | 133       |
Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships, which have, or could be perceived to have, influenced the work reported in this article.

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